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Improving Intersection Safety with Inter-Vehicle Communication

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A DISSERTATION SUBMITTED TO THE INSTITUTE OF COMPUTER SCIENCE OF THE UNIVERSITY OF INNSBRUCK IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Abstract

In the last century road traffic has become an integral part of our society although the likelihood of having an accident is not negligible. Passive safety measures (e.g., seatbelt) have helped to decrease the number of fatalities, but the accident rate cannot be reduced by them. Therefore, active safety measures, i.e., Advanced Driver Assistance Systems (ADAS), aim to assist drivers to prevent accidents.

Such systems use different sensor technologies to assess the situation, but they are limited to visual range. With the help of Inter-Vehicle Communication (IVC), sensor data can be distributed also to vehicles that are not recognizable otherwise. For example, Intersection Assistance Systems (IAS) need information already before vehicles get in visual range. This thesis aims to investigate how IVC can help to improve situation awareness for IAS.

The development of a suitable communication strategy for IAS does not only need a comprehensive understanding of the wireless channel, but also of the safety aspects. To gain insights into safety aspects of vehicles approaching an intersection, this thesis proposes two safety metrics—the risk classification and the intersection collision probability—to estimate the criticality of the situation with the information provided by IVC. These safety metrics are not only used to evaluate current communication strategies, but also to design a novel strategy in the context of IAS.

The developed situation-aware communication strategy adapts the information dissemination rate based on the intersection collision probability in addition to current congestion control mechanisms. With the help of application specific metrics, we are able to show substantially increased situation awareness for vehicles in dangerous situations compared to current communication protocols.

Finally, we address one fundamental challenge of IVC: For IAS it is crucial to distinguish whether communication just failed or no other vehicle is approaching the intersection. The presented cooperative communication strategy allows to deduce whether communication is able to provide the full picture or not, but also improves situation awareness considerably in case approaching vehicles are not able to communicate directly.

Kurzfassung

Im letzten Jahrhundert ist der Straßenverkehr zu einem zentralen Bestandteil unserer Gesellschaft geworden. Es besteht jedoch ein nicht vernachlässigbares Risiko in einen Unfall verwickelt zu werden. Passive Sicherheitsvorkehrungen (z.B. Sicherheitsgurte) haben bereits geholfen die Anzahl der Verkehrstoten zu senken, aber sie können keine Unfälle verhindern. Aus diesem Grund sollen aktive Sicherheitsmaßnahmen, wie zum Beispiel Fahrerassistenzsysteme (ADAS), Autofahrern helfen, Unfälle zu vermeiden.

Solche Sicherheitssysteme verwenden unterschiedliche Sensortechnologien, um die Straßenverkehrssituation einschätzen zu können. Die derzeit verfügbaren Sensoren können allerdings nur die unmittelbar sichtbare Umgebung erfassen. Mit der Unterstützung von Fahrzeug-zu-Fahrzeug-Kommunikation (IVC) können beliebige Sensordaten zwischen den Fahrzeugen auch außerhalb dieses Bereichs ausgetauscht werden. Kreuzungsassistenten (IAS) müssen beispielsweise die Situation bereits einschätzen können, bevor Fahrzeuge füreinander sichtbar sind. Diese Dissertation untersucht, inwieweit Fahrzeug-zu-Fahrzeug-Kommunikation helfen kann, die Situationseinschätzung für Kreuzungsassistenten zu verbessern.

Die Entwicklung geeigneter Kommunikationsstrategien für Kreuzungsassistenten bedarf jedoch nicht nur eines umfassenden Verständnisses für den drahtlosen Übertragungskanal (wireless channel), sondern auch eines tieferen Einblicks in Verkehrssicherheitsaspekte. Deshalb werden in dieser Arbeit zwei Sicherheitsmetriken vorgestellt, die sich mit Sicherheitsaspekten von Fahrzeugen auseinandersetzen, die sich gerade einer Kreuzung nähern. Beide Metriken – die diskrete Risiko-Klassifizierung als auch die Kollisionswahrscheinlichkeit im Kreuzungsbereich – versuchen mit Hilfe der Informationen, welche über Fahrzeug-zu-Fahrzeug-Kommunikation ausgetauscht werden, die Gefahrensituation einzuschätzen. Diese Sicherheitsmetriken dienen nicht nur der Bewertung aktueller Kommunikationsstrategien, sondern auch der Entwicklung neuer Strategien im Hinblick auf Kreuzungsassistenten.

Die hier vorgestellte Kommunikationsstrategie bezieht die Situationseinschätzung der Fahrzeuge in die Informationsverbreitung mit ein und erlaubt Fahrzeu-

gen in gefährlichen Situationen Mechanismen der drahtlosen Überlastvermeidung zu umgehen. Dadurch können Fahrzeuge mit einer erhöhten Kollisionswahrscheinlichkeit öfter Informationen austauschen. Mit Hilfe anderer anwendungsnaher Metriken wird gezeigt, dass die vorgestellte Kommunikationsstrategie es ermöglicht, Gefahrensituationen besser einzuschätzen als mit derzeitigen Kommunikationsprotokollen.

Schlussendlich wird noch eine grundlegende Herausforderung von Fahrzeug-zu-Fahrzeug-Kommunikation diskutiert: Für Kreuzungsassistenten ist es essentiell unterscheiden zu können, ob sich wirklich kein anderes Fahrzeug der Kreuzung nähert oder ob die Kommunikation fehlgeschlagen ist. Darum wurde eine kooperative Kommunikationsstrategie entwickelt, die es den Fahrzeugen ermöglicht zu ermitteln, ob die empfangenen Informationen eine korrekte Einschätzung der Situation zulassen. Darüber hinaus ist die kooperative Kommunikationsstrategie in der Lage die Informationsverbreitung zu verbessern, wenn Fahrzeuge nicht direkt miteinander kommunizieren können.

Contents

Chapter 1

Introduction

Already during the early days of automobiles it was realized that safety is an important aspect when driving a car. The most prominent safety measure, which was introduced in 1950 and is still mandatory in present cars, is probably the invention of seatbelts [1]. Seatbelts belong to the group of *passive safety* measures, which try to reduce the effect of an accident on passgengers. Although passive safety measures probably saved already millions of lives in everyday road traffic in the past decades, the desire to prevent crashes has led to the development of *active safety* systems. One prominent example for active safety systems is the anti-lock braking system, which is mandatory in the EU since 2007.

Figure 1.1 depicts the number of road traffic accidents and fatalities in Austria per year since 1964 reported by Statistik Austria [2]. Concerning the number of fatalities in road traffic accidents, it can be seen that this number continuously decreases starting from 1973. The first major drop can be attributed to first

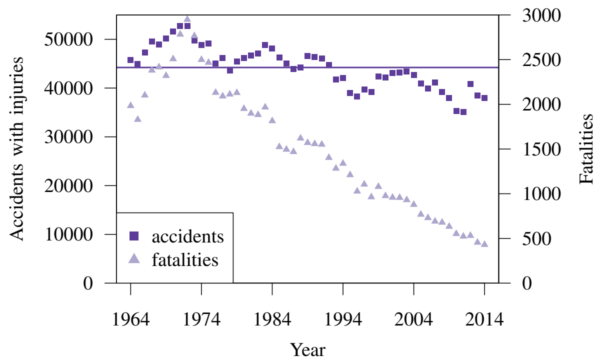


Figure 1.1 – Road traffic accident statistic in Austria from 1964 till 2014 (numbers provided by Statistik Austria in [2]).

passive safety measures, most importantly the mandatory seat belt wearing laws. The further decrease has been the successful result by additional passive safety improvements (e.g., airbag and improvements of the physical structure of vehicles). In total, the number of fatalities has decreased by more than 85 % when comparing 2014 with the maximum number of fatalities reached in 1972. It can be said that modern cars are safer than ever before.

However, the number of road traffic accidents involving personal injuries did not change significantly in the last 50 years and shows only a slight decrease over time. In particular, even recent numbers of road traffic accidents (2000 - 2004) are close to the long term average of 44 220 road traffic accidents per year (indicated as solid horizontal line in Figure 1.1). Considering the efforts by governments to enhance road traffic safety by enforcing speed limits, building safer roads, and educational campaigns, this slight decline seems to be negligible. Indeed, the kilometers travelled by car per year and person are constantly growing [3] and hence the positive trend of the accident rate can be valued already as success, because the accident probability per travelled kilometer decreases. Not only public efforts are enabling this trend, but also the deployment of various recently developed active safety systems such as traction control systems or adaptive cruise control. Nevertheless, the accident statistics show that there is still room for improvement. Therefore, current research efforts concentrate on active safety systems, because only active systems can help to avoid accidents and hence reduce the probability of an accident per travelled kilometer.

The term Advanced Driver Assistance Systems (ADAS) refers to recently introduced active systems, which are to some extent already deployed in present cars. These ADAS usually combine a vast amount of different technologies (i.e., sensing technologies) to assist the driver in a useful and more importantly safe way. In the following technologies and their envisioned sensing environment are listed (a comprehensive overview of available automotive sensors can be found in [4]):

- Ultrasonic sensors [5] are used for short range distance measurements and are currently employed in many cars to enable parking assistants.
- Short [6] and long [7] range radar systems are also used for distance measurements and support Adaptive Cruise Control (ACC) for example.
- Single camera [8] and Stereo camera [9] can be utilized to detect vehicles, but also for pedestrian detection [10].
- LIDAR [11] and 3D LIDAR [12] aim to detect objects (vehicles, buildings, and pedestrians) in the vicinity of cars and are used for ACC and are the main sensor of *Google's Self-Driving Car* [13].

- Time-of-Flight cameras [14] are also used for object detection, but compared to a LIDAR capture the whole scene at once.

However, all these sensor-based ADAS have a common drawback: They are only able to improve situation awareness if the potential cause (vehicle, pedestrian or other obstacle) is within visual range. A promising idea to overcome this visual limitation is to use *wireless communication between vehicles* to provide cooperative awareness of vehicles independent of visibility constraints. In addition, communication between vehicles allows to build not only active safety systems, but to go one step beyond and develop *cooperative safety systems*.

1.1 Vehicular Communication

The potential of communication between vehicles (*vehicular communication*) has triggered research on various communication technologies: For example the SOCRATES [15] project evaluated cellular approaches in the 1990s and studies on ad-hoc communication [16] have been carried out shortly after the IEEE 802.11 standard [17] has been released in 1999. The term *cellular communication* refers to wireless communication, which is coordinated by base stations, where each base station is responsible for one or multiple certain geographic areas so-called *cells*. Mobile phones (cellular phone or cell phone) are the most prominent example for cellular communication and have promoted world-wide deployment in the last decades. On the contrast *ad-hoc communication* does not depend on infrastructure and wireless communication is initiated, coordinated and executed by the nodes in a decentralized fashion.

Vehicular communication research can be still divided into cellular and ad-hoc approaches, although the border is getting fuzzy: Recent cellular standardization efforts push forward to integrate device-to-device communication (e.g., LTE direct [18]), which enables direct communication without infrastructure (i.e., base stations or access points). Though also ad-hoc communication research is moving closer to cellular approaches by considering the usage of infrastructure such as Roadside Units (RSUs) or Stationary Support Units (SSUs).

When looking at communication requirements for vehicular safety applications, it is evident that information delays play a major role. These delay constraints are probably the reason why cellular research only recently paid attention to vehicular safety applications (e.g., [19, 20]). In [21] the authors compared UMTS and LTE for vehicular safety communication and reported round trip times of around 350 ms for UMTS and in between 50–100 ms for LTE. Nevertheless, cellular approaches are a potential candidate for future vehicular safety applications, because the current LTE advanced standard and the next cellular generation (5G) consider direct device-to-device communication [22].

The usability of ad-hoc communication for vehicular safety applications has been a constant source of discussion. However, ad-hoc communication has been considered for safety purposes since the beginning of vehicular network research [16, 23] and recently many studies tried to show safety benefits [24]. But before discussing envisioned safety applications with the help of ad-hoc communication, we briefly outline why ad-hoc communication for vehicles has entailed various names and meanings over time on the different continents.

Dedicated Short-Range Communication (DSRC) refers to wireless communication of vehicles, but in Europe it refers to communication of vehicles with electronic toll infrastructure, whereas in the U.S. it characterizes vehicular ad-hoc communication. Whenever DSRC is mentioned, we refer to the second meaning of it. The vehicular networking community adopted the name Vehicular Ad Hoc Network (VANET), which has a close relationship to Mobile Ad Hoc Network (MANET). However, we use the more recent name IVC, which better reflects the fact that communication between vehicles cannot make use of traditional network topologies or routing protocols. Other names for ad-hoc communication between vehicles include Vehicle-to-Vehicle (V2V) and Car-to-Car (C2C), which are used in the U.S. and Europe, respectively. Moreover, the consideration of infrastructure added more variants such as Vehicle-to-Infrastructure (V2I), Car-to-Infrastructure (C2I), Vehicle-to-X (V2X), and Car-to-X (C2X), where the first two refer to communication of vehicles only with infrastructure and the remaining two terms to communication with both—vehicles and infrastructure.

Coming back to potential safety applications enabled by IVC, we find that according to [25], they are manifold:

- **Emergency Electronic Brake Light** enables vehicles to broadcast if they perform an emergency braking maneuver. By analyzing received information vehicles can assess the situation and present a warning to the driver if necessary.

- **Forward Collision Warning** is similar to the emergency electronic brake lights, but covers not only an emergency braking maneuver. The driver is warned if a forward collision becomes likely.

- **Lane Change Warning / Blind Spot Warning** aim to warn the driver when a dangerous lane change is being performed either due to a vehicle being in the blind spot or vehicles on the other lane decelerating.

- **Do Not Pass Warning** act as an overtaking assistant by issuing warnings if opposite traffic does not allow a safe pass.

- **Intersection Movement Assist** warns the driver in the case the intersection crossing is not safe and yields a high collision probability.

- **Control Loss Warning** allows to warn drivers that other vehicles have lost control.

In the last decade many studies have been carried out on these potential safety applications. Nevertheless, there is still a gap between different research communities: The transportation science and control theory proposed warning systems and controllers for Intelligent Transportation System (ITS) applications without considering potential communication outages. On the other hand, the IVC research community failed to prove the impact of communication performance on safety. The developed communication protocols merely tried to meet simplistic communication requirements instead of studying the communication needs of individual vehicular safety applications. Therefore, the link between the enabling technology—in this case IVC—and vehicular safety is still missing and questions like “How many crashes can (theoretically) be mitigated?” and “Can the impact of crashes be significantly reduced?” have not yet been answered by the IVC research community [26].

We decided to concentrate on a single vehicular safety application—so called *Intersection Assistance Systems (IAS)*. With the term IAS, we refer to future intersection movement assistants, which might consist of solely warning systems, automated reactions or a gradual combination of both. Figure 1.2 illustrates an envisioned driver view when using visual augmentation to highlight a potential danger for the driver. With the help of future IAS, the driver can literally “see through buildings”.

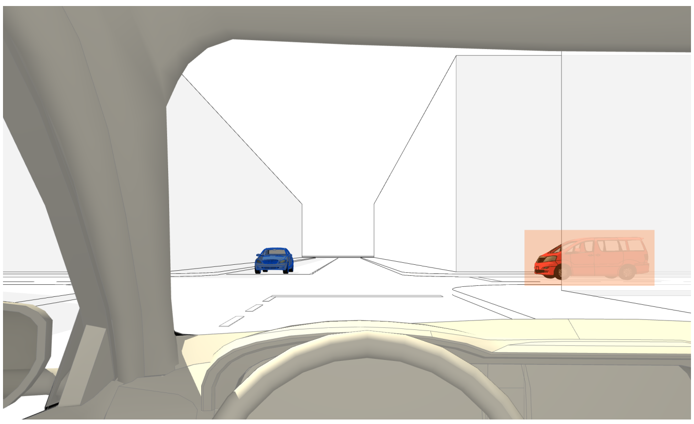


Figure 1.2 – The envisioned driver view when using an IAS (via visual augmentation the driver can literally “see through buildings”).

There are three reasons for concentrating on IAS: First, the number of crashes at intersection is very high and in many cases cause seriously injured people or fatalities [27]. Second, as mentioned before IVC is currently the only possibility to increase situation awareness of vehicles when the vehicles are not in visual range of each other. Since IAS should assist the driver in exactly these situations, they are a perfect example for demonstrate the power of cooperative safety applications in future vehicles. Third, the communication conditions are particularly challenging at many intersections, because buildings obstruct the Line of Sight (LOS) between vehicles that need to communicate. The effects of buildings on radio propagation has been pointed out by several real-world measurement studies [28, 29].

Moreover, the presented work is based on the following assumptions: We assume a penetration rate of 100 % of communicating vehicles, although it is clear that especially in the beginning additional measures will be needed to promote the deployment of communication [24]. The reason for considering full penetration is that this work aims to point out possible and more importantly feasible safety benefits of IVC to improve intersection safety. Another assumption in our studies is that the information of aforementioned sensors is not helpful due to visual obstructions between endangering vehicles and hence cannot improve road traffic safety at intersections. Nevertheless, sensor technologies will be integrated into future IAS to increase accuracy, reliability and plausibility of wireless positioning information in case vehicles come into visual range of each other. Regarding vehicle positioning we assume that almost perfect position information (down to cm accuracy) is available. Currently many different research ideas (e.g., sensor data fusion, integration of vision, and odometer data) are pursued in order to enhance positioning information in particular in urban environments [30, 31].

1.2 Overview and Contributions

In the following an overview of the content of this thesis is provided:

- First, we revisit fundamentals in Chapter 2, which are important in the context of this work. We start with a review of vehicular safety systems and continue with insights on IVC (history, state-of-the-art and standards). This chapter is concluded with a review on performance evaluation of IVC.
- In Chapter 3, we propose two models for simulating driver behavior when approaching an intersection. Then we define and validate two novel safety metrics (the *risk classification* scheme and the *intersection collision probability*), which can be used for different purposes: First, they can be employed to evaluate communication strategies of IAS. Second, they can

also serve as control metric for communication strategies. Since we use the intersection collision probability as control metric, we then explore communication metrics that allow to assess whether communication has been sufficient or not. Moreover, these proposed safety metrics could be used as decision metric for automated reaction controllers for future IAS.

- In Chapter 4 we study communication strategies for IAS in detail. We start with the evaluation of static beaconing approaches using the previously defined safety metrics. This initial study reveals some first insights on the needed dissemination rate for IAS. Since such static beaconing approaches congest the channel, we then evaluate current state-of-the-art beaconing approaches that dynamically adapt their dissemination rate based on current channel conditions. However, these approaches completely neglect the different situations in which vehicles are and hence are not able to provide frequent communication between endangered vehicles. Therefore, we propose the *situation-based rate adaptation* algorithm, which enables vehicles in dangerous situations to communicate more frequently by getting a temporary exception of congestion control mechanisms.

- In Chapter 5 we study the potential of cooperative communication strategies for IAS. First, a simple, but not practicable, relaying mechanism is investigated to demonstrate the potential increase in situation awareness for IAS. Second, a cooperative communication strategy that tries to keep the additional channel load as low as possible is developed. In addition, the cooperative communication strategy aims to detect critical communication outages during intersection approaches, which can be considered essential for developing fail-safe IAS.

- Finally, Chapter 6 summarizes the contributions and shows possible future research directions based on the findings. Moreover, it highlights that although the research is carried out in the context of DSRC, the contributions can be considered as helpful also in cellular communication research. The presented safety metrics in Chapter 3 are valuable and applicable without restriction for any future research in the context of IAS.

The three main contributions (i.e., *safety metrics*, *situation-aware communication*, and *cooperative communication* for IAS) of this thesis are presented in Chapter 3, Chapter 4, and Chapter 5. Hopefully, the presented findings help to develop fail-safe IAS in near future and hence allow the human society to save lives by advancing technology.

Chapter 2

Fundamentals

Safety while driving is for the automotive industry and the human society as important as other improvements to everyday road traffic and it has been a constant stimulus for innovations since the invention of automobiles. Due to the vast amount of safety features in modern cars (cf. Chapter 1), nowadays road traffic is safer than ever before when comparing accidents per travelled kilometer. But since our society is getting more mobile almost every day [3], the number of fatalities has not been reduced substantially in the last 20 years [2].

Therefore, improving road traffic safety is still important and the potential of new technologies to increase vehicular safety are constantly evaluated by researchers. It is a non-trivial task to show safety benefits of new technologies, which are not yet adopted by the market. For this reason, evaluation options of vehicular safety features (including additional technologies) are reviewed with focus on their applicability in the context of IVC as well as IAS.

IVC does not only provide the possibility to enhance vehicular safety, but also to increase efficiency and comfort while driving a car. Nevertheless, we summarize general developments only shortly and concentrate on safety specific research efforts, because they are the focus of this work. A short historical overview of IVC research provides the basis to understand why research efforts have converged to a rather simple communication primitive: one-hop broadcasts, called *beacons*. Current standardization efforts have picked up ideas from these early studies and proposed first standards that consider beacon-based communication. In addition to the IEEE 802.11p standard [32], the available standards cover also specifications regarding spectrum usage, message format, and prioritization. However, channel congestion control methods are needed, because usual Medium Access Control (MAC) mechanisms of the IEEE 802.11 standard are not able to control congestion caused by such broadcast-based communication. Exactly these channel congestion control mechanisms have been one of the major research topics in the past few years in IVC research and hence are covered in more detail.

Besides these general IVC research studies, also application-oriented research tried to show benefits of using IVC. In particular the research community paid much attention to demonstrate safety benefits of this technology, because vehicular safety applications are possibly the main driver for a wide deployment of DSRC radios in vehicles. Again, the focus of this review is the context of IAS.

The last missing fundamental piece is the evaluation of IVC with respect to possible safety improvements. The possible evaluation methods *experimental*, *analytical*, and *simulative* are shortly discussed for the researched vehicular safety application. Although simulations are usually considered as method of last resort, they offer detailed investigations with perfect repeatable experiments that allow to assess different IVC strategies for IAS with exactly the same driver behavior. Therefore, the presented simulation studies in this thesis offer a good possibility to explore IVC for improving road traffic safety at intersections.

Nevertheless, the reproducibility of simulation results is a constant source of discussion and therefore, we reviewed more than one hundred vehicular network simulation studies and discuss the trends in the simulation of vehicular networks from 2009 till 2011. The provided trend analysis shows a clear consolidation of simulation methods and models, but also points out the lack of exhaustive and complete simulation descriptions. To guide future IVC simulation studies a list of five basic building blocks, which need to be covered to ensure reproducibility and comparability of results, is proposed. This list includes also physical layer models, i.e., radio propagation models, although they have not been surveyed at that time, because consolidation of models was still in progress. In order to provide a full overview of IVC simulations we shortly review available models for *unobstructed communication* and *obstructed communication* between vehicles on the road. Finally, the used simulation environment is outlined with respect to the five basic building blocks of IVC simulation studies.

The literature review of IVC simulation studies is based on the following two publications (my contribution was to review the literature body of more than 100 papers and carry out a detailed trend analysis):

- S. Joerer, F. Dressler, and C. Sommer, “Comparing Apples and Oranges? Trends in IVC Simulations,” in 9th ACM International Workshop on Vehicular Internetworking (VANET 2012). Low Wood Bay, Lake District, UK: ACM, Jun. 2012, pp. 27–32.
- S. Joerer, C. Sommer, and F. Dressler, “Toward Reproducibility and Comparability of IVC Simulation Studies: A Literature Survey,” IEEE Communications Magazine, vol. 50, no. 10, pp. 82–88, Oct. 2012.

2.1 Vehicular Safety

Vehicular safety systems need to be designed that they even work or fail without harming the driver when single components of the system fail. Therefore, safety engineering methods have been always integrated in the development process of vehicular safety systems. The aim of safety engineering is to assure that life-critical systems do not harm the user or its environment if single system components fail.

In the case of vehicular safety, redundancy plays a major role to ensure proper functioning of critical safety systems [33] such as the braking system for example. However, even redundancy cannot assure 100 % reliability of systems and it is important to notice that safety is not equal to reliability. In particular, safety considers that if components malfunction they should fail safely without causing severe harms to the system user.

Future vehicular safety applications will rely on multiple sensors to increase redundancy and make use of sensor data fusion [34]. As discussed in the previous chapter, communication is the only technology, which is able to provide situation awareness to vehicles if they are not in visual range. Therefore, the evaluation of communication reliability in the context of vehicular safety applications is of utmost importance, but also the detection of communication failures (as in [35] for example) is compulsory to enable vehicular safety. These two-fold requirements for enabling vehicular safety become particularly visible when carrying out a fault tree analysis as in [33] for drive-by-wire systems.

In order to convince car manufacturers that new safety-enabling technologies are ready for deployment in cars, it needs to be shown that they support a usable degree of reliability as well as the possibility to detect faults of technologies. The first aspect—the usable degree of reliability—can be shown by studying the impact of new technologies on vehicular safety (described in detail in the following). The fault detection and the accompanying requirement that the usage of new technology must not degrade safety at any time is another important aspect that needs to be proven.

2.1.1 Evaluation of Impact on Safety

All future safety-enabling technologies need to be evaluated with respect to their potential vehicular safety application. Sensing technologies such as radar, LIDAR and stereo cameras are usually evaluated in controlled real-world settings (e.g., [9, 12]). These technologies can be mounted on vehicles to gather measurements, which later can be used to analyze various algorithms off-line in more detail.

However, for IVC the situation is different: The information is not sensed by the own vehicle but depends on transmitted information of others to improve its own safety. Therefore, it requires enormous efforts to test IVC safety applications in real-world. Recently large field operational tests have been carried out in the U.S. and Europe (summarized in [24]).

For example, the simTD project [36] in Germany reported that the implemented IAS was technically working in 100 % of the cases where the sender was able to provide the specified information correctly in time (which was the case in only 31 %, reported in [37]). Moreover, it is expected that more communication issues/outages appear in real-world settings where radio propagation might be obstructed by buildings or other obstacles. This field operational test was not able to show a direct impact of IVC on vehicular safety using real-world tests, but they pointed out the safety benefit of IAS by simulating accidents with real-world data [38].

Hence, the safety benefit of using IVC has not yet been demonstrated adequately by these field operational tests. Specifically, the link between the safety benefit analysis using real-world accident data and the technical evaluation of IAS is missing.

One possibility to provide a link between safety analysis and usual technology evaluations (using network metrics for evaluating communication strategies) is to use a *risk estimation*, which reflects the risk for vehicles in different situations. Depending on potential crash situations different models have been proposed:

- **Rear-end collisions** (e.g., [39])
- **Lane-change related collisions** (e.g., [40])
- **Intersection collisions** (e.g., [41–47])
- **Arbitrary collisions** (e.g., [48, 49]).

These models do not only differ in the situation they model, but also in their intended purpose and level of detail.

Oh et al. [39] uses vehicle trajectory data to estimate the risk for rear-end collisions. Pande et al. [40] analyze accident data in order to appraise the risk of lane-change related collisions.

Brännström et al. [49] have modeled lateral as well as longitudinal movements and vehicle dynamics to avoid arbitrary vehicle collisions. Tan et al. [48] proposed the usage of future trajectory prediction to cooperatively avoid collisions. However, the focus of this work was on the feasibility of using simple GPS receivers and motion sensors. In the following the intersection collision risk estimation models are investigated in more detail.

2.1.2 Safety Aspects of Intersection Assistance Systems

Wang et al. [41] investigate the collision risk of bicycles and motor vehicles at signalized intersections. Lefèvre et al. [44] show the feasiblity of risk assessment at intersections by comparing intention and expectation. In [45] Liebner et al. also use interference drivers' intent to estimate collision risks at intersections.

Several works on risk estimation for automated collision avoidance at intersections exist: In [43] Verma and Del Vecchio study a hybrid control approach for cooperative active safety systems. Hafner et al. [46] have developed an automated V2V collision avoidance application for intersections. Collisions are avoided by controlling the longitudinal movements of both vehicles by monitoring the *capture set*, which is the set of all situations where a collision becomes unavoidable [42]. In a controlled two-car testbed they were able to show that the controller is able to avoid collisions under favorable communication conditions.

The approach presented in [47] takes communication data (including sensor data of infrastructure at the intersection), vehicles local perception, and self localization into account and uses Bayesian Networks to estimate collision risks at intersections. Another work that focuses on cooperative multi sensor network for traffic safety at intersections has been published in [50].

In addition to the afore-mentioned field operational tests, the safety benefit of IAS has also already been shown by using *driving simulator* studies. In 2009, Chang et al. [51] studied the effects of audio-based IAS on the drivers' reaction time. They were able to show a substantially reduced accident rate, which is made possible by lower driver reaction times. In [52] Chen et al. studied the impact of different warning systems (audio and visual) and showed that the number of intersection crashes could be reduced by 40–50 % by IAS. Besides these two driving simulator studies, real-world experiments in [46] proved the feasibility of automated intersection collision avoidance systems.

2.2 Inter-Vehicle Communication

In the following the background of IVC is outlined in detail. We start with a short historical overview of IVC research. It reveals that first MANET protocols have been investigated in the vehicular context, but that several peculiarities (regarding the environment and the applications) of vehicular networks have opened a completely new research domain. These early findings did not only influence the current state-of-the-art of IVC research, but obviously also the standardization process in the U.S. and Europe. Finally, we review related work with respect to IAS and discuss how the contributions of this thesis extend the current research of IVC for intersection safety.

2.2.1 Historical Overview

Historically, research on vehicular networks was started by adapting MANETs to the vehicular environment and hence they were called VANETs. One major research direction in these early days of vehicular communication was the deployment and adaptation of existing routing protocols to this new application domain. Examples include AODV [53], OLSR, and DYMO [54].

These early studies neglected the demands of envisioned vehicular applications and tried to apply existing information dissemination strategies. In addition, two other important aspects had been overlooked at the beginning of vehicular network research: the *mobility of vehicles* is different compared to usual simulated mobility patterns [55–58] and the *radio propagation* is influenced by various effects predominant in the vehicular environment [59], for example: by buildings [60, 61], by vehicles [62], or the surrounding environment [63, 64].

It turned out that it is rather difficult to establish usual network topologies in such a dynamic environment. Therefore, the research community started to investigate beaconing approaches, i.e., one-hop broadcasts [65–68]. Such approaches have been identified as promising candidates to enable vehicular safety applications [69–71]. Nevertheless, routing of information for non-safety applications is still being researched (e.g., [72, 73]).

Another kind of communication strategies for vehicular networks are so-called geographical approaches (can focus on geographical routing or addressing). GeoCast [74] describes the original idea and has been first adopted to MANETs [75] before it was transfered to VANETs [76].

DV-Cast [77] aims at mitigating the broadcast storm problem (cf. [78]) by organizing rebroadcasts by the distance to the original sender and making use of the driving direction. It has been designed for highway situations and hence UV-Cast [79] has been developed to cope with the complex road topology in urban environments. Both protocols make use of the store-carry-forward mechanism. Another topographical approach is TO-GO [80, 81], which considers road topology information for routing decisions.

Cluster-based approaches represent another possibility to organize communication in a way that makes use of vehicular mobility [82]. In particular clusters are formed among road users that travel in the same direction. The clustering process can be either proactive [83] or passive [82]. Cluster-based communication can also be used to separate communication on different communication technologies. For example, in [84] the authors proposed to use DSRC for intra-cluster communication and 3G/4G cellular communication to enable inter-cluster communication.

Very recently it has been proposed that vehicles themselves can be the main ICT resource for smart cities [85]. This allows a completely different perspective where cars are not only acting as mobile sensors, but are also used to store information cooperatively.

To conclude this brief and general research history of vehicular networks, we want to emphasize that currently mostly beaconing approaches are considered as communication strategies for vehicular networks and in particular vehicular safety applications.

2.2.2 Communication Standards

In 2010 the IEEE 802.11p standard [32] has been published in order to address the need for DSRC in vehicular environments. This amendment to the original IEEE 802.11 standard [17] (published in 1999) specifies how the existing standard has been altered to better support the demands of wireless communication in the highly dynamic and mobile environment of vehicles. Since 2012 the IEEE 802.11 standard suite [86] also includes the amendments of IEEE 802.11p published in 2010, although it is still important to refer to IEEE 802.11p for wireless communication in vehicular environments.

The vehicular standard specifies a doubling of the Orthogonal Frequency-Division Multiplexing (OFDM) timing parameters (e.g., the guard interval, symbol duration, etc.) and since the bandwidth is halved to 10 MHz, the nominal throughput is halved as well ranging from 3–27 Mbit/s. Another important amendment is the introduction of a wildcard Basic Service Set (BSS), which enables communication without BSS negotiation, and hence facilitates inter-vehicle communication even for very short contact durations in the order of seconds.

Above this common physical layer standard, the U.S. and Europe are currently standardizing different protocol stacks for vehicular networks, but both will operate in the 5.9 GHz band, which has been reserved for vehicular communication. In particular the European standard has already slight differences in the MAC although this is defined as well in IEEE 802.11p. The U.S. are standardizing the vehicular networking stack in the IEEE 1609 standard suite and Europe defines a similar protocol stack in the ETSI ITS-G5 standards. However, regarding the periodic exchange of cooperative awareness messages (in research commonly named *beacons*) they share a common concept, albeit under different names: Basic Safety Message (BSM) [87] and Cooperative Awareness Message (CAM) [88]. Please note that we later use the terms CAM and beacon interchangeably and the our presented findings are valid also for BSM, because both contain all awareness information needed for IAS.

In the following, we first describe the two different protocol stacks to provide a full picture of current communication standards in vehicular networks. We outline a part of the European standard as well as recent research proposals regarding the exchange of cooperative awareness information.

2.2.2.1 North American Standardization Efforts

As mentioned earlier, the U.S. have standardized their higher layer vehicular networking stack in the IEEE 1609 standard suite, which is also called Wireless Access in Vehicular Environments (WAVE). The standardization is ongoing and the working group is continuously updating the standards, but at the time of writing the single-radio assumption for vehicles for these standards was still valid. The FCC has reserved 7 channels for the usage of DSRC in the vehicular environment.

The IEEE 1609 standard suite makes use of synchronized channel switching of all nodes (standardized in the IEEE 1609.4 Standard for WAVE Multi-Channel Operation [89]). The idea behind channel switching is that the nodes spent the first 50 ms of every UTC second on the Control Channel (CCH) where the nodes can announce services provided on the different Service Channels (SCHs) in the next 50 ms. This procedure is repeated for the rest of the time and allows concurrent exchange of data in the SCH interval on multiple channels. To account for possible synchronization errors, a so-called guard interval of 4 ms (which remains unused) has been introduced after every channel switch.

Although channel switching seems to be an important feature in the context of single-radio vehicles, it has been shown that it has several drawbacks on cooperative awareness. One major drawback is that the probability of packet loss is much higher at the beginning of the switching intervals [90]. Another important fact has been highlighted in [91]: For the exchange of BSM only half of the time is available since in the second half not necessarily all nodes might be tuned to the same channel.

Medium Access Control

The IEEE 802.11 standard, which is based on Carrier Sense Multiple Access (CSMA) with collision avoidance, provides two different methods for channel access methods: Distributed Coordination Function (DCF) and Enhanced Distributed Channel Access (EDCA). DCF provides basic access mechanisms without Quality of Service (QoS) classes but with the help of binary exponential backoffs, request-to-send, clear-to-send, and positive acknowledgments for unicast transmissions.

Table 2.1 – Access Categories for EDCA in IEEE 802.11p.

Name	CW_{min}	CW_{max}	$AIFSN$	Arbitrary Inter-Frame Space (AIFS)
AC_BK	15	1023	9	149 µs
AC_BE	15	1023	6	110 µs
AC_VI	7	15	3	71 µs
AC_VO	3	7	2	58 µs

EDCA—as used in IEEE 802.11p—supports four Access Categorys (ACs) by using four different access queues, which differ by contention window, the AIFS time, and have their own backoff timer. Therefore, within the EDCA system *virtual collisions* can occur and are resolved by giving higher priority frames access to the channel. Table 2.1 lists all ACs with their corresponding parameters as well as the resulting AIFS time, which consists of $SIFS\,(= 32\,\mu s) + AIFSN * slottime\,(= 13\,\mu s)$. In order to circumvent capturing of the channel by a single device, after every transmission the device has to enter a post-transmit backoff, which works similar as the normal backoff procedure.

BSM related standards

SAE J2735 standard [87] defines what information can and needs to be included in a BSM:

- Part I (**Basic Vehicle State**) is mandatory and contains information that has to be included in every BSM. It has a total size of 39 bytes.

- Part II (**Vehicle Safety Extension**) is optional and includes information related to the safety state of the vehicle.

Part I contains already all information of the vehicle state that we assume to be available for running IAS: timestamp, position (including latitude, longitude

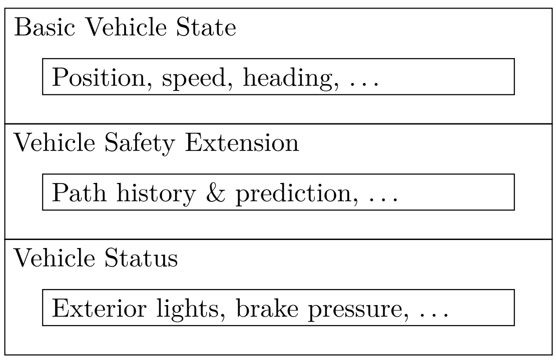


Figure 2.1 – Structure of a BSM.

and elevation), speed, heading, acceleration, brake system status, steering wheel angle, position accuracy and vehicle size.

Figure 2.1 depicts the structure of BSMs and lists also the two optional parts: The *Vehicle Safety Extension* might include for example further information about the past and future driving path. The second part *Vehicle Status* can contain further information such as the status of exterior lights or the currently applied brake pressure for example.

The transmission strategy of BSMs is not yet defined, but it is work in progress in the SAE J2945 standard [92]. This standard will most likely include sending rates of BSM, transmit power control, and an adaptive message rate control.

2.2.2.2 European Standardization Efforts

In Europe, ETSI has standardized the higher layer protocol stack for vehicular networks. It is also based on IEEE 802.11p, but has been adapted for ECC regulations. The standards dealing with vehicular communication are compiled in the ETSI ITS-G5 standard suite and include also other radio access technologies such as ordinary WiFi or cellular communication. Here the focus is on parts closely related to DSRC.

ETSI 202 663 [93] defines the physical and medium access control layer for ITS in Europe. Starting with a look at the multi channel operation of these standards, it can be noticed that these standards assume already a dedicated transceiver for the Control Channel, called G5CC, which is used to exchange safety information (i.e., CAMs) between vehicles. For all other services at least another transceiver needs to be installed to make use of the Service Channels, called G5SC.

Medium Access Control

As shown in Table 2.2, ETSI defines different values for the contention windows CW_{min} and CW_{max} for the four access categories. However, the behavior and functionality of the MAC remain the same as described in Section 2.2.2.1.

CAM concept

As mentioned earlier, ETSI has standardized the exchange of safety relevant information by introducing Cooperative Awareness Messages (CAMs) and the corresponding message exchange mechanisms in [88]. This standard, which has been published in 2014, limits the CAM transmission rate in general from 1–10 Hz per vehicle. The actual CAM generation is triggered by changes in the vehicle dynamics, such as speed, drive direction, and acceleration.

Table 2.2 – Access categories for EDCA in ETSI 202 663 [93].

Name	$CW_{\min}$	$CW_{\max}$	$AIFSN$	AIFS
AC_BK	15	1023	9	149 µs
AC_BE	7	15	6	110 µs
AC_VI	3	7	3	71 µs
AC_VO	3	7	2	58 µs

In the past there was no clear distinction between CAM generation and transmission and hence our simulation models assume that both events coincide. Moreover, the vehicle dynamics based generation of CAMs has not been considered due to its novelty (since August 2013).

Figure 2.2 provides a brief overview of CAMs and their composition. After the ITS PDU header, the basic container contains information about the vehicle type and the geographic position of the vehicle. The HF container consists currently of a single sub-container that takes fast changing (high-frequency) parameters of the vehicle such as heading or speed. The LF container contains all parameters that are static or slow changing (e.g., the dimension of the vehicle or exterior lights). In future also other containers that are not vehicle-related might be added to HF and LF depending on their update frequency. Moreover, the standard mandates that at least the Vehicle HF container is included in every CAM.

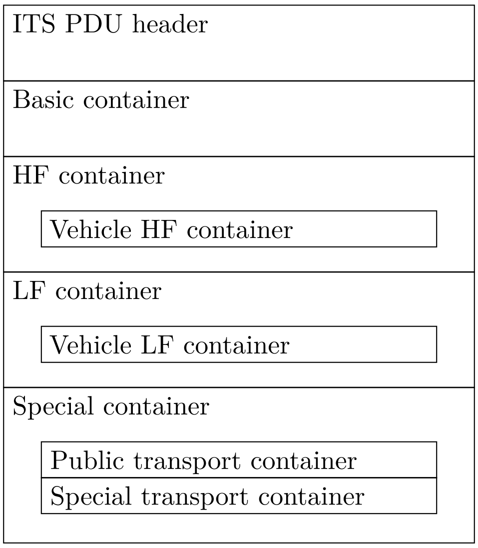


Figure 2.2 – Structure of a CAM.

Depending on the role of the ITS communication participant other role-specific containers can be added: Two examples are: public transport container and the special transport container (e.g., signaling heavy load).

CAM generation and dissemination

The first ETSI standard [94] describing how CAMs are generated and disseminated did not specify any dynamic adaptations to the current channel conditions. However, it specified the range of CAM intervals to be within 0.1–1.0 s. Therefore, research on static (fixed-period) beaconing usually used beacon intervals in this range.

The current ETSI standards carefully distinguish between the generation [88] and the actual transmission of CAMs, which might be subject to channel congestion control mechanisms [95]. The generation now also includes so-called CAM generation triggers, although the allowed interval range remains the same. The CAM generation can be triggered by [88]:

- the absolute difference of the current heading to the last sent heading exceeds 4°,
- the absolute distance between the current position to the last sent position exceeds 4 m, or
- the absolute difference of the current speed to the last sent speed exceeds 0.5 m/s.

2.2.3 Beaconing Approaches

Static beaconing approaches might congest the channel if the density of communicating vehicle is high [96, 97]. Hence vehicular networks demand channel congestion control mechanisms that are based on adaptive beaconing approaches [67,68].

Recent studies have proposed and investigated different mechanisms (e.g., [97–99]). In general, there are three main possibilities to regulate the channel and maintain efficiency: change the transmit power, modify the encoding (bit rate), or adapt the information dissemination rate (beacon rate).

Before we study two dynamic beaconing approaches—namely ETSI Transmit Rate Control (TRC) and Dynamic Beaconing (DynB) [96]—in detail, we briefly discuss recent IVC research related to channel congestion control.

Schmidt et al. explored in [67] the adaptation of the beacon rate by comparing the channel load and position errors for different beacon rates (1–10 Hz). They conclude that the beacon rate is dependent on the situation (i.e., speed and traffic density) and it can be adapted depending the own movement or on surrounding vehicles' movements. Moreover, they point out that microscopic rate adaptation (e.g., own movements) should have higher impact than macroscopic (e.g., the traffic density).

Sommer et al. proposed and investigated in [68, 100] the possibility to apply beacon rate adaptation in the context of traffic information systems—called Adaptive Traffic Beacon (ATB). The adaptation does not only take the channel conditions (i.e., number of neighbors, frame collisions, and channel load) into account, but also a priority scheme for traffic information. This study proved that it is important to consider the message utility in addition to channel metrics.

In [101] Tielert et al. studied the well-known Additive Increase Multiplicative Decrease (AIMD) mechanism (used for congestion control in todays Internet) as adaptation strategy of the transmit rate for vehicular safety applications. The measure for adapting the beacon rate in this work is the sensed channel load and by using the AIMD rate adaptation local as well as global fairness is achieved. Another approach, which uses only transmit rate adaptation, is called LIMERIC [102] and is based on a linear message rate congestion control algorithm. Both proposals aim to provide improved cooperative awareness for vehicular safety applications, but since they are evaluated only in the context of high density scenarios without considering shadowing effects of buildings it has not been shown whether they are able to provide frequent information updates in urban environments.

Tielert et al. also investigated the joint control of transmit power and rate adaptation to optimize packet reception for vehicular networks in [97]. This detailed study of channel congestion control mechanisms revealed that "for each distance and channel load target, there is a particular transmit power which optimizes reception performance independently of vehicle density [97]".

Another study that aimed to increase cooperative awareness of vehicles by changing the transmit power is presented in [103]. This proposal used a random selection of the transmit power to enhance cooperative awareness.

Schwartz et al. examined fairness issues when disseminating data for traffic information systems [98]. By combining beacon rate adaptation with fairness selection they achieved both: efficient usage of the wireless channel as well as a good fairness index.

Sepulcre et al. include three aspects in their protocol proposal presented in [104]: congestion control (channel access time as control metric), fairness (maximize the minimum transmit power of all vehicles) and prioritization (via EDCA mechanisms of IEEE 802.11).

To conclude this review of different approaches of channel congestion control, it needs to be mentioned that none of these general purpose studies investigated safety benefits of communication strategies in the context of IAS as outlined in

Section 2.1. However, there exist several detailed studies of IVC for rear-end collision avoidance [70, 105–107] and lane change assistance [104]. An overview of detailed studies regarding communication aspects of IAS is given in Section 2.2.7.

Regarding the three main possibilities to maintain the channel load at an acceptable level, Tielert et al. showed that the transmit power for a particular distance and channel load target does not need to be adapted [97]. In the context of IAS it is apparent to use the maximum transmit power, because Non Line of Sight (NLOS) communication is challenging enough [28, 29]. The adaptation of the encoding (different bit rate) might also cause problems, specifically in NLOS conditions where the most robust encoding, i.e., a low data rate, should be used. Hence, the most effective method to keep the channel load in an efficient range is to adapt the information dissemination rate.

2.2.4 Decentralized Congestion Control

ETSI standardizes not only general CAM generation and exchange mechanisms but also provides a standard, which ensures that the wireless channel does not get overloaded and hence becomes inefficient. The Decentralized Congestion Control mechanisms are detailed in [95] and outlined briefly in the following.

DCC uses the channel load as measure for varying several adaptation dimensions. The channel load represents the fraction of time where the channel has been declared busy, i.e., the average power level during a very short time (in [95] ETSI suggest to use probing intervals in the order of 10 µs) has exceeded the Clear Channel Assessment (CCA) threshold (ETSI uses −85 dbm as threshold). By using a measurement interval of around 1 s it is assured that several frames may be transmitted by arbitrary hosts in the interval and hence the measured channel load depends not only on a few transmissions. ETSI DCC defines the following possibilities to adapt the transmit behavior of individual nodes to current channel conditions:

- **Transmit power control** refers to the possibility to reduce the transmit power in order to increase spatial reuse of the wireless channel.
- **Transmit rate control** can reduce the information dissemination rate of messages and hence reduce channel usage of single stations dramatically.
- **Transmit datarate control** can restrict the encoding of frames to high datarates, thus increasing throughput albeit loosing robustness.
- **Sensitivity control** allows to adapt the CCA threshold.
- **Transmit access control** defines different handling for access categories depending on their priority.

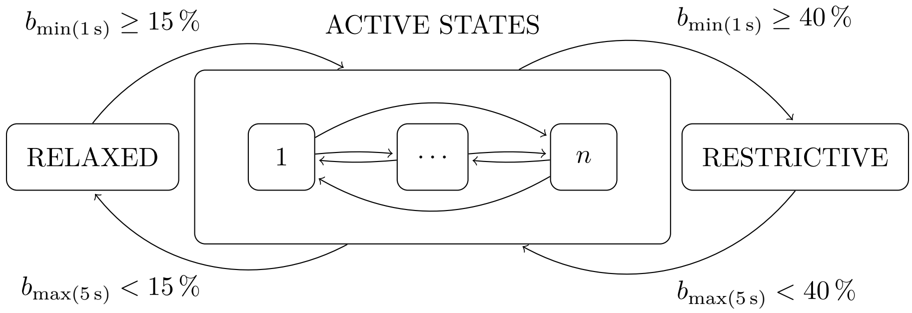


Figure 2.3 – DCC state machine.

Figure 2.3 depicts the full state machine of the DCC algorithm. Although the DCC state machine is defined for an arbitrary amount of ACTIVE sub-states, the default configuration for G5CC uses only one ACTIVE state and the default configuration of G5SC uses four of them. Since we are only interested in the dissemination of CAMs, Table 2.2 lists only the default values for G5CC.

In addition, the DCC [95] also provides an informative standard for an enhanced DCC algorithm, which also takes the DCC restrictions of surrounding vehicles into account (remote information). However, this extension, which has been suggested to improve performance and stability, is only applied when DCC is in the ACTIVE state.

2.2.5 Transmit Rate Control

In the following TRC, which is part of the ETSI DCC standard [95], is described in more detail, because later we compare different communication strategies for IAS with it. The reasons to pick TRC out of the possibilities of ETSI DCC congestion control mechanisms has been explained already in Section 2.2.3.

The current message interval I is adapted by using the DCC state machine depicted in Figure 2.3, where the three different states correspond to different message intervals I. State transitions are triggered when the channel load exceeds the pre-defined thresholds $b_{\min}$ or $b_{\max}$ for the times $T_{\text{up}} = 1\,\text{s}$ and $T_{\text{down}} = 5\,\text{s}$, respectively. The busy ratio b_t is calculated based on a measurement interval T_{m}, where b_t is the fraction of time the channel has been sensed busy when being

Table 2.3 – Default parameters for ETSI TRC [95].

Parameter	Value
$I_{\min}$, 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

probed between t and $t - T_{\mathrm{m}}$. Table 2.3 summarizes the default parameters, which have been used for the simulation studies presented in this thesis.

2.2.6 Dynamic Beaconing

Similar as other congestion control mechanisms DynB [96, 99] uses also the channel load for adapting its beacon rate and it tries to keep the channel load at a fixed, predefined level. The basic idea behind this so-called desired busy ratio b_{des} is that the number of frame collisions should be kept small in order to loose only a few messages. For adapting the beacon interval it monitors the channel busy ratio and adapts it based on this ratio and the current number of neighbors. If the current busy ratio is lower than desired, a configurable minimum value I_{des} is used. But if the current busy ratio exceeds the desired level, the beacon interval gets adapted.

To formally define the computation of the next beacon interval I, the number of neighbors N, which is available by keeping track of beacons from other vehicles, and the current channel busy ratio b_t are needed:

$$I = I_{\mathrm{des}} \left(1 + rN\right), \tag{2.1}$$

where $r = b_t / b_{\mathrm{des}} - 1$, is clipped in the interval $[0, 1]$. The adaptation of the beacon interval is performed each time a beacon is sent or was scheduled to be sent. If the channel conditions got worse, a beacon will be delayed until the current interval I is elapsed. By considering the number of current neighbors for the beacon interval adaptation, the interval is adapted according to the current vehicle density and hence can react faster in dense traffic situations.

We have shown in [99] that DynB is more reactive than TRC and is better able to handle situations where channel conditions are changing dynamically. In detail channel conditions are frequently changing especially in urban environments where buildings cause very strong shadowing effects—exactly the conditions where communication for IAS is of utmost importance.

2.2.7 Related Work for Intersection Assistance Systems

In the last decade several studies on communication aspects of IAS have been published, however, the focus was on different aspects. In 2005, Benmimoun et al. studied in [108] the impact of IVC on intersection safety. They reported that IVC without infrastructure support will only increase road traffic safety if the penetration rate is very high ($\geq 80\,\%$) and that infrastructure support can substantially reduce crash rates at intersections. Moreover, this very first study on IVC-based IAS revealed that there is an interdependence between necessary minimum communication range and speed levels at the intersection.

In [109] a complete simulation architecture for IVC-based intersection warning systems has been proposed in 2005. This early study on intersection warning systems included already many aspects, which are important for realistic simulations of IAS: radio propagation models (which consider both LOS and NLOS communication, discussed in Section 2.3.2), physical layer model, and driver behavior model. The authors reported that transmitting cooperative awareness information every 5 m (evaluation range from 5–50 m) is able to reduce the number of accidents by 36 %. Since the IEEE 802.11p standard [32] has only been released in 2010, the examined communication protocol considered a slotted non-persistent CSMA mechanism.

In 2007, OPRAM proposed opportunistic power and rate adaptation in so called algorithm regions, which need to be defined differently for each vehicular safety application in [110].

Le et al. investigated the channel load of DSRC systems for intersection safety in [111], but they employed only a simplified radio propagation model, which is based on a fixed unit-disk communication range. Appropriate radio propagation models for different vehicular environments are discussed in Section 2.3.2.

Tang et al. [112] studied timings for IAS by evaluating different transmission delays of 25 ms and 300 ms, which should represent normal and poorer channel conditions, respectively. To evaluate IAS the *time to avoid collision* metric has been introduced. This time represents the time frame until the point where the collision can be avoided just in time. The focus of this work was on event triggers within this time frame: when should drivers be warned, earliest and latest, reaction of driver, and different deceleration rates. The time to avoid collision metric might be a good possibility to compare communication strategies for IAS, but it depends on the behavior of both cars and hence it is not able to provide a full picture of the intersection approach situation. Moreover, the presented analysis used only two fixed transmission delays for communication, which in real-world environments will vary considerably.

Haas et al. [71] have analyzed the requirements on communication for crash avoidance applications in 2010. To study critical situations at intersections, they altered collision-free vehicle traces and introduced artificial collisions with constant velocity and high speed (> 7 m/s), which represent only a small portion of possible crash situations. Since radio propagation models for vehicular environments were not well investigated at that time, the authors also employed an idealistic radio signal propagation.

Sepulcre et al. evaluated an intersection collision warning system in real-world tests and found that in good channel conditions the beacon rate needs to be larger than 2 Hz in order to achieve 100 % successful warnings. In addition, they also investigated an interference scenario where a single interfering node was placed at the intersection or on one crossroad and congested the channel at different levels. The findings indicate clearly that the scenario where the interferer is located on one crossroad is more challenging. This study proved that IAS are feasible even under challenging communication conditions. However, it did not consider current state-of-the-art congestion control mechanisms and how they would affect desired beacon rates of vehicles in danger.

Very recently Zinchenko et al. in [113] used the path prediction error to derive the required information freshness (similar to the required update lag in [114]). They reported that depending on the vehicular safety application, path prediction errors ranging from 0.25–2 m might be acceptable and lead to required update lags in the order of 0.04–1.5 s for velocities of 13.89, 16.67 and 19.44 m/s. For IAS they considered required update lags of 0.15, 0.3 and 0.6 s.

In [115] Zinchenko et al. investigated the reliability of V2V communication at intersections in a simulation study by keeping the transmitter at different positions (crossroad, intersection center, and same road) and moving the receiver along its road. First, they study the effect of different densities on static message generation rates (5, 10 and 15 Hz) and conclude that in order to fulfill a required information freshness of 0.2 s the message generation rate needs to be higher than 5 Hz. Second, they highlight the impact of different intersection layouts by investigating closed (buildings placed at all corners), half-open (buildings at the two corners from where the receiver is approaching), and open (no buildings) intersections. Their results reveal that due to shadowing effects of buildings the communication performance in general is better the more buildings surround the intersection, because they split interference domains.

Privacy issues in IVC are of particular concern and hence several works proposed privacy preserving strategies. However, most of this privacy strategies conflict with the goals of IAS. In [116] it the impact of current privacy preserving strategies on IAS has been studied.

2.3 Performance Evaluation of Vehicular Networks

The performance evaluation of vehicular networks and their possible applications is very challenging, because the communication behavior of single vehicles depends not only on the surrounding network nodes, but also on the current situation of vehicles (e.g., speed, acceleration, and heading). Due to this complexity and the fast changing environment of vehicular networks, *analytical evaluations* are mostly helpful to investigate basic behavior of communication protocols where no movements of vehicles need to be considered. However, without considering movements of vehicles safety benefits of different communication strategies cannot be demonstrated. Therefore, only *experimental* and *simulative* performance evaluations remain practical to show that vehicular safety can be improved by IVC.

In recent years first prototype devices for the IEEE 802.11p standard have become available and field operational tests in the U.S. and Europe have been conducted, but as outlined in Section 2.1.1 they were not able to show a safety benefit of IVC. One experiment that investigated the feasibility of IAS was [46], however, the focus of this work was not to study challenging communication conditions, but to demonstrate the feasibility of such systems from the control theory point of view.

We use simulation as the primary tool for evaluating IVC for IAS. In the following we first highlight the trends of vehicular network simulations in the years 2009 till 2011, which is based on our simulation studies surveys in [117,118]. Then radio propagation models for vehicular network simulations are discussed in detail, because they have a major impact not only on the communication performance, but also on safety aspects of future vehicular applications. Finally, we shortly introduce the used simulation environment and the employed simulation models.

2.3.1 Trends in Simulation of Vehicular Networks

In 2012 the progress in the field of IVC protocols and applications has promoted the feeling that first applications will enter the market soon and this trend at that time had been confirmed by the automotive industry, which invested in IVC projects and was eager to commercialize many of the ideas.

The credibility of simulations is a constant source of discussions. Pawlikowski et al. [119] reviewed numerous papers in the telecommunication network simulation area checking for two important items: the use of appropriate Pseudo Random Number Generators (PRNGs) and the proper analysis of simulation output data. The majority of the reviewed simulations were not able to satisfy these two basic requirements, which would provide at least basic credibility. This discovery led to a substantial credibility crisis in the field of simulation and modeling after 2002, but these findings were able to influence the way simulation studies are carried out very positively. Regarding appropriate PRNGs such as the *Mersenne Twister* we can note that now all major simulation toolkits provide them. However, the general lack of credible simulation results analysis is still there. We contribute to these findings by looking at an additional aspect influencing the credibility of simulation studies: *repeatability* of simulation experiments. Repeatability is essential, because each scientific activity should be based on controlled and independently repeatable experiments [119].

For vehicular network simulation studies, it turns out that generating reproducible and validated simulation results is even more difficult. Fortunately, a variety of simulation tools and models are already available (e.g., iTetris [120] or Veins [121]) and support the evaluation of new ITS applications and IVC protocols. Moreover, newly developed and updated models help to continuously increase the degree of realism. Examples include road traffic simulation models and tools, new and updated radio signal propagation models, as well as the implementation of IVC standards such as IEEE 802.11p.

In order to provide insights on the used tools and models, as well as the degree of realism provided in published ITS solutions, we surveyed vehicular network papers published between 2009 and 2011 at leading IVC conferences.

2.3.1.1 Investigated Simulation Studies

The database used for this survey of simulation studies of IVC protocols and applications is based on a selection of the most focused events in the vehicular networking domain. All related papers published between 2009 and 2011 that were presented at leading IVC conferences have been reviewed. This amounts to a literature body of more than 1000 papers. Out of this literature body we selected all 116 simulation studies focusing on IVC using DSRC. In particular, we excluded all cellular networking approaches for this particular study. The following leading IVC conferences have been considered:

- **ACM VANET** (Workshop on VehiculAr Inter-NETworking) was held annually in conjunction with ACM MobiCom since 2004. The workshop initially focused on VANET topics, but widened its scope to vehicular networking in general, recently also including topics related to cellular communication.

- **IEEE VNC** (Vehicular Networking Conference) is the youngest of the major vehicular networking centric events and has been taking place annually since 2009. This IEEE Communications Society conference focuses on vehicular networking in general and has a strong focus on IVC in particular.

- **IEEE VTC** (Vehicular Technology Conference) is held semiannually (in spring and fall—aligned by the seasons of the northern hemisphere) as a flagship conference of the IEEE Vehicular Technology Society and has a long history, which dates back to 1950. Considering only the last decade of vehicular networking research, the conference focused mainly on research topics related to the physical layer and medium access.

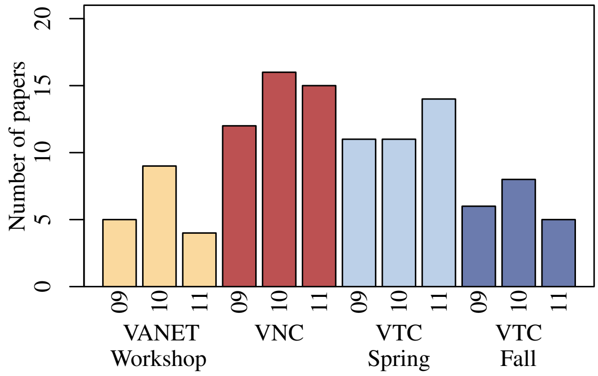


Figure 2.4 – Number of reviewed papers per year and conference/workshop [118], © 2012 IEEE.

Figure 2.4 shows the number of papers that we reviewed for each edition of the selected conferences. It can be seen that the number of IVC related simulation studies has been rather constant between 2009 and 2011. Please note that the papers have not been filtered according to any other criteria as the ones mentioned above.

2.3.1.2 Network Simulator

The employed *network simulator* is an important aspect, because the availability and hence also the validity of simulation models highly depend on it. Several network simulation toolkits are available such as ns-2, ns-3, OMNeT++, OPNET, QualNet, and SWANS, which are all based on a discrete-event simulation core. All of them are long established in the networking community and can be considered as good candidates to start IVC protocol studies with.

Figure 2.5 depicts the distribution of employed network simulators. First of all, it can be seen that ns-2—most probably the best known network simulator—has been utilized in more than 45 % of all simulation studies in 2009. But its successor ns-3 has been gaining more acceptance in 2010 and 2011. Moreover, compared to 2009, OMNeT++ was able to increase its usage by 400 %, making it the second most used network simulator for IVC simulation studies.

The commercial simulator OPNET has been used by a small proportion, which was quite constant from 2009 till 2011. A more drastic effect can be observed for the usage of QualNet. Its usage is shrinking to almost zero after being widely used in 2009, where about 25 % of simulation studies employed QualNet. This negative trend might be explained by the fact that QualNet is a commercial version of the former GloMoSim tool and focuses more on battlefield applications.

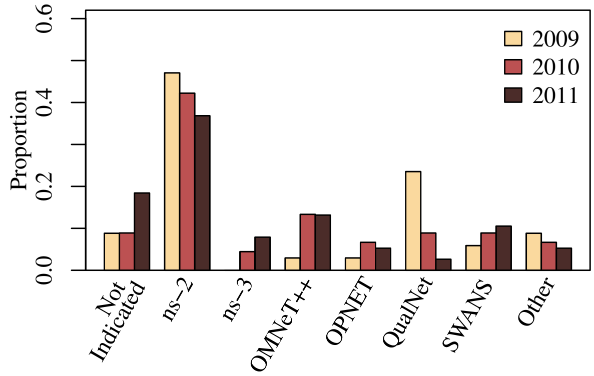


Figure 2.5 – Distribution of network simulators [118], © 2012 IEEE.

The JiST/SWANS simulator, the third most used in 2011, shows a slight but steady positive trend from 2009 till 2011. Although the simulator SWANS itself has not been developed further since 2005, this positive trend in the IVC research community can be explained because several research institutions took SWANS as a basis for their own extensions to build fully-featured vehicular network simulators. Finally, Figure 2.5 shows that a small portion of simulation studies employed some *other* network simulators, and their use has been decreasing over time.

Although it seems that the choice of network simulator has little to no consequence on the results of simulation studies, the usage commonly implies a certain set of models as well as default parameters. An overview of available simulation toolkits suitable for IVC simulations as well as recommendations can be found for example in [120–122]. Therefore, even the choice of the network simulator might substantially impact the validity, comparability, and reproducibility of the results. Thus, it is particularly worrying that our literature review revealed a rather high proportion and an increasing number of simulation studies, which do not indicate the used network simulation tool at all: their proportion was nearly 10 % in 2009 and 2010, and rose up to 18 % in 2011.

2.3.1.3 Physical Layer

Starting with the lowest level—the physical layer—the first factor influencing performance evaluations of vehicular networks is the employed radio propagation model. The interest in obtaining better and more realistic results with a strong focus on the physical layer increased after a first study on the impact of radio propagation on vehicular networks in [59]. Several studies [60, 62, 123] proposed new models for radio propagation in different scenarios and validated them with real-world measurements and field tests. This includes models for signal fading, attenuation by buildings and other obstacles, reflection effects, and the impact of the Fresnel zones.

All these models together build a good basis for very precise simulation of the physical layer in different IVC scenarios. However, since many vehicular networking simulation studies have been simplifying or even neglecting the radio channel effects (as reported in [124]), we decided not to evaluate the degree of realism of physical layer modeling in this literature review. Nevertheless, we want to emphasize the importance of them for IVC simulation studies and hence provide in Section 2.3.2 a comprehensive overview of available radio propagation models for vehicular network simulations.

2.3.1.4 Medium Access

One of the major achievements in IVC research was the definition of the standard MAC protocol within the IEEE 802.11 family, namely the *IEEE 802.11p standard*. Since this standard was released in 2010, the use of an adequate MAC model, along with the corresponding physical layer model, was a major concern when simulating vehicular networks from 2009 till 2011.

In [90] it has been shown that it is important to use a fully featured IEEE 802.11p MAC model; especially at higher node densities, when high channel load is experienced. We therefore decided to specifically check the employed MAC models, most importantly investigating the impact of the newly published IEEE 802.11p standard. As expected, the reviewed simulation studies used a wide variety of MAC protocols until the new standard was released, followed by a phase of quick consolidation.

Table 2.4 gives a brief overview (including the publication year, the dedicated frequency, and the desired maximum data rate) of the most popular MAC standards that have been used for vehicular network simulations from 2009 till 2011. In 2009, more than 15 % of the reviewed simulation studies have investigated new proposals for *New MAC* protocols or for enhanced versions of existing ones. It can be seen that this number decreased substantially after the IEEE 802.11p standard was published in 2010. After 2010, most of the research

Table 2.4 – IEEE 802.11 standards used in IVC simulation studies [118], © 2012 IEEE.

Protocol	Year	Frequency	Data rate
802.11	1997	2.4 GHz ISM	2 Mbit/s
802.11a	1999	5 GHz U-NII	54 Mbit/s
802.11b	1999	2.4 GHz ISM	11 Mbit/s
802.11p	2010	5.9 GHz reserved	27 Mbit/s

activities have settled on building on this standard and are now focusing on the higher layer network and application protocols. An almost similar trend can be observed for simulation studies relying on an *Ideal MAC*, which refers to models where every node has perfect knowledge about the current state of the medium. Similarly, the usage of IEEE 802.11a has dropped to zero—initially, this protocol has been used widely, because it operates in almost the same frequency range as IEEE 802.11p. After the latter one became a standard, most simulation studies moved to the new standard instead.

The fact that the number of simulation studies using IEEE 802.11b is quite constant over time (cf. Figure 2.6) may be explained by having a closer look at the objectives of simulation studies. Interestingly, nearly all of those using IEEE 802.11b have studied vehicular networks that incorporate RSUs.

A significant number of simulation studies also relied on using modified parameters to emulate the behavior of IEEE 802.11p (named 802.11p') with other IEEE 802.11 models. However, it has been shown that using IEEE 802.11b models without or with simple adaptations to mimic the behavior of IEEE 802.11p can only be used in low density scenarios [90]. Nevertheless, the number of simulations that use these adaptations stays constant in the surveyed period.

Finally, we can report a very positive finding: the number of simulation studies using an IEEE 802.11p model has increased sharply after 2010 and already reached about 30 % in 2011. Figure 2.6 supports the expectation that proportions will further shift towards using fully-featured IEEE 802.11p models. Hopefully, in the near future the majority of IVC simulations will use models of wireless communication specifically geared towards vehicular networking.

To conclude this survey on MAC models it should be noted that a relatively large number of simulation studies did indicate the use of 802.11 models, but did not state which one out of the current IEEE 802.11 family of standards was used or whether they relied on the plain IEEE 802.11 standard published in 1997.

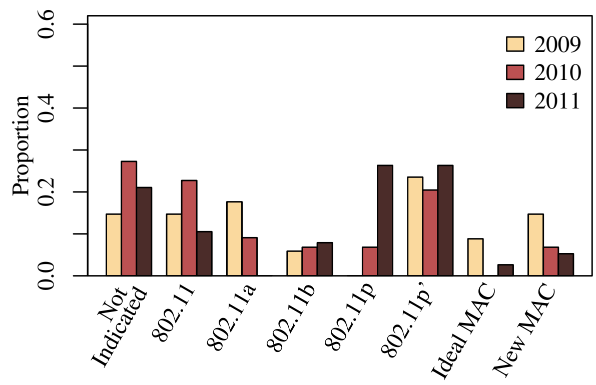


Figure 2.6 – Distribution of MAC protocols [118], © 2012 IEEE.

2.3.1.5 Road Traffic Mobility

It has been shown in [55] that the *mobility model* used for IVC simulations has a substantial influence on metrics like the number of unreachable nodes, the average path length, and topology changes. This finding has driven a clear trend towards using dedicated *road traffic simulators* in addition to a network simulation toolkit [125]. Both worlds, road traffic and network simulation, need to be coupled bidirectionally if the studied IVC protocol should be able to influence the behavior of the vehicles on the roads [121].

Road traffic simulators have been designed for different purposes and hence use different kinds of granularity to model road traffic. Macroscopic road traffic simulations concentrate on traffic flow characteristics like the vehicle density or the average speed and generally treat traffic like fluids. Whereas microscopic simulations models each car individually, thus making them more suitable to study IVC.

Road traffic simulation models are established on top of either *car-following models* or *cellular automaton models*. Car-following models derive future acceleration/deceleration decisions based on the velocity and the distance to the vehicle ahead of it. Models inspired by cellular automatons divide the roads into small sections of a certain length that can be either empty or completely occupied by a single vehicle. The velocity of a vehicle is modeled by occupying multiple segments in one discrete time step.

There are numerous approaches available for both classes of models, which mostly differ in the level of detail and the degree of realism. In the following, we outline well-known car-following models, because most of the microscopic road traffic simulators are based on this class of models. Historically, the Wiedemann model (published in 1974) was the first car-following model. It has been developed further to consider physical and psychological aspects of drivers and is currently implemented in the VISSIM road traffic simulator.

Two other car-following models are the Gipps model and the Intelligent-Driver Model (IDM); implementations for both are available in the Simulation of Urban Mobility (SUMO) simulator. The IDM has been developed after the Gipps model and tries to reproduce effects (like traffic instabilities), which are not considered in the Gipps model.

In Figure 2.7 it is immediately visible that the most popular road traffic simulator for IVC simulation studies is SUMO; it has constantly been used in more than 20 % of all studies with a peak of 30 % in 2010. The dedicated vehicular network movement simulator VanetMobiSim has been used in almost 20 % of the studies in 2009, but has experienced a negative trend with only a marginal proportion of less than 10 % in 2011.

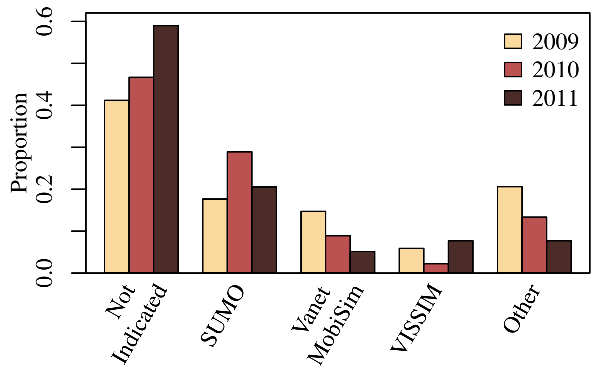


Figure 2.7 – Distribution of road traffic simulators [118], © 2012 IEEE.

The commercial road traffic simulator VISSIM maintained an average proportion of about 6 % during the review period. The category *other* contains all implementations of mobility models with functionality close to one of the validated road traffic simulators. This category also experienced a negative trend from 2009 till 2011.

Finally, we need again to discuss a peculiar trend of road traffic simulation for IVC simulation studies. Although the impact of accurate mobility modeling has been shown already in 2004 [55] and confirmed in 2008 [125], there is no positive trend observable towards applying realistic mobility models. Even worse, the proportion of simulation studies that do not indicate which road traffic simulator has been employed or if one has been used at all, has grown from 40 % in 2009 to almost 60 % in 2011.

2.3.1.6 Scenario Description

It has been shown that the impact of all the aforementioned aspects—the network simulation models, the radio propagation models, and the mobility model—strongly depends on the chosen scenario [125, 126]. Therefore, an adequate *scenario description* is needed for assessing the validity and promoting the reproducibility of IVC simulations.

The scenarios in vehicular network simulations can be divided into two main types: highway and urban. Highway scenarios usually refer to one dimensional simulation studies where only the number of simulated lanes account for the second dimension. Whereas urban scenarios always model two dimensional road topologies of different urban environments. Please note that, for exact modeling of the physical layer, urban scenarios need to be further divided into suburban (characterized by spaces between sparsely distributed buildings) and downtown (characterized by very densely crowded buildings like in downtown Manhattan).

Urban scenarios are dominated by buildings, intersecting roads, and more complex movement patterns. Three different scenario types can be distinguished when reviewing the literature. First, single/multiple intersection scenarios focus on small-scale interactions of communicating vehicles. Accordingly, these scenarios need a very detailed description of how many intersections and lanes have been simulated. Additionally, parameters like turning probabilities help to increase the repeatability of such simulation studies. Second, Manhattan grid scenarios represent any grid-like scenario that is similar to the downtown Manhattan area. Hence, the description needs to contain at least the distance between vertical and horizontal roads and how many lanes have been simulated on each road. Finally, real-world scenarios simulate the movement based on a real-world map data. Therefore, the city or area, which was simulated and what aspects were imported, need to be described, because they have a strong influence on simulation results.

Highway scenarios usually simulate a single trunk road, which does not have any intersections with other roads. A description of a highway scenario needs at least to contain the number of lanes that have been simulated in each direction. Moreover, it should be noted that for most IVC simulation studies it is important to simulate both driving directions because the bimodality in relative speeds has a serious impact.

In Figure 2.8, we first distinguish between urban and highway scenarios, then between their respective subclasses (please note that papers studying more than one subclass contribute to each). We found that the same number of papers investigated urban and highway scenarios, both 58, and only nine papers investigated neither. This ratio was similar during the investigated years, so we do not present the results by year. Looking at the subclasses of urban scenarios, we found that the majority of papers either investigated Manhattan grid or

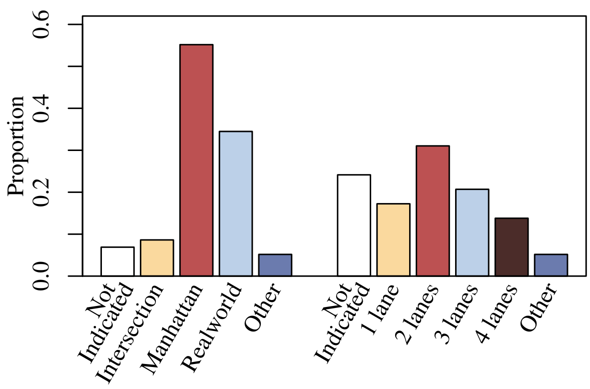


Figure 2.8 – Distribution of scenarios simulated (left: urban, right: highway) [118], © 2012 IEEE.

real-world scenarios with other subclasses only playing a minor role. Only a very small number of studies gave no further information on the used scenario.

Looking at highway scenarios we found most papers evaluating between one and four lane (per direction) scenarios; the majority simulated two lanes. Surprisingly, compared to urban scenarios the proportion of highway simulation studies giving no detailed information on the scenario subclass was substantial: roughly one in four studies only stated that some highway or trunk road was simulated. This even more surprising, because a highway scenario needs much less information for a comprehensive description (number of lanes in each direction vs. intersections, lanes, traffic lights, etc.) than a urban scenario.

Moreover, we also investigated the used vehicle densities as well as the assumed vehicles' speed (Figure 2.9 and Figure 2.10, again split by the scenario environment). An interesting artifact is visible in the density distributions. In urban scenarios, low (below 100 vehicles per km^2) and high density (above 300

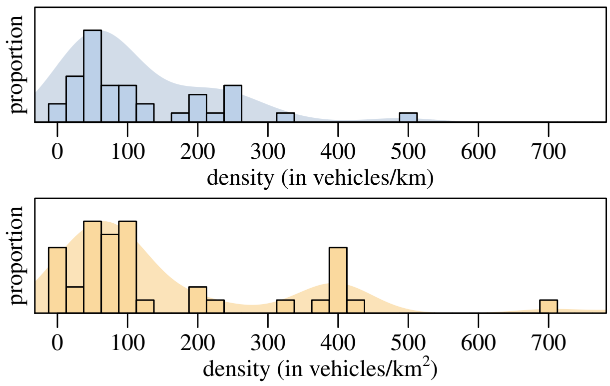


Figure 2.9 – Distribution of used vehicle densities (top: highway, bottom: urban) [118], © 2012 IEEE.

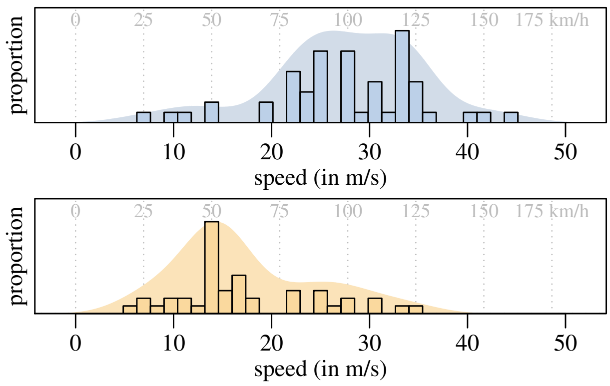


Figure 2.10 – Distribution of used vehicle speeds (top: highway, bottom: urban) [118], © 2012 IEEE.

vehicles per km^2) scenarios have been investigated. However, the majority of investigations for highway scenarios studied only low densities. This is not in line with observations on real highways, where extremely high densities can be observed especially in severe traffic jam situations on highways.

Finally, the observed speed distributions behave as expected. Only a few simulation studies used rather high speeds (75–125 km/h) in urban environments, which might be not realistic.

2.3.1.7 Current Trends in IVC Simulation

So far we investigated the trends of single models and simulation tools that need to be considered for ensuring reproducibility and comparability of simulation studies of IVC protocols and applications. Of course, the single models need to be described, but in fact all parts of the used models and tools need to be described in detail. Therefore, we generated an aggregated view of the individual aspects per simulation study.

In Figure 2.11 it can be seen that both network simulation tools and related models (again, with a focus on the MAC) are very well described with only 10–20 % of papers lacking a proper description. Moreover, it shows that road traffic simulators have been used (and described) by nearly 60 % in 2009 with a negative trend down to 40 % in 2011. The used scenario has been described in most of the papers even though details such as on the number of lanes or the vehicle density are missing for some instances.

Although the descriptions for individual factors (tools, models, and scenarios) are getting better except for the road traffic simulator, the overall quality of the described simulation setups still requires improvements. Looking at the whole set of aspects, we found that only about one third of the simulation studies

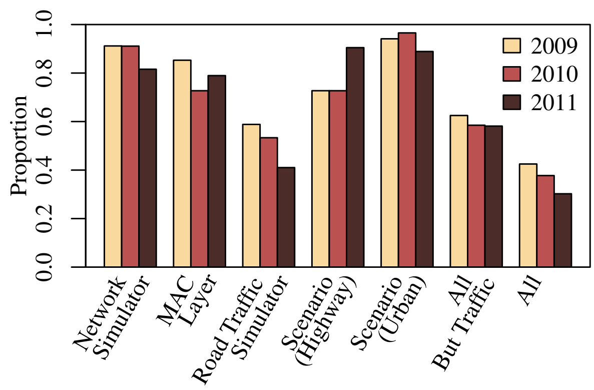


Figure 2.11 – Trends in current IVC simulation studies. Prevalence of model descriptions by aspect and year [118], © 2012 IEEE.

has specified *All* of them correctly. The results indicated as *All But Traffic* summarize those publications taking into account all the listed categories but leaving out the road traffic simulator. It can be seen that only about 50 % of the reviewed studies properly mention the used network simulator, the employed MAC protocol, and the studied scenario. This result underlines that even though all these individual aspects have been mentioned in a rather large subset of the publications, only around 50 % indicate all these parameters together.

Unfortunately, for almost every category plotted in Figure 2.11, a slightly negative trend can be observed over time, i.e., even less information is provided in 2011 papers compared to those in 2009. One explanation for this trend is that a vast amount of information would be needed to provide a comprehensive description of the vehicular network simulation. However, it is clear that by not mentioning all necessary details (as is currently done by more than the half of the surveyed simulation studies) we harm both the reproducibility and the comparability of papers and might end up *comparing apples and oranges* [117].

2.3.1.8 Conclusion

Substantial improvements of tools and models have been made simulation studies in the field of IVC protocols and applications more credible. However, the presented literature review of 116 simulation studies published between 2009 and 2011 clearly indicates the need to describe selected aspects better.

Therefore, we derive the following five basic building bocks that need to described by each and every IVC simulation studying to ensure validity, comparability, and reproducibility [118]:

1. **Network Simulator**. There are well established network simulators available; relying on any of the established ones will imply a certain set of models and default parameters, thus supplementing the model description.

2. **Physical Layer**. The radio propagation models employed at the physical layer need to be chosen carefully depending on the simulated scenario.

3. **Medium Access**. The importance of using an appropriate MAC protocol has been well documented. The IEEE 802.11p standard is gaining acceptance in the community and should (if nothing else) serve as a benchmark for IVC studies.

4. **Road Traffic Mobility**. The vehicles' mobility can easily be modeled using publicly available traces or validated road traffic simulators.

5. **Scenario Description**. We see the strong need to motivate the vehicular networking community to work on a set of standard scenarios that can and should be used for performance evaluation of IVC protocols.

2.3.2 Radio Propagation Models

Already in 2006 Dhoutaut et al. have demonstrated in [59] the impact of radio propagation models on the performance evaluations of vehicular networks. Several measurement campaigns [28, 29, 61] confirmed in detail that usual radio propagation models used in simulations for wireless networks do not resemble the necessary level of detail of radio wave propagation for the proper evaluation of IVC.

In the following we spilt the discussion of radio propagation models by whether propagation is obstructed (e.g., by a building or a truck) or not. In the literature this fact is also often referred to as LOS and NLOS communication where the first one refers to situations where sender and receiver have a direct line-of-sight available and the latter one where this is not the case. In the case of IAS these communication conditions can also refer to different scenarios. LOS communication is predominant at rural intersections where usually only vegetation or occasionally light buildings hamper communication. In contrary communication in an urban environment or even downtown intersections is usually more restricted to NLOS communication.

However, the received signal strength and quality does not only depend on LOS conditions, but is also influenced by reflection, diffraction, refraction, and absorption of indirect rays. Some of the presented radio propagation models take reflections and absorption into account, but minor variations of the received signal strength and quality are usually modelled with fast fading models based on statistics. Examples that can be adopted for vehicular network simulations include Rayleigh fading and Rician fading, but are not discussed further.

Physical layer models for wireless network simulations usually use the received signal strength as measure for deciding whether a frame can be decoded or it only accounts for interference. Nevertheless, advanced measurement campaigns using channel sounders have revealed more detailed information on delay spreads of multiple paths and the Doppler shift [127]. A detailed survey on propagation channels in vehicular networks can be found in [128]. In order to keep the computational load for simulations in an acceptable range, only the attenuation of wireless signals has been simulated and hence is discussed in the following.

2.3.2.1 Unobstructed Communication

As mentioned before, unobstructed radio propagation usually refers to LOS conditions where between the transmitter and the receiver a direct line without interruption can be drawn. Since the received signal strength in an unobstructed environment mainly depends on the distance between the sender and the receiver, they are also called *path loss models*.

Free-space Model

This path loss model assumes that there are no obstructions as well as no reflections available in between the sender and receiver. Therefore, the formula depends solely on the distance d between them and the wave length λ.

$$L_{\text{freespace}}[\text{dB}] = 20 \log_{10} \left(4\pi \frac{d}{\lambda} \right) \tag{2.2}$$

Equation (2.2) (as listed in [63]) presents the Free-space radio propagation formula for ideal channel conditions. However, in vehicular environments the channel conditions are truly not ideal and hence usually the formula is extended by using a path loss exponent α, which can be adjusted to the environment. Equation (2.3) (as defined in [63]) shows the empirical Free-space formula with the path loss exponent α, which can be determined empirically by fitting actual measurements.

$$L_{\text{emp-freespace}}[\text{dB}] = 10 \log_{10} \left(16\pi^2 \frac{d^\alpha}{\lambda^\alpha} \right). \tag{2.3}$$

Measurement campaigns have revealed values ranging from 1.8 [129] to 1.9 [130] for highway scenarios, 1.79 [131] to 2.3 [130] for rural scenarios, and 2.1 to 2.5 for suburban scenarios [132]. Figure 2.12 depicts the range of path loss exponents mentioned in literature.

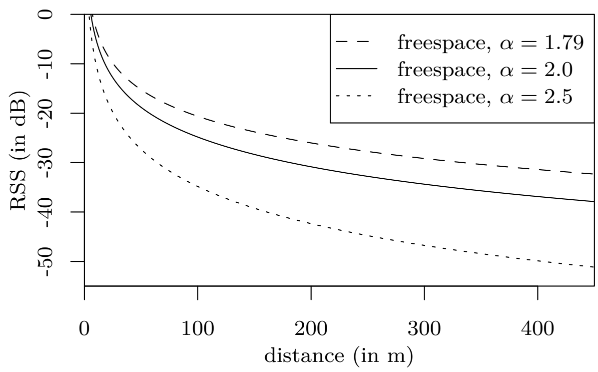


Figure 2.12 – Model comparison for the empirical Free-space model showing the impact of different α values proposed in literature.

Two-ray Interference Model

Although the Free-space model with adaptation of the path loss exponent to the scenario can better resemble radio propagation, it is not able to capture one predominant effect, which is present under LOS conditions: The reflection off the ground causes constructive or destructive interference at the receiver depending on the distance between sender and receiver as well as the height of the antennas. The following equations are similar to those in [63].

To calculate whether the interference is constructive or destructive, one needs to compute the phase difference φ, which depends basically on the difference between the direct distance of transmitter and receiver $d_{\mathrm{los}} = \sqrt{d^2 + (h_{\mathrm{t}} - h_{\mathrm{r}})^2}$, and the length of the indirect ground reflection path $d_{\mathrm{ref}} = \sqrt{d^2 + (h_{\mathrm{t}} + h_{\mathrm{r}})^2}$.

The phase difference φ of the interfering rays can then be derived based on the length difference of these paths and the wavelength

$$\varphi = 2\pi \frac{d_{\mathrm{los}} - d_{\mathrm{ref}}}{\lambda}. \tag{2.4}$$

By taking the phase difference φ and the reflection coefficient $\Gamma_{\perp}$ (calculation based on incident angle and permittivity of the material and detailed in [63]) the path loss can be calculated as

$$L_{\mathrm{tr}}[\mathrm{dB}] = 20 \log_{10} \left(4\pi \frac{d}{\lambda} \left| 1 + \Gamma_{\perp} e^{i\varphi} \right|^{-1} \right). \tag{2.5}$$

Figure 2.13 shows the comparison of the Free-space model with a path loss coefficient $\alpha = 2.0$ and the Two-ray model assuming the same height (1.895 m) of transmitter and receiver. In particular for small distances a non-marginal difference can be seen. The necessity of using the Two-ray model for simulating IVC has been highlighted in [63].

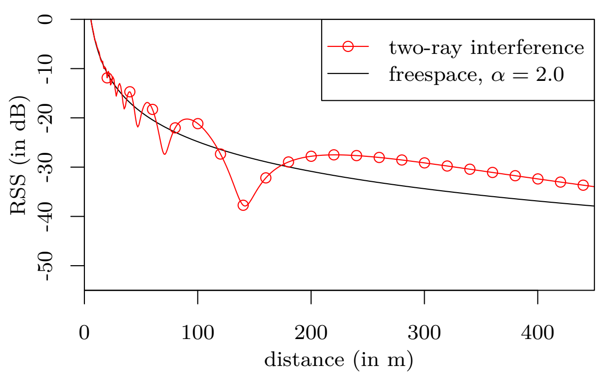


Figure 2.13 – Model comparison of the Free-space model with path loss coefficient $\alpha = 2$ and the Two-ray model.

Impact on Vehicular Networks

It has been shown that the Two-ray interference model has an impact on the performance of vehicular networks [63, 133]. In [63] we highlighted the impact on the number of neighbors, i.e., the number of vehicles that are in communication range, when using the Two-ray interference model. Moreover, we pointed out that most Two-ray simulation models used a simplified version, which in the context of vehicular networks means that normal free-space propagation with $\alpha = 2$ has been considered for all distances smaller than 886.6 m.

Regarding the applicability of the Two-ray model, it can be noted that it is well-suited where reflections of buildings do not dominate the signal. Recent measurements have also demonstrated that the Two-ray model might also be used for very wide streets in suburban environments [64]. Hence, the Two-ray model is a good candidate for highway scenarios and rural scenarios.

In the context of IAS we relied on the simple Free-space model for one reason: We were only concerned about vehicles very close to the intersection (less than 100 meter) and when there were no buildings in our scenario present, we assumed that all vehicles are in communication range of each other and hence form a single interference domain.

2.3.2.2 Obstructed Communication

As explained before, measurement campaigns have revealed that radio propagation models for vehicular networks need to be adapted to resemble the necessary level of detail. In particular, the modeling of obstructed or NLOS communication is challenging because the environment is versatile and radio propagation depends on numerous parameters. One very accurate possibility to model radio propagation is ray-tracing where reflection and diffraction of single radio waves are calculated in detail and hence even multi-path effects can be simulated. These approaches are only feasible if a few transmissions of radio frames need to be simulated. However, when simulating vehicular networks for the purpose of evaluating ITS applications, it is not sufficient to simulate the transmission of a few frames.

Therefore, the IVC research community has extensively explored possibilities to keep the computational overhead of radio propagation models low, but still resembling real-world radio propagation as much as possible. In 2009 the authors of [61] found out that radio propagation depends on the communication situation (LOS referred to as “Down the Block”, NLOS called also “Around the Corner” communication) and hence proposed the usage of a probabilistic shadowing model. In [134] the authors show the necessity of modeling urban radio communication in more detail than Two-ray in particular for NLOS communication by using the analytical path-loss prediction formula presented in [135]. Another model with focus on NLOS communication at intersections was presented in [136] and takes the street widths into account. In [60] Sommer et al. proposed a computationally inexpensive shadowing model, which allows to simulate NLOS communication not only at intersections and is particularly useful in suburban scenarios. Very recently Tchouankem et al. found that even vegetation, which obstructs the LOS has a strong impact on radio propagation [137].

In the following we investigate three radio propagation models in detail and discuss their applicability in the context of vehicular networks.

CORNER Model

The *CORNER Model* [135] provides a path loss model in urban street grids for micro-cellular environments. The model assumes that all walls have flat surfaces and streets are straight and of uniform width. Additionally, the model does not account for the exact position on the street, but locates all vehicles in the middle of the street. However, the model does take diffraction and reflections into account, but considers only the path with minimum number of reflections. In [123] it has been validated for vehicular networks in an urban environment and showed comparable connectivity results to real-world tests.

VirtualSource11p Model

Mangel et al. proposed to use the *VirtualSource* model published in [138] and adapt it to their measurement data recorded at intersections [29]. The resulting model has been called *VirtualSource11p* and has been published and validated in [136].

The formula of the *VirtualSource* model [138] is listed in Equation (2.6) and uses a break even distance d_b that depends only on the height of transmitter h_t and receiver h_r as well as the wavelength. Depending on the receiver distance d_r and the break even distance, the model accounts for the fact that diffraction is predominant at higher receiver distances. Moreover, the model considers the widths of both streets (receiver street width w_r and transmitter w_t), the distance of the transmitter to the wall x_t to the blocking building as well as a street specific parameter α.

$$PathLoss = \begin{cases} 10\log_{10}\left(\frac{1}{\alpha}\left(\sqrt{\frac{2\pi}{x_t w_r}}\frac{4\pi d_t d_r}{\lambda}\right)^2\right), d_r \leq d_b \\ 10\log_{10}\left(\frac{1}{\alpha}\left(\sqrt{\frac{2\pi}{x_t w_r}}\frac{4\pi d_t d_r^2}{\lambda d_b}\right)^2\right), d_r > d_b \end{cases} \quad (2.6)$$

$$d_b = \frac{4h_t h_r}{\lambda} \text{ (Break even distance)}$$

As a first modification, the constant factor $\sqrt{\frac{2\pi}{\cdots}}$ for $x_t w_r$ was replaced with an adjustable exponent E_S, because it has been shown that the influence of the street width is not properly reflected in the original formula Furthermore, the authors argued that the distance of the transceiver d_t plays a major role and hence added another adjustable exponent E_T. Finally, the adapted formula also accounts for an increased loss at suburban intersections by introducing the factor L_{SU} that is enabled by the boolean variable i_s.

When calculating the break even distance for usual transceiver heights (1.8 m) and the reserved frequency spectrum (5.9 GHz), it turns out that it is rather large: 255.1 m. Since the measurement data used to parameterize the *Virtual-Source11p* has not provided data for such large distances, it has been validated for receiver distances larger than the break even distance. For this reason, we list in Equation (2.7) only the validated part of the model.

$$VirtualSource11p = C + i_s L_{SU} + 10 \log \left(\left(\frac{d_t^{E_T}}{x_t w_r^{E_S}} \frac{4\pi d_r}{\lambda} \right)^{E_L} \right) \tag{2.7}$$

Obstacle Shadowing Model

The *Obstacle Shadowing Model* [60] has been deduced from extensive measurement data and combines the ideas of other approaches that focus on the analysis of the direct line between transmitter and receiver: In [139] it has been proposed that different path loss exponents should be used when the wireless signal is travelling through matter or free-space. Another study suggested to use a fixed attenuation factor per obstacle [140]. And finally in [141] the authors proposed to calculate the attenuation based on the number of walls that need to be penetrated. The Obstacle Shadowing Model combines the ideas of the three of them by accounting for the attenuation caused by walls and the distance within obstacles (i.e., buildings in the case of vehicular networks).

The model uses geodata provided by the OpenStreetMap project[1] to compute the buildings intersecting the direct line. Equation (2.8) depicts the principle computation of the model when only a single building disturbs the direct communication line. Reflection as well as diffraction has been disregarded in order to create a computationally inexpensive model.

The computationally most expensive part of this model is the search for obstacle intersections between the sender and receiver in order to calculate the additional attenuation. However, this can be achieved in $\mathcal{O}(n \log n)$ time if the *red and blue line segment intersections* algorithm [142] is applied.

[1] `http://www.openstreetmap.org/`

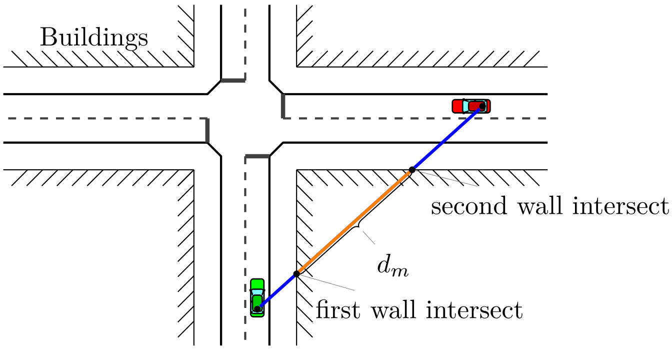


Figure 2.14 – Graphical representation of the *Obstacle Shadowing Model*.

Deriving the formula of the model is straightforward and Figure 2.14 depicts a simple case where the direct communication line is obstructed by a single building. The model considers a new term L_{obs}, which accounts for the attenuation caused by obstacles in between sender and receiver, in addition to Free-space attenuation usually with a path-loss coefficient of $\alpha = 2.0$ (cf. Section 2.3.2.1).

For every intersected obstacle, the model counts the number of walls n that have been intersected, as well as the distance d_m travelled within the obstacle (the orange part of the line between the two vehicles in Figure 2.14). The model assumes that for walls a constant, but empirically determined, attenuation β (attenuation loss per intersecting wall in dB) can be added. The second attenuation value γ (in dB/m) represents the average loss per meter where the signal had to travel "through" a building. By using Equation (2.8), the additional attenuation L_{obs} can be calculated.

$$L_{obs} = \beta n + \gamma d_m \tag{2.8}$$

2.3.3 Simulation Framework

In Section 2.3.1 we have discussed the trends from 2009 till 2011 in vehicular network simulations. From these findings, we have derived five basic building blocks (cf. Section 2.3.1.8), which need to be described by each IVC simulation study. Accordingly the common building blocks for all presented simulation studies within this thesis are summarized here:

- **Network Simulator** The Vehicles in Network Simulation (Veins) framework[2] has been used and hence the employed network simulator was OMNeT++. Veins extends the MiXiM physical layer simulation framework [143] for realistic simulation of IVC protocols and applications.

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

- **Physical Layer**. Veins has the following radio propagation implemented: Free-space, Two-ray Interference [63], and Obstacle Shadowing [60].
- **Medium Access**. The well-validated IEEE 802.11p model [90] is also implemented in Veins. For the presented simulation studies it always has been configured to a single radio / single channel DSRC system.
- **Road Traffic Mobility**. Veins provides a bidirectional coupling [121] between the road traffic simulator SUMO and the network simulator OMNeT++ and hence well-validated car-following models such as the IDM model are available.
- **Scenario Description**. Since the scenario description is very specific for each simulation study, we describe the scenario separately.

To ensure comparability and reproducibility of this work we also list all relevant communication as well as road traffic simulation parameters for each simulation study in the corresponding sections.

To conclude this chapter, we briefly summarize the capabilities as well as the used features of the Veins simulation framework. It provides a bidirectional coupling of the network simulator OMNeT++ with the road traffic simulator SUMO [121]. The bidirectional coupling allows not only to simulate realistic vehicle movements and positions in the network simulator, but also enables the simulations of driver reactions, which are based on received information. For example in [144], the authors investigated the environmental impact of ITS. Although Veins provides the possibility to simulate driver reactions, most of the presented simulation studies in this thesis concentrate on the analysis of communication without altering the driver behavior. Detailed MAC parameters and which radio propagation models have been used, are listed separately for each simulation study.

Since the road traffic simulator SUMO is not prepared to simulate crash situations at intersections, this will be starting point in the next chapter, which investigates safety metrics for crash situations at intersections.

Chapter 3

Safety Metrics

In 2010 a Dagstuhl seminar with the topic "Research Challenges in Inter-Vehicle Communication" revealed important future research directions. One interesting conclusion was that the focus should be rather on the application benefits and not only on the network properties [26]. Translated to vehicular safety applications—such as IAS—this means that questions like "How many crashes can (theoretically) be mitigated?" and "Can the impact of crashes be significantly reduced?" should be answered.

Obviously, it is possible to compare IVC communication strategies and protocols with usual network metrics and then pick the approach which works best from network perspective, but the communication requirements for vehicular network applications are clearly driven by application demands. Hence the best approach from the communication perspective needs not to be the most suitable for vehicular applications. In particular the translation of application demands to communication requirements is not necessarily straightforward.

For example, a vehicular safety application might profit from ultra-low latency, because the best decision can be taken on very recent data. This goal can be pursued during design and used for evaluation of communication protocols. However, when we have a closer look at one particular vehicular safety application (lets assume we look into IAS), we can notice that this very low latency is only beneficial for very few vehicles which are in a precarious situation. The majority of vehicles would use and hence occupy channel capacity that could have been used to facilitate communication of endangered vehicles. Therefore, a measure is needed to express such extraordinary circumstances for individual vehicles. Since this measure reflects the safety status of vehicles, we refer to them as *safety metrics*.

So far, in most IVC studies on 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 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. To study dangerous situations, we needed to take driver behavior into account (as already suggested in [26]).

In order to enable studies on crash mitigation for IAS, we first need to be able to simulate crash situations. Because available IVC simulation platforms have not been able to simulate crash situations, we have built different models, which allow to simulate simple random crashes as well as more complex crash situations. The last missing building block to study the effectiveness of communication for IAS was the development of a collision detection algorithm, which determines whether an intersection approach of two vehicles resulted in a crash or not. These mechanisms for simulating crash situations at an appropriate level of detail for IVC research are described in Section 3.1.

As a first safety metric, we developed the *risk classification* (defined and validated in Section 3.2), which gives a first idea about how often vehicles are able to communicate in different stages of criticality. However, the transition between these risk classes is instantaneous and hence no fine-grained risk assessment is possible. Therefore, we decided to develop this discrete risk assessment metric further into a continuous safety metric. We thus developed an estimation of the *intersection collision probability* (defined and validated in Section 3.3) that is able to indicate the collision risk of two approaching vehicles towards an intersection.

Basically, both developed safety metrics can be used as metric for evaluation of communication strategies/protocols, as input for communication strategies, or as decision metric in control systems for IAS. Although the intersection collision probability could be used as decision metric for controllers in IAS (demonstrated in [145, 146]), we decided to not further pursue this research direction. Instead, we use both safety metrics in Chapter 4 first to investigate current communication strategies from an application point of view. Second, we make use of the intersection collision probability as input for situation-aware communication strategies in the context of IAS.

Since it does not make sense to use the same metric as input for communication strategies and as evaluation metric, it was necessary to look for other meaningful evaluation possibilities for IAS. In order to show the impact of different communication strategies on IAS without the help of safety metrics, we have explored worst-case analyzes of single intersection approaches. These worst-case analyzes provide application-specific network metrics in the context of IAS and are described in Section 3.4.

This chapter is based on the following publications:

- S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, “To Crash or Not to Crash: Estimating its Likelihood and Potentials of Beacon-based IVC Systems,” in 4th IEEE Vehicular Networking Conference (VNC 2012). Seoul, Korea: IEEE, Nov. 2012, pp. 25–32. My contribution was the development of the risk classification as well as the validation and evaluation.

- S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, “A Vehicular Networking Perspective on Estimating Vehicle Collision Probability at Intersections,” IEEE Transactions on Vehicular Technology, vol. 63, no. 4, pp. 1802–1812, May 2014. My contribution was the implementation of the intersection collision probability as well as the analysis.

- S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. Lo Cigno, and F. Dressler,“Fairness Kills Safety: A Comparative Study for Intersection Assistance Applications,” in 25th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2014). Washington, D.C.: IEEE, Sep. 2014, pp. 1442–1447. In this chapter only the evaluation metrics used in this publication are presented. They have been proposed by myself.

- S. Joerer, B. Bloessl, M. Huber, A. Jamalipour, and F. Dressler, “Simulating the Impact of Communication Performance on Road Traffic Safety at Intersections,” in 20th ACM International Conference on Mobile Computing and Networking (MobiCom 2014), Demo Session. Maui, HI: ACM, Sep. 2014, pp. 287–289. My contribution was the setup of the Demo as well as the development of the simulation of crash situations.

- S. Joerer, B. Bloessl, M. Huber, A. Jamalipour, and F. Dressler, “Assessing the Impact of Inter-Vehicle Communication Protocols on Road Traffic Safety,” in 20th ACM International Conference on Mobile Computing and Networking (MobiCom 2014), 6th Wireless of the Students, by the Students, for the Students Workshop (S3 2014). Maui, HI: ACM, Sep. 2014, pp. 21–23. My contribution was the real-world assessment of different communication strategies.

3.1 Modeling Crash Situations at Intersections

To enable simulation studies that can assess the performance of IVC for IAS we need a model for intersection approaches of vehicles. Although there have been measurements, how drivers approach an intersection [147], we were not able to find a suitable model for this purpose in literature (available simulation models described in Section 2.1). Current car-following models such as the Krauss model [148] or the IDM [149] use simple mechanisms to model intersection approaches. For example IDM models a red light or a stop sign at an intersection as virtual vehicle which stands exactly at the stopping line. So we first investigate the applicability of these car-following models as driver models for intersection approaches.

Another issue with these car-following models is that they do not consider the possibility of collisions between vehicles, i.e., they are designed to be *collision-free*. We therefore extended SUMO to support intersection approaches which result in a crash by selectively disabling right-of-way checks for individual vehicles when approaching an intersection. SUMO version 0.20.0 also allows to switch off individually different safety checks, i.e., the checks which enable collision-free driving. Nevertheless, this allows only to simulate simple crash situations where basically both vehicles are crossing as they would if they have the right-of-way. Therefore, we implemented a more sophisticated method to enable a wide range of different crash situations at intersections. Finally, the last missing piece for enabling studies on safety metrics and communication strategies for IAS—the crash detection—is described.

3.1.1 Investigation of Driver Models

We use the road traffic simulator SUMO, because it already provides a set of car-following models including the Krauss model [148] and the IDM [149]. The car-following models of SUMO are primarily designed for medium to large scale simulations and it has not been investigated yet if the reproduced driver behavior when approaching an intersection is close to reality. Both models have different characteristics and generate different mobility patterns, which, however, might not be realistic on a local scale.

We therefore compare the Krauss and the IDM models with the real-world measurements shown in [147, Fig. 4], by plotting the speed of the cars as a function of the distance to the intersection in Figure 3.1. For better readability and comparability, we plot two theoretical curves showing the dynamics for constant deceleration values of 1 and $3\,\mathrm{m/s^2}$ when performing a full stop towards the intersection entry.

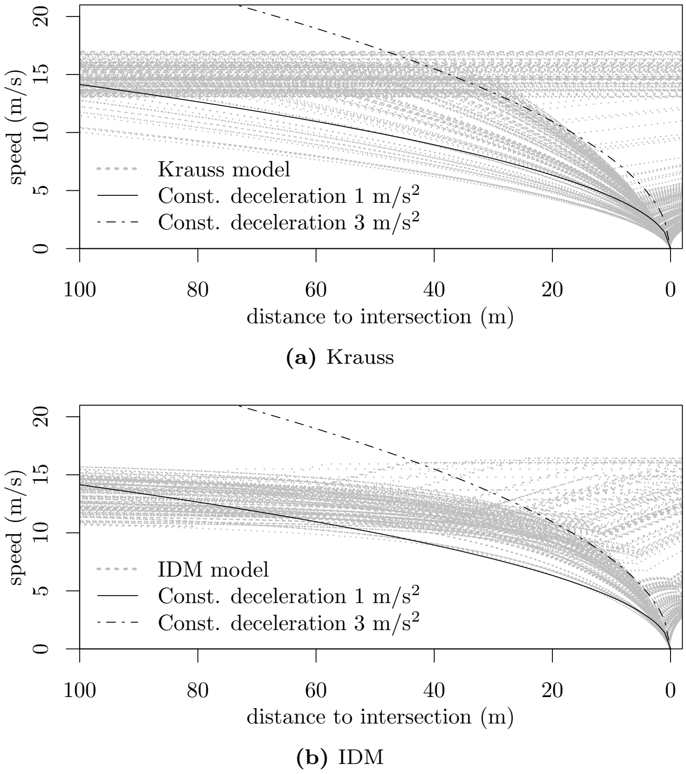


Figure 3.1 – Different braking behaviors for Krauss and IDM car-following models [69], © 2012 IEEE.

The results show that, with the Krauss model, the cars approach the intersection at a constant speed and, at a certain point (depending on the desired deceleration) start to slow down instantaneously (see Figure 3.1a). Moreover, cars with the right-of-way do not decelerate at all, as shown in the upper part of the plot by the continuous horizontal lines. When comparing this behavior with the real-world measurements [147], we can conclude that the Krauss model, i.e., the default car-following model used by SUMO, does not reproduce realistic driver behavior. In particular, it does not reproduce human driver behavior neither if a car has the right-of-way nor a car has to yield.

IDM shows very different behavior (depicted in Figure 3.1b): vehicles start to smoothly decelerate far from the intersection (already around 80 m) and then increase the deceleration rate as they get closer to 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 again. Therefore, we can conclude that IDM better resembles the measurements in [147] and it is better to use IDM as car-following model if the intersection approach behavior is controlled by it.

3.1.2 Simple Random Crash Situations

To simulate simple random crash situations at intersections, we modified SUMO in a way, 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. Since the driver model investigation in Section 3.1.1 revealed that IDM better resembles realistic intersection approach behavior, we use IDM for simulating these crash situations.

We checked the behavior of these traffic offending vehicles and found that they act as expected, i.e., slowing down slightly before the intersection, but not performing a full stop as, if they would have to yield. Moreover, the other cars' behavior is not affected, i.e., their drivers' model ignore that some cars may not abide to rules. Obviously, this simulation approach does not cover all possible real behaviors and situations, but it is sufficient for some first initial studies on how CAMs dissemination impacts predictability of possible crashes. In particular this approach does not allow to simulate atypical intersection approaches, for example, the car without right-of-way first slowing down to the intersection and then based on misjudgement, accelerating too early.

When these simple random crash situations are simulated, a typical X-intersection is used, where its lane geometry is imported from OpenStreetMap. To simulate this crash situations two vehicles approach the intersection, then cross it without turning. Figure 3.2 shows the precise geometry of the intersection and vehicle: the lane width $w_{\text{lane}} = 3.2\,\text{m}$ as well as the vehicle length and width.

As explained before, we used the IDM car-following model [149] for these simulations (in order to reproduce realistic braking behavior [147]) as well as a modified version of SUMO that allows us to let selected vehicles ignore traffic

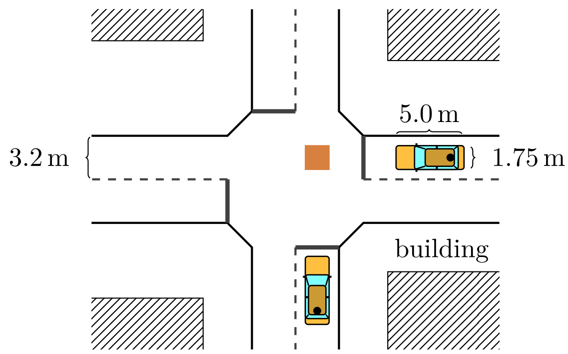


Figure 3.2 – Map view of the simulated X-intersection showing the potential collision area, buildings, and two approaching vehicles [150], © 2014 IEEE.

Table 3.1 – 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 $v_{\max}$ [52, Tab. IV]	$\sim \mathcal{N}(13.89, 2.92)$ m/s
Maximum acceleration $a_{\max}$	2.1 m/s^2
Desired deceleration a_{des} [52, Tab. IV]	$\sim \mathcal{N}(3.47, 2.76)$ m/s^2
Initial speed v_0	$\sim \mathcal{U}(0, v_{\max})$m/s

rules [69]. We randomly selected 50 % of approaching vehicles to ignore traffic rules. For inducing situations of different criticality at the intersection, the two vehicles used uniform distributed initial speeds as well as normal distributed maximum speeds and desired deceleration values as listed in Table 3.1. The variation of IDM parameters resembles the different behavior of drivers. Since this intersection approach model is only used to evaluate IAS regarding their communication requirements, the simulated intersection approaches do not resemble any lateral vehicle dynamics. To better isolate the vehicles' behavior, we ensured that always only two vehicles approach the intersection at the same time.

3.1.3 Arbitrary Crash Situations

There are two reasons why the aforementioned simulation model for simple random crashes needed to be enhanced: First, the lack of determinism for collisions at the intersection resulted in only very few critical intersection approaches, which is not very useful in the context of IVC simulation studies, where the computational load is dominated by simulating the wireless communication [60]. Second, the simple random crash situations model produced only one form of collisions: both cars were driving at a high speed. Hence strong braking maneuvers and probable acceleration actions of drivers are neglected.

To simulate and analyze arbitrary intersection approaches, a simulation model has been developed which uses the *aggressiveness* and *discipline* of the driver, as proposed in [152], as parameters. The aggressiveness parameter resembles the fact that drivers are pushing the brake pedal differently. The second parameter simulates driver's braking reaction (i.e., drivers do not always brake in time) and hence called discipline. Using these two parameters, arbitrary crash situations with different speeds and acceleration/deceleration behaviors can be simulated by ignoring right-of-way rules or traffic lights. The vehicles in the

Parameter	Value
Maximum speed v_{max} [52, Tab. IV]	$\sim \mathcal{N}(13.89, 2.92)$ m/s
Maximum acceleration a_{max}	2.1 m/s^2
Maximum deceleration a_{min} [151]	9.55 m/s^2
Driver aggression D_{agg}	$\sim \mathcal{U}(10, 90)$ %
Driver discipline D_{dis}	$\sim \mathcal{U}(10, 90)$ %
Crossing speed v_{cross}	$\sim \mathcal{U}(3, 12)$ m/s
Desired time delta $t_{\delta\text{ desired}}$	$\sim \mathcal{U}(0.1, 1.0)$ s
Collision detection time step	5 ms
Vehicle length	5.0 m
Vehicle width	1.75 m
Safety boundary for *Near Crash*	0.4 m

Table 3.2 – Parameters for simulating arbitrary collision situations at intersections.

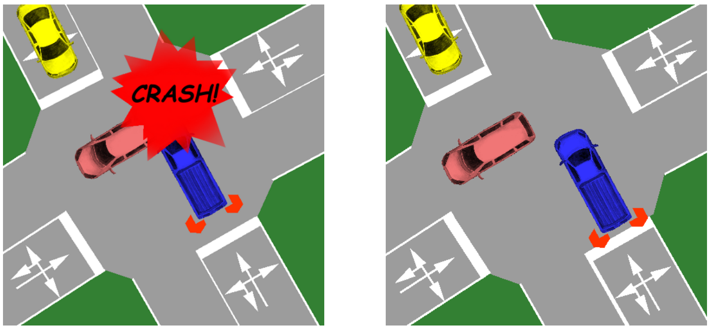
road traffic simulator SUMO ignore traffic rules as described earlier. The speed as well as acceleration or deceleration of the two vehicles (potential collision pair) are completely controlled via a so-called `CollisionScenario` implemented in OMNeT++.

Basically, the `CollisionScenario` chooses the simulated driver behaviors by randomly choosing aggressiveness and discipline (D_{agg} and D_{dis}, respectively) as well as crossing speed (v_{cross}). Based on the chosen parameters, the crossing times of both vehicles (t_{c1} and t_{c2}, respectively) at the potential collision position can be computed. Moreover, the time delta t_δ can be calculated by $t_\delta = |t_{\text{c1}} - t_{\text{c2}}|$. There is a correlation of this time delta t_δ and the outcome of the `CollisionScenario`, i.e., crash or no crash: Depending on the speed and outline of the vehicles very small t_δ (less than 1 s) result in a crash. Whereas, larger deltas (more than 1.0 s) usually still imitate dangerous driving behavior, but do not lead to a crash.

To study mostly interesting situations, the parameter $t_{\delta\text{ desired}}$ can be used by specifying the distribution of wanted time deltas. For example a desired time delta range $\sim \mathcal{U}(0.1, 1.0)$ s results in mostly dangerous situations at the intersection. The parameter values used for the intersection approach model are listed in Table 3.2.

3.1.4 Crash Detection in Network Simulator

In normal operation, SUMO detects collisions between vehicles and 'teleports' one of the two colliding vehicles to a future edge on their route; this is not a realistic behavior. Moreover, this behavior is even disabled at intersections because SUMO does only consider the length of vehicles for collision detection, but not the width of vehicles which is necessary to detect collisions for turning/crossing vehicles.



(a) *Crash* Situation **(b)** *No Crash* Situation

Figure 3.3 – Screenshots of the intersection area rendered by the road traffic simulator SUMO (used for visualizing the imact of communication performance on road traffic safety in the demo in [145]).

Therefore, we developed a crash detection module within the network simulation part of the Veins simulation framework and enhanced the graphical user interface of SUMO to visualize crash situations as shown in Figure 3.3. The developed crash detection module uses precise vehicle dimensions (length and width) as well as position and speed information from the road traffic simulation. It detects 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 [142].

Since all described simulation studies in this thesis are based on the *discrete* road traffic simulator SUMO and the linearly interpolating mobility model of Veins, the necessary simulation granularity for vehicle movements has been assessed by investigating the maximum possible inaccuracies of the simulation models. 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

$$\epsilon_{\text{dec}} = \frac{1}{2} \left| a_{\text{min}} \right| {t_{\text{step}}}^2, \ \epsilon_{\text{acc}} = \frac{1}{2} \left| a_{\text{max}} \right| {t_{\text{step}}}^2, \tag{3.1}$$

$$\epsilon = \max(\epsilon_{\text{dec}}, \epsilon_{\text{acc}}). \tag{3.2}$$

We decided to use a very small time step of $t_{\text{step}} = 5\,\text{ms}$ for the road traffic simulator, because the focus of our evaluations is on estimating safety benefits of IAS. The chosen time step for simulating the longitudinal movements within SUMO leads to a maximum error $\epsilon = 0.12\,\text{mm}$ (i.e., the vehicle is braking with maximum deceleration of $9.55\,\text{m/s}^2$).

In addition, the selected simulation time step results in a maximum step distance of $v_{\text{max}} \times t_{\text{step}} = 8.405\,\text{cm}$ and hence allows the collision detection module to recognize almost all vehicle collisions. Still, with a low probability, it might fail to detect slightly "touching" vehicles. Therefore, we also implemented a detector for *Near Crash* situations by extending the outer shape of the cars with a safety boundary. Hence the crash detection module reports not only a binary decision whether an intersection approach resulted in a *Crash* or *No Crash*, but also situations in which a driver would feel already very uncomfortable by signaling a *Near Crash*. This group covers also crash situations which have not been detected due to simulation time step size. The third group *No Crash* contains only intersection approaches where the vehicles did not collide, nor violate the additional safety boundary of each other.

3.2 Risk Classification

In order to understand under which circumstances communication is possible and necessary during intersection approaches, we propose a risk classification. The focus is on classifying situations' criticality by using positioning and heading information of two approaching vehicles.

3.2.1 Definition

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 $a_{\mathrm{max}} > 0$ and deceleration of $a_{\mathrm{min}} < 0$. The time t_{brake} and distance d_{brake}, which are needed in order to come to a full stop, can be calculated as follows:

$$t_{\mathrm{brake}} = \frac{v_0}{-a_{\mathrm{min}}} \tag{3.3}$$

$$d_{\mathrm{brake}} = \frac{v_0 t_{\mathrm{brake}}}{2} = \frac{v_0^2}{-2a_{\mathrm{min}}}. \tag{3.4}$$

We are further interested in the earliest possible point in time a crash can happen, given a certain situation (defined by d_0 and v_0). For this reason, we calculate the time interval $\mathcal{I} = [t_{\mathrm{min}}, t_{\mathrm{max}}[$ during which a car may pass the intersection.

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

$$t_{\mathrm{min}} = \frac{-v_0 + \sqrt{v_0^2 + 2a_{\mathrm{max}} d_0}}{a_{\mathrm{max}}}. \tag{3.5}$$

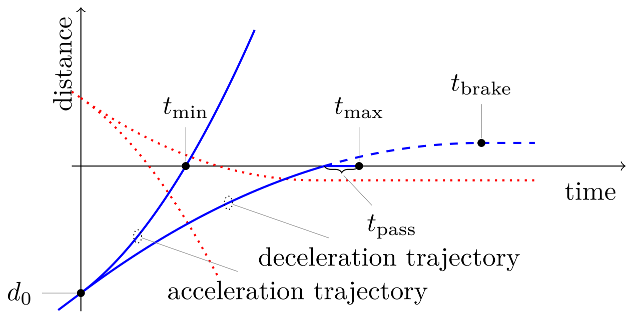


Figure 3.4 – Graphical derivation of t_{min} and t_{max}. All labels and variables refer to solid blue line (first car), mirrored w.r.t. x axis for clarity. The dotted red line represents another car [69], © 2012 IEEE.

For our purposes, a maximum time t_{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_{min}. The time t_{max} is defined only if the space equation admits a positive solution; otherwise, t_{max} is infinite. If t_{max} is not infinite, we have to account for the time t_{pass} that a vehicle needs to pass through the lane it crosses:

$$t_{\text{max}} = \begin{cases} \frac{-v_0+\sqrt{v_0^2+2a_{\text{min}}d_0}}{a_{\text{min}}} + t_{\text{pass}} & \text{if } v_0^2 + 2a_{\text{min}}d_0 \geq 0 \\ \infty & \text{otherwise.} \end{cases} \tag{3.6}$$

t_{pass} depends on the length of the vehicle l_{vehicle}, the lane width w_{lane}, and the vehicle speed v_{pass} when entering the intersection. For the sake of simplicity we assume that v_{pass} is constant during the time of crossing, and that each vehicle takes a maximum of 5 s to cross[3]:

$$t_{\text{pass}} = \min\left(\frac{l_{\text{vehicle}} + w_{\text{lane}}}{v_{\text{pass}}}, 5\,\text{s}\right). \tag{3.7}$$

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

$$t_c = \min\left(\mathcal{I}_1 \cap \mathcal{I}_2\right). \tag{3.8}$$

A graphical example is depicted in Figure 3.4; at time $t = 0$, the first vehicle has a distance d_0 from the intersection. By accelerating at a constant rate of a_{max}, it follows the solid blue trajectory on the left, crossing the intersection at time t_{min}. By constantly decelerating at a_{min} (second solid blue trajectory),

[3]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 occupy it for minutes.

instead, it leaves the intersection at time $t_{\max}$, which includes the time t_{pass}. As shown in Figure 3.4, the vehicle is not able to stop before the intersection in this situation and hence $t_{\max}$ exists and $t_{\text{brake}} > t_{\max}$. The dotted red lines represent a possible intersection approach of a second vehicle. The two vehicles can collide in the overlapping interval $\mathcal{I}_1 \cap \mathcal{I}_2$.

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 criticality of the intersection approaches: No-Crash, Safe, Attention, and Critical.

If both vehicles are able to stop before the intersection (meaning that $t_{\max}$ is undefined for both vehicles), we consider the situation as Safe.

No-Crash represents situations when no collision can happen at all, meaning that the intersect of the two intervals $\mathcal{I}_1$ and $\mathcal{I}_2$ is empty. 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 ($t_{\max}$ exists for one of the two). Thus, from the vehicles dynamics point of view this situation is very different from Safe, where both $t_{\max}$ are infinite.

If only one vehicle can stop and the intervals do overlap (the intersect is not empty), 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 and the intervals still overlap: 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.

3.2.2 Validation

Here, we validate the risk classification based on a X intersection scenario. A detailed analysis using the risk classification which investigates the impact of the beacon interval is discussed in Section 4.1. Moreover, the risk classification is used for an initial study on the benefits of cooperative communication in Section 5.1.

3.2.2.1 Simulation Setup

We simulated 5000 different intersection approaches for each experiment. The intersection approaches are simulated with the simple random crash situations model as described in Section 3.1.2. For every two vehicles driving toward the intersection and leaving the intersection area or crashing, we observed the final

Parameter	Value
Building wall attenuation β [60]	9 dB
Building internal attenuation γ [60]	0.4 dB/m
Frequency	5.89 GHz
Channel width	10 MHz
Tx rate	18 Mbit/s
Tx power	20 mW
Sensitivity	−94 dB
$\mathrm{CW}_{\mathrm{min}}$, $\mathrm{CW}_{\mathrm{max}}$	3, 7
AIFSN	2

Table 3.3 – Communication simulation parameters for signal attenuation, physical layer, and MAC.

outcome at the intersection as described in Section 3.1.4: Out of all simulated intersection approaches 3.7 % resulted in a *Crash*, 1.6 % in *Near Crash*, and 94.7 % in *No Crash*. In the following, we show selected results from this extensive set of simulations to validate the proposed risk classification.

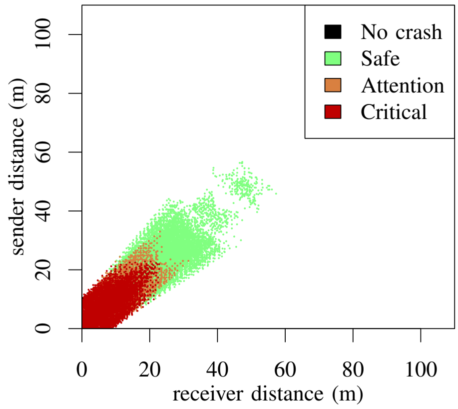
During the approach, we classify the received beacons into warning levels using the classification defined in Section 3.2.1. Note that the behavior of the vehicles is not influenced, because our key focus is on assessing the possibilities arising from the use of beaconing based approaches. To treat the vehicles' behavior as truly unknown (although the maximum acceleration and deceleration are well known in simulation), we decided to use $a_{\mathrm{max}} = 2.5\,\mathrm{m/s^2}$ and $a_{\mathrm{min}} = -5\,\mathrm{m/s^2}$ as conservative parameters for calculating the intervals $\mathcal{I}_1$ and $\mathcal{I}_2$[4].

For this simulation study we used the vehicular network simulator Veins described in Section 2.3.3 and the building shadowing model presented in Section 2.3.2.2. Relevant parameters of the physical and MAC models are summarized in Table 3.3.

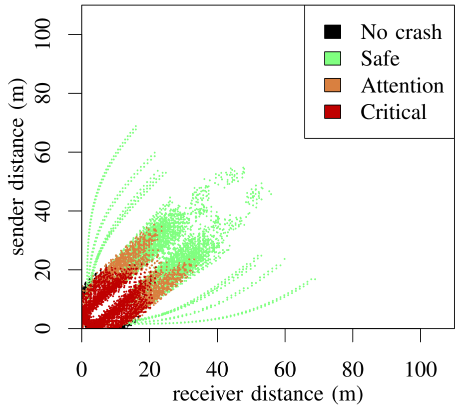
3.2.2.2 Results

Figure 3.5 plots the class of all received beacons by sender and receiver distance for understanding the behavior of the risk classification in various situations. To validate the intended behavior of the classification, we split by the final situation at the intersection (*Crash*, *Near Crash*, *No Crash*). For better readability, the No-Crash points are drawn first, followed by Safe, Attention, and Critical, because otherwise the more critical classes would be hidden by less critical ones.

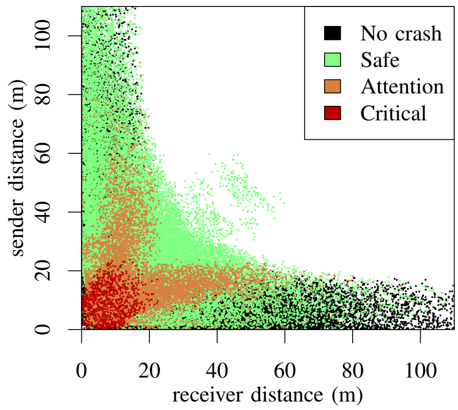
[4] We have also performed the same set of simulations with a higher deceleration rate of $a_{\mathrm{min}} = -7.5\,\mathrm{m/s^2}$. Except for the fact that an approach is classified as critical for shorter distances only, the results are similar and are not shown for the sake of brevity.



(a) *Crash* situations



(b) *Near Crash* situations



(c) *No Crash* situations

Figure 3.5 – Risk classification of received beacon as a function of the sender and receiver distance from the intersection subdivided by the intersection situations [69], © 2012 IEEE.

Figure 3.5a shows all beacons that have been received while approaching the intersection for those intersection approaches where the two vehicles finally crashed at the intersection (*Crash*). It can be seen that beacons get classified as SAFE until a distance of approximately 30 m, i.e., no actions by safety systems are needed. Furthermore, we see that most of the beacons received closer than 30 m to the intersection are classified 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 and hence lead to different risk classifications. Finally, all beacons received closer than approximately 20 m are classified as CRITICAL. Since no beacon at all gets classified as NO-CRASH, it can be concluded that no false negatives exist for this metric.

Figure 3.5b summarizes all intersection approaches where a crash has almost occurred, i.e., taking a safety guard in this case of 1 m into consideration. This intersection approaches are called *Near Crash* situations. It is obvious that most of the real *Crash* situations are located on the diagonal and *Near Crash* situations are close to the diagonal but not directly 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 potential collision area. Moreover, some beacons have been classified as NO-CRASH where one of the two involved vehicles was already very close and the other one was still far away.

Finally, Figure 3.5c depicts all other intersection approaches and hence contains various different situations. Here, the impact of the building shadowing model can be noticed: We can see sporadic 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.

This validation has shown that the risk classification is able to omit false negatives, but its real-world applicability for IAS is harmed by the amount of false positives and hence needs additional measures to prevent unnecessary warnings or unneeded automated reactions of the vehicles.

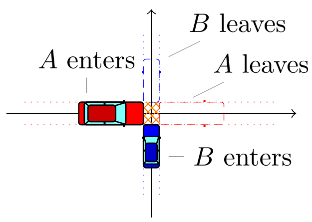
3.3 Intersection Collision Probability

The risk classification—developed and validated in the previous section—provides a first safety metric for evaluating vehicular safety applications. However, it lacks fine granularity due to its four class categorization and it allows instantaneous transitions between classes. For example it can happen that an approach at some point in time gets already classified as CRITICAL, because none of the two vehicles is able to come to a full stop before the intersection anymore and their potential crossing intervals overlap. While the cars are getting closer to the intersection, their potential crossing interval gets narrower. If the initial overlap was very small, it can happen due to the narrowing of the crossing intervals that a transition from CRITICAL to NO-CRASH is triggered. Such a transition is not intuitive and demonstrates the need for a continuous safety metric. Therefore, we want to establish a continuous criticality metric for intersection approaches.

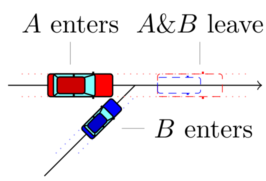
Moreover, the review of other risk estimation models in Section 2.1.2 revealed that available models either focus on serving as a decision metric for automated controllers (such as [42, 43, 46]) or used driver intent inference to model risk estimation (as in [44, 45]). In our opinion, driver intent inference restricts the risk estimation to one particular estimated driver behavior which might be not applicable. Therefore, our approach models safety aspects of intersection approaches by considering the probability of all possible future trajectories and exploiting their likelihood to estimate collision probabilities. The proposed intersection collision probability is developed as safety metric for IVC and hence its goal is not designing a novel vehicle controller; thus we do not consider aspects (i.e., lateral and longitudinal vehicle dynamics, sensor errors, and feedback control) that would be needed in this case.

The purpose of this metric is to calculate the probability of a possible collision whenever new information about two potentially colliding vehicles is available, i.e., every time a car receives a beacon message (which includes position information, speed, heading, etc. of the sender). 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) $a_{\min}$. Note that $a_{\min}$ and $a_{\max}$ are different for the vehicles A and B, because in reality they depend on the vehicle model, tires and even road surface conditions. To simplify the notation, 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 Cartesian coordinate system, where the axes are defined by the driving path of the vehicles and are not necessarily orthogonal as depicted in Figure 3.6a. The axes' origins are at the center of where the vehicles' trajectories intersect. By considering the interdependence of the two distances also a Y-intersection as depicted in Figure 3.6b can be modeled similarly.



(a) X-intersection



(b) Y-intersection

Figure 3.6 – Coordinate space for vehicles A and B for different intersection types [150], © 2014 IEEE.

3.3.1 Definition

In order to define the intersection collision probability, we start by modelling 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 driver behaviors while approaching an intersection) are possible. Starting with the current time t_0, a trajectory is a feasible function of time that describes the vehicle's distance from the intersection center respecting the initial conditions (d_A and v_A) and acceleration limits ($a_{\min}$ and $a_{\max}$)

$$\mathcal{T}_A(t_0) = d_A, \quad \dot{\mathcal{T}}_A(t_0) = v_A, \quad a_{\min} \leq \ddot{\mathcal{T}}_A(t) \leq a_{\max}. \tag{3.9}$$

The measurable set of all possible future trajectories is called $\mathbb{T}_A$ and defined by $\mathbb{T}_A = \bigcup \mathcal{T}_A$ and depends on the current distance d_A and speed v_A of vehicle A since every single $\mathcal{T}_A$ does. In addition, this set is limited by the two trajectories applying constant maximum acceleration $a_{\max}$ and maximum deceleration $a_{\min}$, as depicted in Figure 3.7.

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 $\operatorname{coll}(\mathcal{T}_A, \mathcal{T}_B)$ as

$$\operatorname{coll}(\mathcal{T}_A, \mathcal{T}_B) = \begin{cases} 1 & \text{if there is a collision} \\ 0 & \text{otherwise,} \end{cases} \tag{3.10}$$

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.

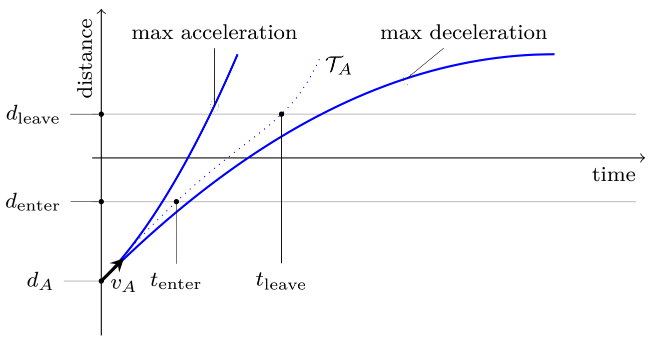


Figure 3.7 – Sample trajectory $\mathcal{T}_A$ of vehicle A depends on its distance d_A and speed v_A. The distances d_{enter}, d_{leave} and times t_{enter}, t_{leave} are depicted for an orthogonal X-intersection [150], © 2014 IEEE.

3.3.1.1 General Form of Collision Probability

Intuitively, the intersection collision probability $\mathcal{P}_C$ depends on the probability that two trajectories $\mathcal{T}_A$ and $\mathcal{T}_B$ which lead to a crash are chosen. Hence the intersection collision probability $\mathcal{P}_C$ can be calculated by integrating over all possible trajectories $\mathbb{T}_A$ and $\mathbb{T}_B$ of two approaching vehicles as follows

$$\mathcal{P}_C = \int_{\mathbb{T}_B} \int_{\mathbb{T}_A} p(\mathcal{T}_A, \mathcal{T}_B) \operatorname{coll}(\mathcal{T}_A, \mathcal{T}_B)\, \mathrm{d}\mathcal{T}_A \, \mathrm{d}\mathcal{T}_B. \tag{3.11}$$

The function $p(\mathcal{T}_A, \mathcal{T}_B)$ provides the probability that the trajectories $\mathcal{T}_A$ and $\mathcal{T}_B$ are chosen and hence gives the possibility to model different kinds of driver behavior. In particular, this general form of the intersection collision probability does not assume the two chosen trajectories to be independent of each other. This allows to model possible interdependence of the driver behavior for example if drivers misinterpret the driving situation. In the following we continue with a simplified version of this general approach, because for evaluating communication strategies for IAS we do not need to model details like lateral movements and/or longitudinal vehicle dynamics, for example. However, this general approach could be also used to take decisions that influence the future evolution of driver's trajectories (by triggering an automated reaction or warning a driver), but we leave these aspects open for future works.

3.3.1.2 Assumptions for Computability

The presented form of the intersection collision probability is very general and has great expressiveness. However, without some additional assumptions it is hardly tractable. Thus, several simplifying assumptions are introduced that can be selectively relaxed when additional insights on a specific issue are needed. As a first simplification, only orthogonal X-intersection crossings without turning maneuvers are considered in the following. 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 3.6a 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 with a given trajectory can be calculated using the trajectory, the vehicle length, and the distances d_{enter} as well as d_{leave}, which depend on the width of the other vehicle. 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 3.7.

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). Therefore, we assume that the probabilities for two trajectories $\mathcal{T}_A$ and $\mathcal{T}_B$ are independent as a second simplification. Moreover, we are especially interested in situations where the drivers are not aware of each other (i.e., they cannot see 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 $a_{\max}$, because this allows to use the acceleration values for integration. Under this constraint, every trajectory $\mathcal{T}$ can be identified by a tuple (a, v, d) and we can define a new function $\operatorname{coll}(\cdot, \cdot)$ analogous to Equation (3.10), but only depending on these values. Hence, we can calculate $\mathcal{P}_C$ by integrating over the interval $a_{\min}$ and $a_{\max}$ for both vehicles as follows:

$$\mathcal{P}_C = \int_{a_{\min}}^{a_{\max}} p(a_B) \int_{a_{\min}}^{a_{\max}} p(a_A) \operatorname{coll}\left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix} \right) \mathrm{d}a_A \, \mathrm{d}a_B. \tag{3.12}$$

The behavior of drivers, i.e., how likely it is that a driver chooses a certain acceleration, can then be modeled by defining the distribution of accelerations/decelerations. In the following we present two possible distributions, which are used throughout the thesis to calculate the intersection collision probability. They represent two possibilities to model acceleration distributions, but cannot be considered to be very close to reality, however, they suffice to study the performance of communication for IAS.

3.3.1.3 Uniform Acceleration Probability Distribution

One simple example is a uniform distribution of all possible accelerations between $a_{\min}$ and $a_{\max}$. This distribution is used to demonstrate the applicability of the collision probability defined in Equation (3.11). The probability $p(a)$ can then be calculated as

$$p(a) = \begin{cases} \frac{1}{a_{\max} - a_{\min}}, & \text{if } a_{\min} \leq a \leq a_{\max} \\ 0 & \text{otherwise,} \end{cases} \tag{3.13}$$

resulting in the simplified collision probability calculation

$$\mathcal{P}_C = \frac{1}{(a_{\max} - a_{\min})^2} \int_{a_{\min}}^{a_{\max}} \int_{a_{\min}}^{a_{\max}} \operatorname{coll}\left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix} \right) \mathrm{d}a_A \, \mathrm{d}a_B. \tag{3.14}$$

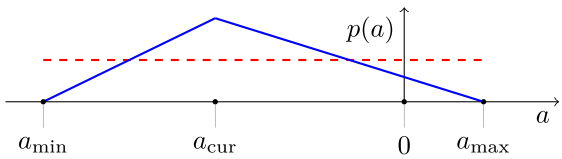


Figure 3.8 – Example of a triangular acceleration probability distribution conditioned on the present acceleration (solid line), compared to a uniform distribution (dashed line) [150], © 2014 IEEE.

3.3.1.4 Towards More Realistic Driver Behavior

As the uniform acceleration distribution does not account for the current acceleration of the car, it does not represent typical human driver behavior well. It might be more likely that a driver continues to drive with the current acceleration and it might be very unlikely to perform extreme accelerations such as full acceleration or deceleration. One possibility to model such behavior is to use a triangular acceleration probability distribution with lower limit $a_{\min}$, mode a_{cur}, and upper limit $a_{\max}$ as depicted in Figure 3.8. By using this triangular distribution, it is more likely that a driver continues with the current acceleration than to switch to another extreme. However, when using this distribution, the collision probability $\mathcal{P}_C$ can still be calculated using Equation (3.12).

3.3.2 Validation

Here in this chapter, we carefully check whether the defined collision probability is behaving as intended and is able to provide a suitable risk estimation for intersection approaches. The intersection collision probability is validated for both the most general form of acceleration probability distribution (uniform) and the more realistic distribution (triangular). The collision probability needs to have the following two properties which are essential for vehicular safety applications:

- **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 %).

3.3.2.1 Simulation Setup

We conducted an extensive simulation study to validate and evaluate the proposed collision probability estimation with the help of the vehicular network simulator Veins 2.0 described in Section 2.3.3.

The presented results are based on a simulation study where the vehicle movements are controlled by IDM with varying input parameters (as described in Section 3.1.2). By varying initial speed as well as acceleration and deceleration behavior different driver behaviors and hence a wide variety of intersection approaches can be evaluated. In the following, the intersection collision probability estimation is evaluated based on the three different outcomes of the intersection approaches: *Crash*, *Near Crash*, and *No Crash* (as described in Section 3.1.4). The second group—called *Near Crash*—uses a vehicle's safety boundary of 0.4 m in this simulation study.

For each simulation parameter set we simulate 5000 intersection approaches using the parameters in Table 3.1 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 intersection approaches across these groups has been as follows: 3.76 % of runs resulted in *Crash*, 0.84 % *Near Crash*, and 95.4 % *No Crash*.

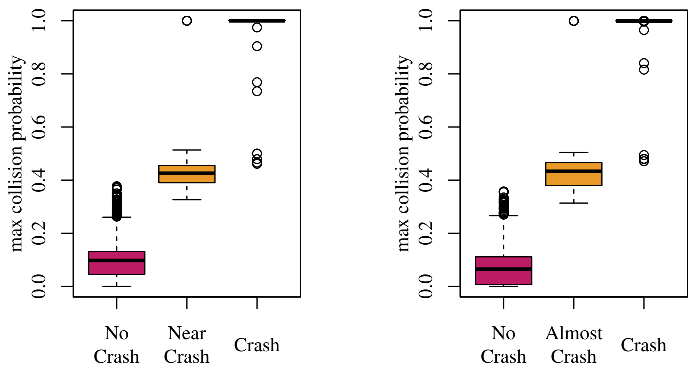
All communication relevant parameters are the same as for the validation of the risk classification and summarized in Table 3.3 to ensure comparability. For these simulations we also use the obstacle model described in Section 2.3.2.2 to account for radio obstructions by buildings at intersections.

3.3.2.2 Validation with Sensor Data

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 information, the maximum collision probability has been calculated for each approaching vehicle and the distribution is presented in box plots grouped by the different outcomes in Figure 3.9 for both acceleration distributions separately. For each data category, 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 that are outside the range of the box and the whiskers are considered as 'outliers' and are drawn singularly as circles.

Starting with Figure 3.9a we first concentrate on the results gathered with the uniform acceleration distribution. 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, it can be seen that almost all approaching vehicles have reached a maximum collision probability of 100 %. We carefully checked all



(a) Uniform Distribution [150], © 2014 IEEE

(b) Triangular Distribution

Figure 3.9 – Boxplots showing the maximum collision probability per approaching vehicle calculated using exact sensor data, grouped by the outcome, and presented for both acceleration distributions.

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 orthogonal intersection layout assumed for the probability calculation. To crosscheck, we simulated a perfect intersection with exact (down to the millimeter) layout. 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.

In Figure 3.9b we see almost identical results for the triangular acceleration distribution. Most notably it can be seen that the distribution for *No Crash* situations shows slightly smaller probabilities than when using the uniform distribution (cf. Figure 3.9a). Hence, it can be concluded that, under the given assumptions and with perfect knowledge of position and speed, the proposed intersection collision probability shows no false positives and no false negatives.

3.3.2.3 Evaluation with Communication Delay

We now go one step further and calculate the collision probability based on the CAM information received from the other vehicle and hence consider communication delay and the implied information inaccuracy. The probability calculation is carried out using exact local information together with delayed CAM data received from the other vehicle.

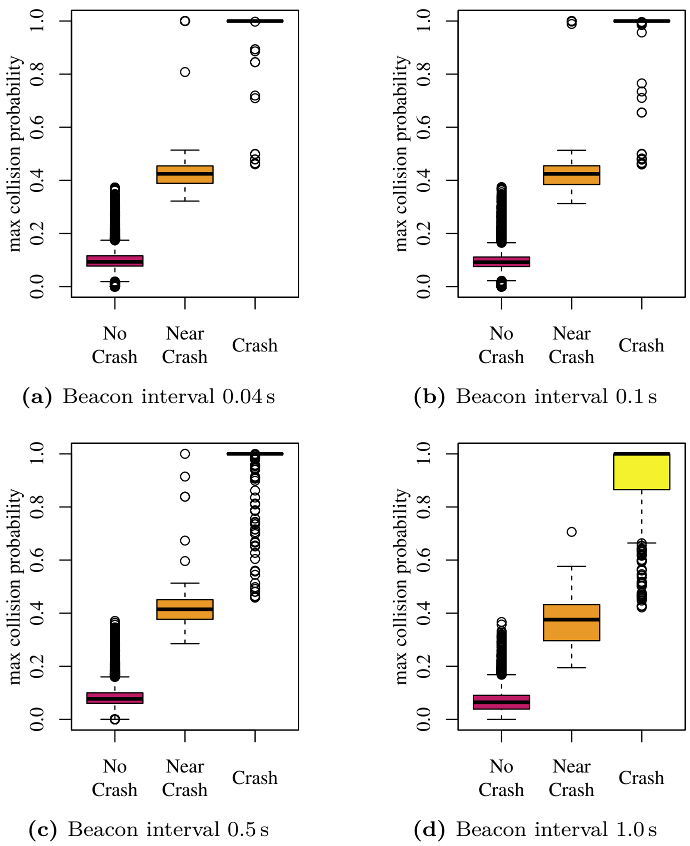


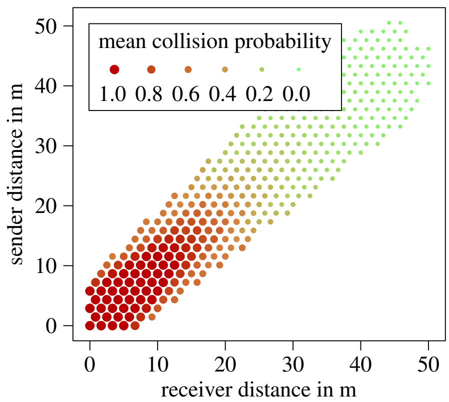
Figure 3.10 – Comparison of the maximum collision probability per approaching vehicle for all received beacons, grouped by the final outcome of the intersection approach and showing the results for different beacon intervals [150], © 2014 IEEE.

The purpose of this evaluation with communication delay is to show the applicability of the intersection collision probability in the context of static beaconing approaches. Please note that our scenario with only two approaching vehicles periodically sending CAM messages represents an idealized (best) case with respect to channel conditions and medium access delay. Here we study the following four static beacon intervals: 0.04 s, 0.1 s, 0.5 s, and 1.0 s.

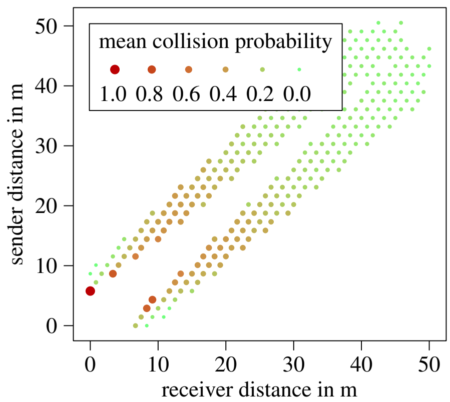
Figure 3.10 shows the distribution of the maximum collision probability per vehicle for different beacon intervals and grouped by the three different outcomes of an intersection approach. Basically, we can observe that for the group *No Crash* the distribution of the maximum collision probability does not significantly change for the different beacon intervals. Hence, it can be concluded that the beacon frequency has no effect on false positives when using a warning threshold of 40 %.

However, when looking at the group *Crash* it can be seen that the number of vehicles which do not reach a high collision probability is substantially increasing for larger beacon intervals. This fact is very clear when comparing Figure 3.10a, which shows a similar distribution as shown in the validation (cf. Figure 3.9), and Figure 3.10d, which reveals that already a major portion of the approaching vehicles has not reached a reasonable high collision probability before crashing.

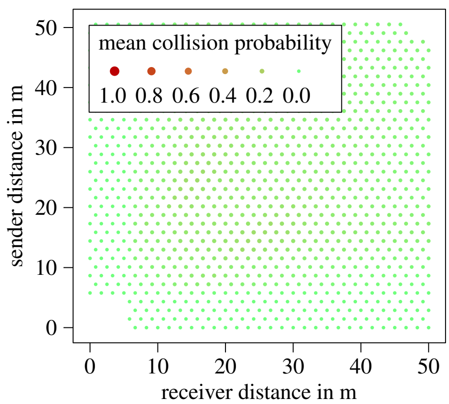
For understanding the correlation between the vehicles' distances and the resulting estimated collision probabilities, Figure 3.11 presents the mean collision probability that has been reached for the vehicles' positions at the time a beacon was received (similar as for the risk classification in Section 3.2.2). Here, we



(a) *Crash*



(b) *Near Crash*



(c) *No Crash*

Figure 3.11 – 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 mean collision probability of the bin by showing large dots for high collision probabilities [150], © 2014 IEEE.

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 color and size of the dots. The presented plots are grouped by the three outcomes *Crash*, *Near Crash*, and *No Crash*, and show the calculated mean collision probabilities for a beacon interval of 0.04 s.

We start with *Crash* approaches plotted in Figure 3.11a. All points close to the potential collision area (receiver and sender distance $\leq$ 10 m show a very high mean collision probability, which is steadily decreasing when looking at points further away from the intersection. For the outcome *Near Crash* (cf. Figure 3.11b), no beacons are received close to the diagonal and the estimated collision probabilities reach mostly a medium level (about 50 %) at a distance of 20 m, but they decrease again towards the intersection. Additionally, the outliers in Figure 3.9, that have been already identified as not detected collisions, are visible as high probability dots close to the intersection and diagonal. Figure 3.11c shows very low estimated collision probabilities for *No Crash* approaches and obviously no beacons are received for very small distances ($\leq$ 5 m), because these points would be already in the potential collision area.

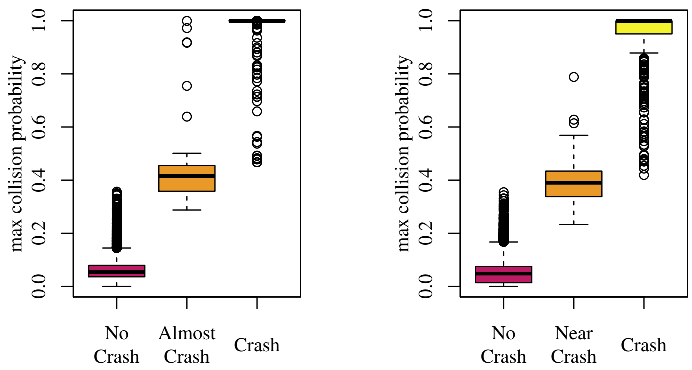
3.3.2.4 Evaluation of More Realistic Driver Behavior

In Section 3.3.1.4 we proposed to use a triangular acceleration probability distribution as an example for modeling more realistic (but certainly not the real) driver behavior.

Figure 3.12 shows again the maximum reached collision probability per approaching vehicle. When comparing these distributions in different situations for the beacon interval of 0.5 and 1 s with Figure 3.10, we notice that the distribution of the triangular distribution is more compact for the outcome *Crash*, whereas the other two outcomes have similar distributions.

Exactly in these situations we have seen quite a lot false negatives, but with this more realistic behavior (triangular distribution), we see fewer. This is already a first positive aspect when using this acceleration distribution for calculating the intersection collision probability.

Another positive aspect when using the triangular distribution is shown in Figure 3.13. We plotted the minimum or maximum 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). When comparing Figure 3.13a (minimum of the uniform distribution) and Figure 3.13b (minimum of the triangular distribution), it turns out that the collision probability estimation allows the prediction of a future crash already at larger distances from the intersection. For IAS this might allow to intervene



(a) Beacon interval 0.5 s

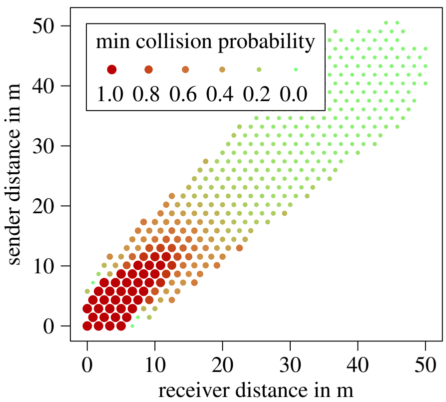
(b) Beacon interval 1.0 s
[150], © 2014 IEEE

Figure 3.12 – Maximum collision probability per approaching vehicle for all received beacons (beacon interval 0.5 and 1 s) using the triangular distribution.

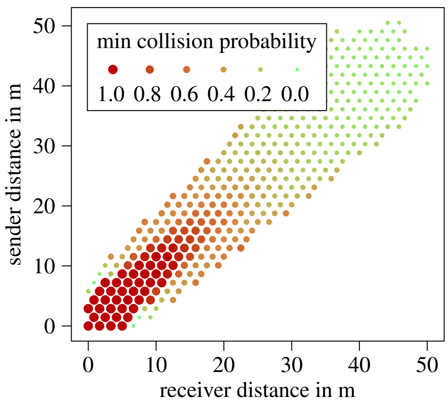
earlier in critical situations, because there is no negative impact of using this distribution for *No Crash* situations either (shown already in Figure 3.12).

Plotting the minimum collision probability also reveals some low collision probabilities close to the borders (in Figure 3.13a and Figure 3.13b). We verified that the outliers are caused by intersection layout inaccuracies.

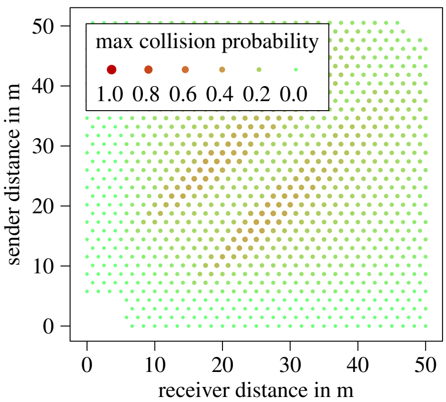
To analyze the worst-case for the outcome *No Crash*, the maximum reached collision probability per bin for the triangular distribution is plotted in Figure 3.13c. Although the collision probability values are higher compared to the mean (cf. Figure 3.11c), the plot is able to confirm the trend that close to the intersection the collision probability is decreasing and showing very low probabilities of around 5 %.



(a) Minimum, uniform distribution, *Crash*



(b) Minimum, triangular distribution, *Crash*



(c) Maximum, triangular distribution, *No Crash*

Figure 3.13 – Worst-case collision probabilities per bin calculated based on beacons received using a beaconing interval of 0.04 s; the dot size and color represent the collision probability of the bin by showing large dots for high collision probabilities [150], © 2014 IEEE.

3.4 Metrics for Evaluation of Communication Strategies

Both proposed safety metrics, the risk classification and the intersection collision probability, can be used either for evaluating communication strategies, as input for them or as decision metric for automated reactions of IAS [150]. The risk classification was a first step towards evaluating IVC for one specific safety application, i.e., Intersection Assistance Systems. And we used it to investigate and evaluate static beaconing approaches in the context of IAS [69].

In addition, these static beaconing approaches have been also evaluated using the intersection collision probability using the *Last Before Unavoidable* beacon described in Section 3.4.1. Since we decided to use the intersection collision probability as input for novel communication strategies for IAS, additional safety related network metrics were needed to evaluate safety aspects of current standards and novel communication strategies.

First, we started with a worst-case analysis of the last few seconds before a crash has happened, explained in Section 3.4.2. Then we defined so-called *update lag* requirements that basically describes the necessary update frequency of information. We used this safe time requirements to analyze how much time individual vehicles spent in an *unsafe* state, presented in Section 3.4.3.

3.4.1 Last Before Unavoidable Beacon

Figure 3.14 shows an exemplary evolution of the intersection collision probability over time for a *Crash* approach, i.e., the evolution is printed only for one vehicle although two are approaching an intersection and finally crashing. Two aspects become immediately apparent when looking at Figure 3.14: The intersection collision probability is only updated when a beacon has been received; in particular it remains unchanged in case of lost beacons. Loss of beacons can, for example, occur if radio communication is obstructed or if the channel becomes overloaded. Both effects are studied in detail in the next chapter. The second aspect is that

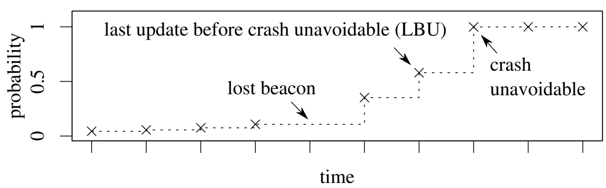


Figure 3.14 – Evolution of the intersection collision probability for a typical *Crash* intersection approach [150], © 2014 IEEE.

the step height of the collision probability strongly depends on the interval at which new information is being received and hence transmitted by the potential collision candidates.

When an approach has been identified as *unavoidable crash*, i.e., the collision probability reached 100 %, all future beacons will also yield an intersection collision probability of 100 %. Consequently, actions to prevent a crash need to be triggered at least one beacon prior to receiving one yielding 100 % collision probability. Hence, this beacon is called *LBU* beacon.

By analyzing the intersection collision probability for these LBU beacons, a safety measure can be deduced. The collision probability reported for LBU beacons relates to the very last step of the intersection collision probability, because no further beacons are received before the crash becomes physically unavoidable. The very last step in the intersection collision probability $step_{\text{last}}$ is calculated as follows: $step_{\text{last}} = 1 - \mathcal{P}_C(LBU)$.

If the distribution of the intersection collision probability for LBU beacons also includes small values, it is apparent that the last step would be really large. This means that already with a low intersection collision probability warnings should be issued or automated reactions triggered. Obviously, such a behavior of IAS would cause many false alarms or unnecessary automated actions, which are annoying to drivers. To conclude, the distribution of the intersection collision probabilities for LBU beacons provides a good opportunity to understand how frequent communication partners are communicating with respect to the collision probability. In particular usual timing metrics are replaced with an application specific metric.

3.4.2 Worst-case Update Lag Metric

To evaluate IVC communication strategies for safety, usual network metrics like channel load, collisions, and update delay are not sufficient [150]. Therefore, we propose an update lag analysis, which is specific for vehicular safety applications, and takes the time to crash into account. The time to crash is calculated retrospectively for all received CAMs during the analysis by using the data recorded by the crash detection module Section 3.1.4. To highlight the behavior of different communication strategies we split the last N seconds before a crash in N bins of one second each: BIN 1 covering the interval [1.0–0.0 s] before the crash, BIN 2 covering [2.0–1.0 s], and BIN N [N − (N − 1)s].

Figure 3.15 demonstrates this bin splitting for the last three seconds before a crash. The points in time when a CAM has been received are marked with $b_0, b_1, \ldots, b_6$.

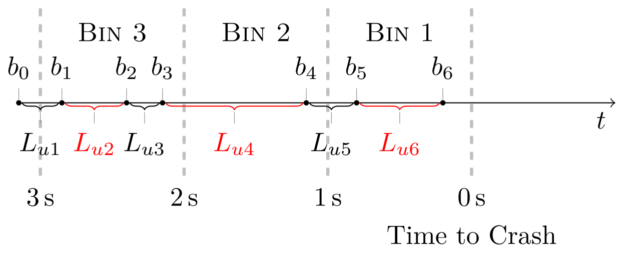


Figure 3.15 – Illustration of the update lag L_u and the worst-case update lags L_u^w (in red) for the different bins.

The *update lag* L_u measures the time between two consecutive received CAMs for one approaching vehicle, i.e., $L_{u_i} = t_{b_i} - t_{b_{i-1}}$. Hence the update lag L_{u_i} belongs to b_i and is counted in the bin where b_i has been received.

Investigating the impact of IVC protocols on road traffic safety, it is not sufficient to look at the average update lag [150], as it is the worst-case that determines the most dangerous situation. For this reason, we make use of a *worst-case analysis* by exploring the worst update lag L_u^w in the different bins per approaching vehicle. The worst-case update lag L_u^w per vehicle is calculated by taking the maximum update lag that has been experienced in the corresponding bin. Since the timestamps of two consecutive CAMs t_{b_i} and $t_{b_{i-1}}$ might have been recorded in different bins, L_u^w might be larger than the bin size.

Figure 3.15 depicts the update lag calculation for all received beacons and demonstrates also the fact that these update lags are calculated across bin boundaries (compare L_{u1}, L_{u4}, and L_{u5}). Moreover, it shows the worst-case update lags per bin in red: in BIN 3 L_{u2} is clearly the worst update lag out of L_{u1}, L_{u2}, and L_{u3}; in BIN 2 L_{u4} is anyhow the only candidate since it is the only CAM which has been received in this bin; and L_{u6} is the worst-case update lag in BIN 1.

3.4.3 Unsafe Time Metric

The worst-case update lag metric presented in the previous section does not allow to assess the communication conditions for an individual vehicle during an entire intersection approach. In order to be able to assess the time a vehicle has spent in an *unsafe state*, i.e., the time a vehicle had to deal with outdated information, we define a specific *required update lag* L_{req}.

Then we can calculate the set of unsafe times $T_{\text{unsafe}} = \{t_{\text{unsafe-0}}, \cdots, t_{\text{unsafe-n}}\}$ that an individual vehicle has spent in such an unsafe state. When summing up all $t_{\text{unsafe-i}}$ in a single measure t_{unsafe}, the entire duration in which the vehicle has not received sufficient information can be assessed.

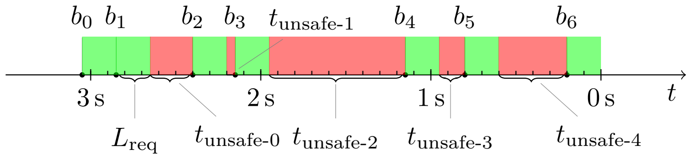


Figure 3.16 – Demonstration of the unsafe time analysis considering a required update lag L_{req} of 200 ms.

In Figure 3.16 the reception of seven CAMs are depicted by the time points $b_0, b_1, \ldots, b_6$. The green coloured duration after the reception of a CAM reflects the required update L_{req} which in this case is 200 ms. Whereat the red coloured durations represent the unsafe times in this example.

The single unsafe times for the depicted intersection approach are: 250, 50, 800, 150 and 400 ms and sum up to a total unsafe time of $t_{\mathrm{unsafe}} = 1650$ ms. Moreover, it can be noticed that there is no numbering correlation of unsafe times and CAMs, because not every CAM will yield to an unsafe time (e.g., b_0 does not yield an unsafe time).

3.5 Conclusion

To analyze safety aspects of IAS the first important building block is a simulation model for crash situations at intersections (described in Section 3.1). After an initial investigation of available car-following models, we presented two different possibilities to model dangerous intersection approaches. The simple random crash situations model allowed first evaluations of safety aspects for IAS.

Nevertheless, it generated too few critical intersection crossing situations, which are indeed the interesting ones. In particular when the goal is to evaluate the behavior of different communication strategies in a crowded wireless channel scenario, it is important to generate mostly critical situations at the intersection. Therefore, we developed and presented a second crash situation model that allows to simulate arbitrary driver behavior. In addition, it also fulfills the control requirement of intersection approaches by taking a parameter which provides the possibility to influence whether a *Crash*, *Near Crash* or *No Crash* situation should be simulated.

The second building block is the crash detection module which is needed to monitor the intersection approach and record the situation accordingly. It checks in small periodic intervals whether the approach needs to be classified as *Crash*, *Near Crash* or *No Crash* and hence enables evaluations for the different situations.

The rest of this chapter deals with the definition and validation of various different safety metrics which can be used to evaluate safety aspects of IAS—the last missing building block.

Starting with the risk classification a basic instrument for such evaluations has been presented in Section 3.2. It makes use of two physical properties: The first one determines whether the two involved vehicles are able to come to a full stop before the intersection. The second one then derives whether the two vehicles will eventually cross the intersection in the same time frame. Using this two properties the collision risk of two approaching vehicles can be categorized in: No-Crash, Safe, Attention, and Critical.

The intersection collision probability addresses the issue of instantaneous transition between the different risk classes in Section 3.3. In particular the non-obvious transitions from Attention and even Critical to No-Crash are possible. They are hardly understandable and demonstrate the lack of granularity. In order to circumvent such non-intuitive transitions, we developed a continuous measure of the criticality of intersection approaches that can be calculated by every approaching vehicle on its own.

As presented in the validation of the intersection collision probability, it complies with its design goals and provides a safety metric that shows:

- **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 %).

The goal of the presented safety metrics, especially of the intersection collision probability, is not only to evaluate communication strategies for IAS, but also to influence the design of them by using evaluation results or using them as input metric for them. In the next chapter we will make use of the intersection collision probability as input metric for communication strategies. Therefore, we also proposed additional useful network metrics with which the discussion of safety aspects of vehicular safety applications is possible. We discussed the importance of the LBU beacon and proposed the *worst-case update lag analysis* which analyzes the last few seconds before a crash has happened. In addition, the *Unsafe Time Analysis* provides a possibility to evaluate how much time a vehicle has spent in an unsafe state—meaning that it did not receive updates in time.

In summary this chapter addressed the following scientific problems: In order to study safety aspects of IAS, two different driver behavior models for simulating intersection crash situations have been proposed. By the proposed risk classification, we tried to come up with a safety metric that is able to distinguish normal and critical intersection approaches. Motivated by the drawbacks of a discrete metric, we proposed the continuous intersection collision probability which can be used for evaluating IVC communication strategies, as control metric for them, or as decision metric for autonomous reaction controllers. Finally, the missing link between safety and network metrics has been addressed by providing network metrics which are related to the actual safety event under observation (i.e., an intersection crash).

Chapter 4

Situation-Aware Communication

Several works (described in Section 2.1.2) pointed out the potential of Intersection Assistance System using Inter-Vehicle Communication and several studies on different aspects of IAS are available (discussed in Section 2.2.7). The studies concentrated either on analyzing communication aspects only or on preventing crashes by using safety measures. However, none of the communication related works studied realistic intersection crash situations using safety metrics as evaluation criterion. Therefore, we employ the methods presented in Section 3.1 to simulate various different intersection crash situations and to investigate IVC performance in a realistic setup.

Since static beaconing (as described in Section 2.2.2.2) was one of the first envisioned information dissemination strategies for vehicular safety applications, we start with the investigation of different static beaconing rates. Moreover, it provides a good baseline, which allows us to draw some first conclusions on the needed update frequency. The presented results are based on an evaluation that makes use of both safety metrics—the *risk classification* and the *intersection collision probability*—presented and validated in Chapter 3.

The evaluation of these simple static beaconing approaches with the intersection collision probability already reveals that IAS do not always require the same communication performance. In particular, the necessary information dissemination rate is dependent on the individual situations the vehicles are, i.e., the seconds before a crash happens are more important for IAS. For this reason, we propose in Section 4.2 the *situation-based rate adaptation* algorithm, which allows vehicles in dangerous situations to communicate more frequently than the ones in normal situations. To assess the situation of vehicles we use the *intersection collision probability* and adapt the information dissemination rate with the help of two different adaptation strategies.

By using this self-adaptive approach in conjunction with dynamic beaconing approaches—TRC and DynB (outlined in Section 2.2.5 and Section 2.2.6, respectively)—we can ensure that the wireless channel does not get overloaded and hence we avoid inefficient use. In addition, we show that the sole use of dynamic beaconing approaches would lead to insufficient communication for IAS in various scenarios.

Since radio propagation in vehicular networks heavily depends on the environment, we investigate the situation-based rate adaptation algorithm in two different scenarios. The first one represents intersections in a rural environment where radio communication is not influenced by buildings and hence all vehicles close to the intersection are within a single interference domain. The benefit of the situation-based rate adaptation in this scenario is only recognizable, if there is a reasonable amount of vehicles in communication range of each other, because otherwise the dynamic beaconing approaches would not restrict the usage of the channel. This *Rural Scenario* is described in Section 4.3.

The second scenario focuses on downtown intersection where radio communication experiences shadowing effects of buildings and hence communication for IAS is very challenging. In particular, already a smaller number of vehicles on the crossroads can have a significant impact on the information dissemination. First we study various densities using a synthetic scenario and finally compare it with a real-world scenario, both presented in Section 4.4

This chapter is based on the following publications:

- S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, "To Crash or Not to Crash: Estimating its Likelihood and Potentials of Beacon-based IVC Systems," in 4th IEEE Vehicular Networking Conference (VNC 2012). Seoul, Korea: IEEE, Nov. 2012, pp. 25–32. This chapter presents the investigation of static beaconing using the risk classification which has been carried out by myself.

- S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, "A Vehicular Networking Perspective on Estimating Vehicle Collision Probability at Intersections," IEEE Transactions on Vehicular Technology, vol. 63, no. 4, pp. 1802–1812, May 2014. The intersection collision probability is used to get further insights on static beaconing approaches and to measure the criticality of intersection approaches, which are both my contribution.

- S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. Lo Cigno, and F. Dressler,"Fairness Kills Safety: A Comparative Study for Intersection Assistance Applications," in 25th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC 2014). Washington, D.C.: IEEE, Sep. 2014, pp. 1442–1447. This paper presents the initial idea of the situation-based rate adaptation as well as the analysis in the *Rural Scenario* and has been proposed and carried out by myself.

- S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. Lo Cigno, A. Jamalipour, and F. Dressler, "Enabling Situation Awareness at Intersections for IVC Congestion Control Mechanisms," IEEE Transactions on Mobile Computing, 2015, in print, available online: 10.1109/TMC.2015.2474370. Further investigations such as the *Synthetic Downtown Scenario* and the cubic situation-based rate adaptation have been published in this paper. The adaptation strategy as well as the more sophisticated scenario setup have been proposed and carried out by myself.

4.1 Initial Study Using Static Beaconing

In this section, we study the feasibility of using static (fixed-period) beaconing for exchanging safety critical information in the context of IAS at downtown intersections such as the one depicted in Figure 4.1. In general, beaconing has been identified in a couple of studies as a suitable communication strategy for many challenging vehicular networking applications [66–68, 100, 153]. Furthermore, the first standards considered to broadcast CAMs periodically every 1–10 Hz (compare Section 2.2.2). These communication mechanisms, which do not adapt to current channel conditions, are usually referred to as *static beaconing* approaches.

Although these static communication approaches are not suitable for crowded channel conditions, they are useful to gain first insights on the needed update

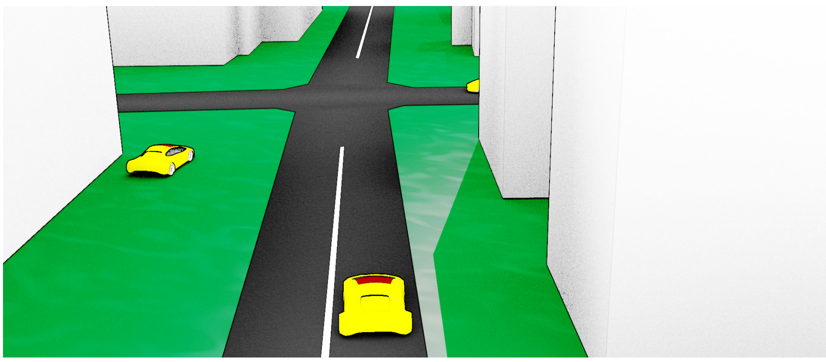


Figure 4.1 – Perspective view of the simulated downtown X intersection [69], © 2012 IEEE.

frequencies of IAS. Therefore, we study in this section only the best case with respect to channel conditions, i.e., only the two approaching vehicles try to exchange CAMs.

For evaluating static beaconing we always let only two vehicles approach the intersection for two reasons: First, other vehicles could influence the two vehicles under analysis from a road traffic point of view and second we want to study the best case regarding communication conditions (where only the two approaching vehicles try to access the wireless channel). In order to study critical situations we disable road traffic safety checks for the two approaching vehicles as described in Section 3.1.2. Static beaconing with rates in the range of 1–25 Hz is based on top of a IEEE 802.11p PHY/MAC. A detailed description as well as the full list of parameters can be found in Section 3.2.2.1.

First, we use the *risk classification* (presented in Section 3.2), which has been validated already in Section 3.2.2. The presented results have been gathered to understand how much communication is needed to fulfill safety requirements of IAS and hence to draw some first conclusions on the necessary update lag.

Then we use the intersection collision probability to draw some more meaningful conclusions in the context of IAS. In particular, the *Last Before Unavoidable beacon* is explored to demonstrate possible reaction thresholds for IAS. Finally, we can draw some conclusions on communication demands of IAS based on the evaluation of these static beaconing approaches.

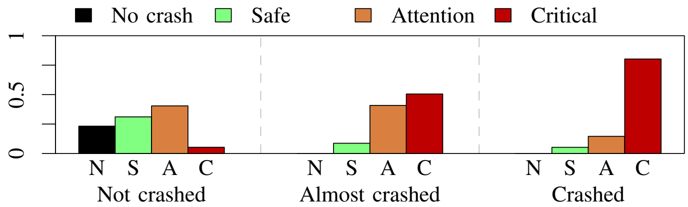
Please note that all results in this section resemble a best case study from a communication perspective, because no other cars were present and attempted to communicate in these experiments.

4.1.1 Influence of the Beacon Interval

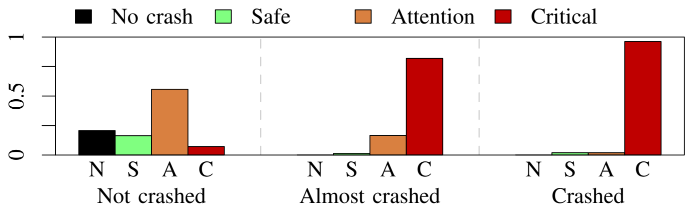
In the validation of the risk classification (cf. Section 3.2.2), we investigated the classification on a per-beacon basis, i.e., how each beacon is categorized depending on the distance at which it has been sent and received. For understanding the impact of different beacon intervals, we now concentrate on how each intersection approach as a whole gets classified and present two different perspectives or possible event classifications.

Figure 4.2 shows the ‘worst’ categorization that each vehicle has assigned to at least one of the beacons received during the intersection approach. By ’worst’ categorization we refer to the following order, where later listed categories are considered ’worse’: NO-CRASH, SAFE, ATTENTION, and CRITICAL. Results are shown for different beacon intervals, split by the situation at the intersection.

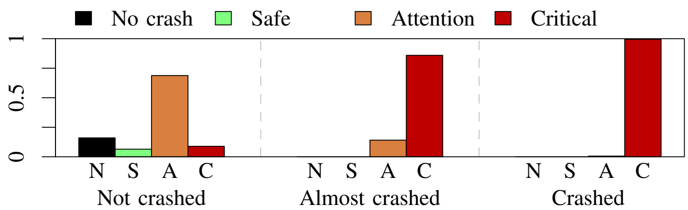
Let us first concentrate on the intersection approaches that resulted in a *Crash*.The worst-case classification gets better as the beacon interval decreases.



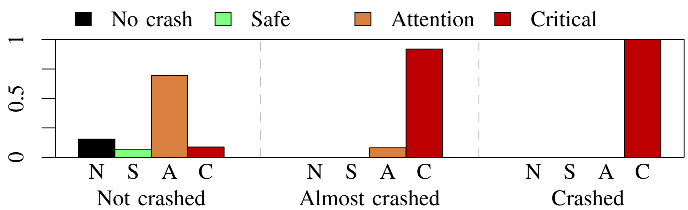
(a) Beacon interval 1.0 s



(b) Beacon interval 0.5 s



(c) Beacon interval 0.1 s



(d) Beacon interval 0.04 s

Figure 4.2 – Worst-case risk classification of beacons during single intersection approaches [69], © 2012 IEEE.

In detail, for a beacon interval of 1.0 s more than 20 % of vehicles 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 100 % correct classifications. A similar trend can be observed for the *Near Crash* approaches.

Using a beacon interval of 0.5 s the update lag between two consecutive beacons is too large even under optimal channel conditions to correctly identify some of the dangerous situations. This fact demonstrates already the need of beacon intervals lower than 0.5 s for IAS based on IVC.

For *No Crash* intersection approaches, we see that independent of the beacon interval only very few beacons are classified as CRITICAL; however, the majority of situations show ATTENTION as worst-case categorization, which is too high if this level should be used for issuing warnings, because too many false alarms would be triggered.

In Figure 4.3 we also plot the overall distribution of the risk classification for a beacon interval of 0.04 s. As expected, the risk class CRITICAL is almost never triggered for *No Crash* situations and vice versa the class NO-CRASH never for *Crash* situations.

In order to understand, which warning levels are triggered, Figure 4.4 shows a different perspective of the risk classification. For each warning level (NO-CRASH, SAFE, ATTENTION, and CRITICAL), we plot the proportions of approaches during which the level was triggered at least once.

In general the majority of approaches trigger all warning levels, showing that beacons were received at different points and hence situations of the approach. Two notable exceptions are: a reasonable portion of class CRITICAL approaches that did not end in a *Crash* and only a very few of NO-CRASH in approaches that did result in one.

Focusing on Figure 4.4a, which shows results for a beacon interval of 1 s, it is clear that the awareness level is hardly acceptable for IAS. While none of the approaches that ultimately ended in a *Crash* were ever misclassified as NO-CRASH, more than 15 % never triggered SAFE (approaching vehicle detected,

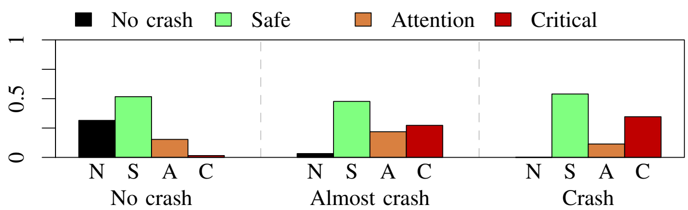
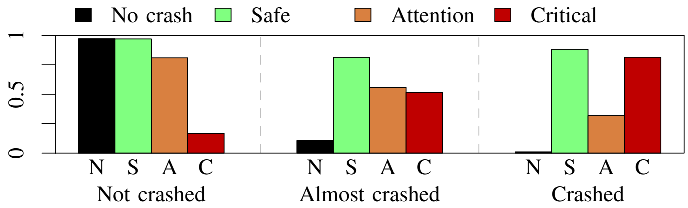
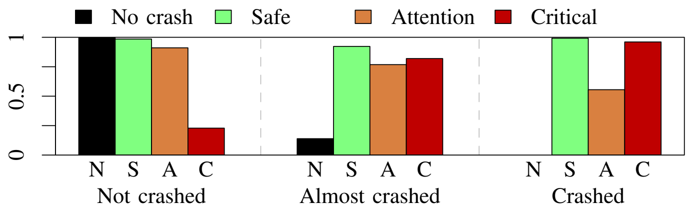


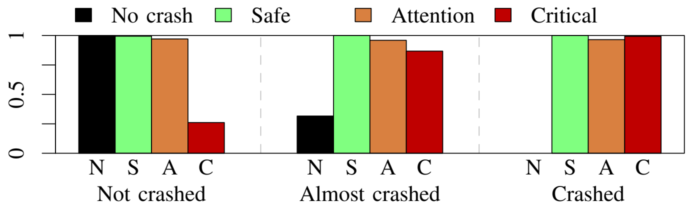
Figure 4.3 – Risk classification of all beacons for the experiment with a beacon interval of 0.04 s.



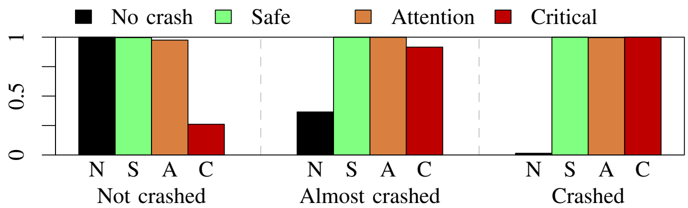
(a) Beacon interval 1 s



(b) Beacon interval 0.5 s



(c) Beacon interval 0.1 s



(d) Beacon interval 0.04 s

Figure 4.4 – Proportion of approaches during which a certain warning level was triggered. Plotted for all investigated beacon intervals [69], © 2012 IEEE.

both vehicles can still stop before entering the intersection). For these approaches the vehicles only triggered either Attention (approaching vehicle detected and only one of the vehicles can still stop before entering the intersection) or Critical (neither can stop). 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.

For *Crash* situations, however, it is necessary that the risk classes Safe, Attention, and Critical are triggered at least once. Therefore, we can conclude when looking at Figure 4.4c and Figure 4.4d that a beacon interval of 0.1 s is close to satisfy this essential requirement and 0.04 s fully complies.

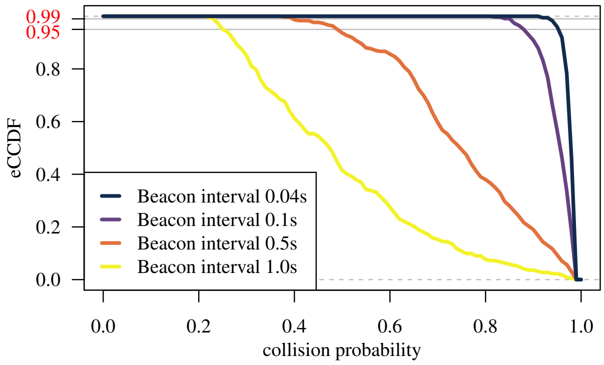
4.1.2 Impact of Beacon Intervals on Reaction Thresholds

In the following we investigate the intersection collision probability that has been estimated for Last Before Unavoidable (LBU) beacons (described in Section 3.4.1) and how the revealed values can be used as reaction thresholds for IAS. For this investigation we consider again static beaconing with beacon intervals of 0.04, 0.1, 0.5 and 1.0 s. Moreover, we still examine a best case scenario where only the two approaching vehicles make use of the wireless channel. A more comprehensive description including all simulation parameters can be found in Section 3.3.2.1. The definition of the intersection collision probability and the underlying assumptions are described in detail in Section 3.3.

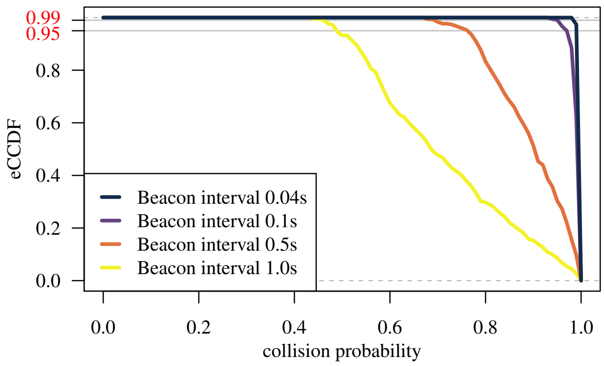
Figure 4.5 shows the empirical Complementary Cumulative Distribution Function (eCCDF) of the calculated intersection collision probability for LBU beacons, depending on the configured beacon interval. In Figure 4.5a the intersection collision probability calculation is based on a uniform distribution of driver behavior—assuming that all possible future trajectories are equal likely. As reported in Section 3.3.1.4, this is not very close to human driver behavior. Hence Figure 4.5b explores a more realistic distribution of driver behavior—the *triangular distribution*, which takes the current acceleration of both involved vehicles into account.

Starting with the results for the uniform distribution in Figure 4.5a 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 fact and the overall eCCDF for these beacon intervals would already call for a fairly small threshold for automated reactions, because no further useful information is to be expected after receiving the LBU beacon.

When considering safety applications, such as IAS, it is necessary to cover almost all possible situations; thus, the 95th and 99th percentiles (also listed in



(a) Uniform acceleration probability distribution



(b) Triangular acceleration probability distribution

Figure 4.5 – eCCDF of collision probability for Last Before Unavoidable (LBU) beacons and approaches in group *Crash* [150], © 2014 IEEE.

Table 4.1) are a better indication of how a reaction threshold would need to be chosen. Looking at these numbers it becomes clear that slow beacon intervals (0.5 s and 1 s) are not suitable, because the implied reaction thresholds for them are as low as 21 % and 48 %. Thus they would lead to many false positives since even in *No Crash* situations such values are easily reached (cf. Section 3.3.2). When considering the more realistic acceleration distribution (as illustrated by the triangular acceleration probability distribution in Figure 4.5b and Table 4.1), the necessary reaction threshold might be chosen some percentage points higher (from 39 % to 76 %), but it still remains low for these beacon intervals.

For smaller beacon intervals (0.04 s and 0.1 s), we see that the necessary reaction thresholds are appreciably high. The reaction threshold can be as high as 99.3 % assuming a triangular acceleration probability distribution, when targeting the 95th percentile, and using the fastest beaconing interval of 0.04 s. Nevertheless, these values are only applicable for these highly idealistic network conditions assumed in the simulation. It has been shown in [68] that static

Table 4.1 – Reaction thresholds based on Last Before Unavoidable intersection collision probability [150], © 2014 IEEE.

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

beaconing with such high rates would overload the wireless channel already in medium dense road traffic situations. An overloaded wireless channel is leading to excessive packet loss, which would have fatal implications for IAS.

4.2 Situation-based Rate Adaptation

To prevent blackout periods for vehicles in dangerous situations, we propose to use a *situation-based rate adaptation* algorithm. We study in the following only IAS and hence investigate only dangerous situations at intersections. Nevertheless, the situation-based rate adaptation might be used also to prevent communication outages for other driver assistance systems. The situation-based rate adaptation for IAS makes use of the presented intersection collision probability (cf. Section 3.3) and can be added to arbitrary congestion control mechanisms. We show its applicability for ETSI TRC and DynB, described in Section 2.2.5 and Section 2.2.6, respectively.

4.2.1 Derivation

In Section 4.1.2 we have analyzed the intersection collision probability for the LBU beacons. This analysis investigates of the last step of the intersection collision probability before a crash becomes unavoidable. Hence it provides a first understanding of feasible reaction thresholds for automated IAS. Nevertheless, the decision of IAS will not be based on this single and very last message before a crash becomes unavoidable. Therefore, we analyze in the following the criticality of all received messages within the 10 seconds time window before a crash.

Figure 4.6 depicts the evolution of the collision probability as a function of the *time to crash* for various intersection approaches when using a static beacon rate of 5 Hz. We only consider intersection approaches that finally resulted in a *Crash* and we post-calculated the time to crash.

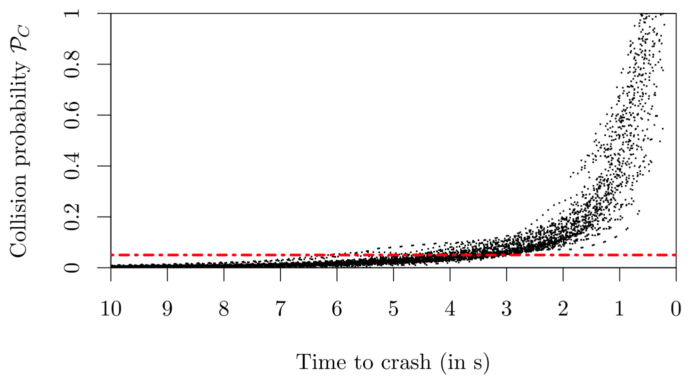


Figure 4.6 – Evolution of the collision probability $\mathcal{P}_C$ for various intersection approaches that resulted in a *Crash* [154], © 2015 IEEE.

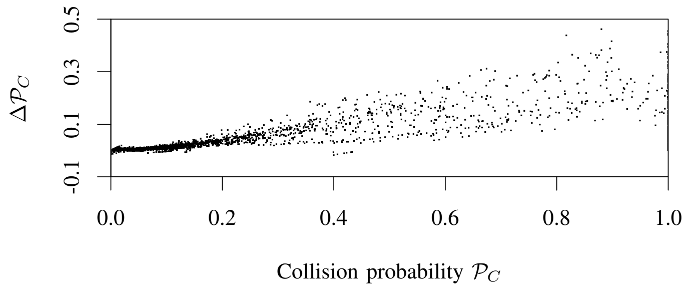


Figure 4.7 – Variation of $\Delta\mathcal{P}_C$ of the intersection collision probability with respect to $\mathcal{P}_C$ computed at the preceding CAM (y-axis) vs. the collision probability (x-axis) plotted for approaches that resulted in a *Crash* [154], © 2015 IEEE.

Figure 4.6 shows that the collision probability of approaching vehicles rises only in the last few seconds, which is exactly the time frame when IAS need reliable and continuous communication. Therefore, we propose to use the intersection collision probability as measure for the situation-based rate adaptation.

Since the timespan when vehicles need to communicate depends on the situation of the vehicles and is not known a priori, we introduce a threshold $\mathcal{P}_{th}$ for the intersection collision probability below which the situation-based rate adaptation is not used. We opted for a threshold $\mathcal{P}_{th}$ of 5 %, because most of the intersection approaches shown in Figure 4.6 do not exceed this threshold earlier than 5 s before a crash. Please note that this threshold will likely be variable for different situations, criticality metrics, and vehicular safety applications.

In addition, Figure 4.6 shows that the collision probability $\mathcal{P}_C$ during intersection approaches rises non-linearly in time. However, it is difficult to assess the evolution of the increments of the collision probability $\mathcal{P}_C$ in this plot. Let $\Delta\mathcal{P}_C$ be the difference of two successive evaluations of $\mathcal{P}_C$. Figure 4.7 plots $\Delta\mathcal{P}_C$ for the same intersection approaches as Figure 4.6 for a static beacon rate of 5 Hz as a function of $\mathcal{P}_C$. It shows a clear trend: $\Delta\mathcal{P}_C$ increases for higher intersection collision probabilities $\mathcal{P}_C$.

4.2.2 Strategy

The integration of the intersection collision probability as control metric for the rate adaptation is not a trivial task, because the trade-off between additional channel load and required update frequency needs to be considered. The first promising idea is to use a *linear adaptation* strategy with a maximum beacon rate of $r_{\text{linear}} = 100\,\text{Hz}$ (as explored in [114]).

However, the linear adaptation has one major drawback, which is visible in Figure 4.8: The linear adaptation adapts the dissemination rate only slowly especially for low intersection collision probabilities. When looking again at Figure 4.6, it can be seen that most vehicles spend a non-marginal period in low collision probability situations and hence a slow adaptation might not suffice to ensure reliable communication between endangering vehicles during intersection approaches.

Therefore, we decided to explore a more aggressive adaptation strategy, namely the *cubic adaptation*. However, to make a correct comparison of the two strategies, we need to impose that the additional channel load is kept at a comparable level. Otherwise, the strategy that uses higher beacon rates for endangered vehicles is more likely to show benefits, but it would also congest the channel more.

To equalize the average channel load, we use the maximum beacon rate for the cubic adaptation r_{cubic} as free variable. We compute the average channel load for both adaptation strategies by calculating the surface integral of the adaptation function over the intersection collision probability in the interval

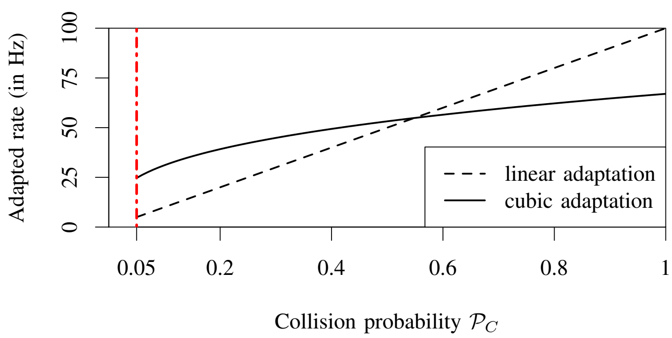


Figure 4.8 – Comparison of the adapted rate of the *linear* and *cubic* situation-based rate adaptation depending on the intersection collision probabilities [154], © 2015 IEEE.

[0.05, 1.0] (i.e., starting from the threshold $\mathcal{P}_{th}$ till 100 %). The equalization of the average channel load yields to a maximum beacon rate for the cubic rate adaptation strategy $r_{\text{cubic}} = 67.76\,\text{Hz}$.

The rate adaptation for the linear adaptation strategy is calculated as follows

$$r = \max(r_{\text{default}}, p \times r_{\text{linear}}). \tag{4.1}$$

In contrast, the more aggressive cubic adaptation strategy uses

$$r = \max(r_{\text{default}}, p^{1/3} \times r_{\text{cubic}}). \tag{4.2}$$

4.2.3 Algorithm

Algorithm 4.1 lists the procedures of the situation-based rate adaptation for both strategies. When a vehicle receives a CAM, the procedure ReceivedCAM (line 1) is triggered. It calculates the intersection collision probability $\mathcal{P}_C$ using the data contained in the received CAM and the current position and speed of the own vehicle. The calculated collision probability is used to adapt the beacon rate by calling the procedure AdaptBeaconRate (line 6).

1: **procedure** ReceivedCAM
2: calculate $\mathcal{P}_C$ ▷ see Equation (3.12)
3: call AdaptBeaconRate
4: **end procedure**
5:
6: **procedure** AdaptBeaconRate
7: $r \leftarrow r_{\text{default}}$
8: $p \leftarrow \mathcal{P}_C$
9: **if** no CAMs received for at least t_{out} **then**
10: $p \leftarrow \mathcal{P}_{\text{self}}$
11: **end if**
12: **if** $p > \mathcal{P}_{th}$ **then**
13: calculate r ▷ see Equation (4.1) and Equation (4.2)
14: **end if**
15: (re-)schedule calls of SendCAM with rate r
16: **end procedure**
17:
18: **procedure** SendCAM
19: flush MAC queue
20: enqueue CAM
21: call AdaptBeaconRate
22: **end procedure**

Algorithm 4.1 – Situation-based rate adaptation [154], © 2015 IEEE.

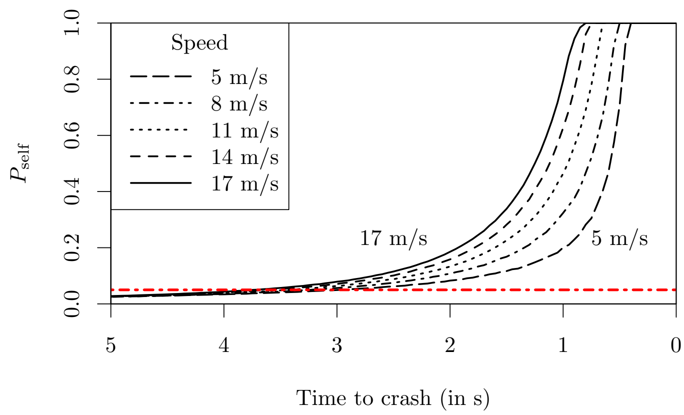


Figure 4.9 – Evolution of the self collision probability $\mathcal{P}_{\text{self}}$ computed assuming that there is a car in the exact same situation approaching the crossroad from the other road; it is computed for several different approaching speeds and no acceleration; the red line shows a potential threshold $\mathcal{P}_{th}$ of 5 % [154], © 2015 IEEE.

The procedure AdaptBeaconRate performs the situation-based rate adaptation itself in multiple steps. In the beginning it ensures that the rate r is kept by default at r_{default} (the rate chosen by the congestion control algorithm). The situation-based rate adaptation uses the current collision probability $\mathcal{P}_C$ if a CAM was received recently (defined by a timeout t_{out}). If no recently received CAM is available for computing $\mathcal{P}_C$, a default probability $\mathcal{P}_{\text{self}}$ is calculated. This fall-back collision probability helps to improve situation awareness if there was no initial communication yet possible among the approaching vehicles (e.g., if the building shadowing effects do not allow direct communication). It assumes a worst-case scenario where another car would approach the intersection on the crossroad at exactly the same distance to the intersection and traveling with the same speed and acceleration—hence it is called self-collision probability. Figure 4.9 shows the evolution of $\mathcal{P}_{\text{self}}$ for different constant speeds for the last five seconds before a crash happens.

Independent of whether $\mathcal{P}_C$ or $\mathcal{P}_{\text{self}}$ is used, the adaptation overrides the information dissemination rate of the congestion control mechanism only if the intersection collision probability p exceeds the threshold $\mathcal{P}_{th}$ (line 12). The adapted rate r is set to the higher value out of the current dissemination rate and the situation-based adapted rate calculated either by Equation (4.1) or Equation (4.2), depending on the adaptation strategy. The rate r is then used for rescheduling the calls of sending CAMs.

The procedure SendCAM (line 18) is called whenever a CAM needs to be transmitted. It ensures that the most recent CAM is transmitted by flushing CAMs from the MAC queue before queuing the current CAM for transmission.

In order to keep the dissemination rate synchronized with the current situation of the vehicle, it checks also after every transmission if the beacon rate needs to be adapted by calling AdaptBeaconRate.

4.2.4 Validation

In Section 4.2.1 we have shown that the intersection collision probability is rising non-linearly in time and proposed two different adaptation strategies of the information dissemination rate. To validate the linear adaptation strategy for IAS we plot again the change of the intersection collision probability $\Delta\mathcal{P}_C$ against the intersection collision probability itself $\mathcal{P}_C$. Figure 4.10 confirms that the linear adaptation of the beacon rate successfully keeps the change of the intersection collision probability in a reasonable small and constant range.

The changes of the intersection collision probability for the cubic adaptation strategy leads to similar results (not plotted for the sake of brevity). To investigate the distribution of the $\Delta\mathcal{P}_C$ in detail Figure 4.11 plots the eCDF above the threshold $\mathcal{P}_{th}$ for the baseline (i.e., no adaptation and using a constant beacon rate of 5 Hz), linear adaptation and the cubic adaptation strategy.

Starting with the eCDF of baseline, it can be seen that more than 20 % of CAMs yield changes of the intersection collision probability of more than 10 %. When looking at the distribution for the situation-based rate adaptation, it can be seen that both strategies are able to keep the changes in a small range, i.e., there are no steps larger than 5.9 % during any intersection approach. In general, Figure 4.11 shows that the cubic adaptation causes smaller changes of the intersection collision probability, although it uses a lower maximum information dissemination rate.

Moreover, a slight difference between the two adaptation strategies can be seen by looking at the 99th percentile: For the linear adaptation 99 % of the

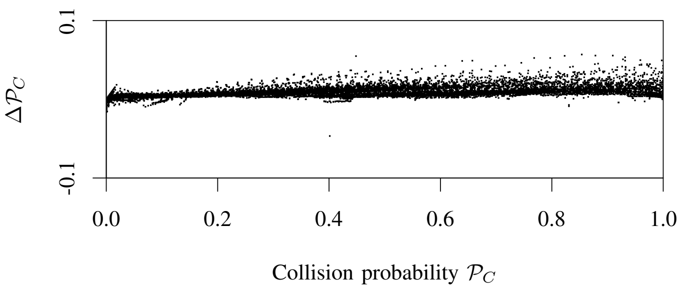


Figure 4.10 – Change of the collision probability ($\Delta\mathcal{P}_C$) (y-axis) when the information dissemination rate is adapted as proposed in Section 4.2.3 (data of *Crash* approaches only): It remains small, almost constant and within a safe range.

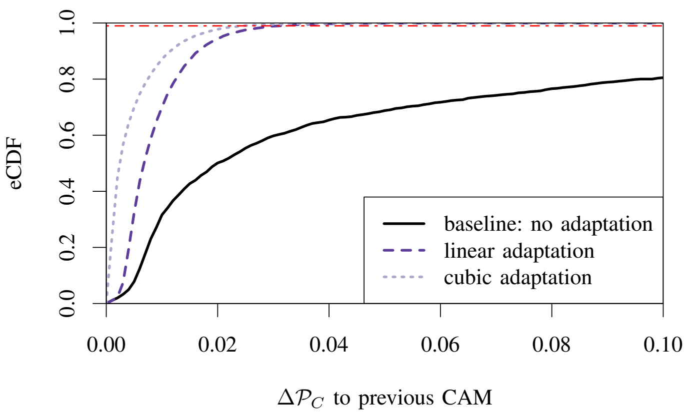


Figure 4.11 – eCDF of the $\Delta\mathcal{P}_C$ for a constant beacon rate of 5 Hz (i.e., w/o adaptation) and linear as well as cubic situation-based rate adaptation.

increases are smaller than 3.2 %, whereas the increases for the cubic adaptation are smaller than 2.5 %. However, this validation does not show yet that the cubic adaptation is also advantageous in crowded communication scenarios, but we investigate this aspect in Section 4.3 and Section 4.4 in detail.

4.3 Situation Awareness at Rural Intersections

The best case scenario used in Section 4.1 to evaluate static beaconing approaches resembles optimal conditions regarding the concurrent usage of the wireless channel of vehicles. Obviously, the wireless channel will not only be used by the two approaching vehicles, but also by all others in the vicinity of the intersection. Moreover, multiple IVC applications might operate concurrently and demand the channel too. To account for these additional users of the wireless channel we created a scenario where not only the approaching vehicles contend for channel access, but also a variable, but fixed number of vehicles.

To analyze the communication performance at intersections for crowded wireless channels, we added "ghost" vehicles, which generate additional communication load. These vehicles use the same communication strategies as the two vehicles under analysis. To ensure that these additional vehicles are not interacting with the two monitored vehicles from a road traffic point of view, these background communication vehicles are simulated only in the network simulator and not in the road traffic simulator SUMO.

We refer to this scenario as *Rural Scenario*, because we do not account for shadowing effects by buildings, which are usually present in urban environments.

4.3.1 Scenario Description

In this scenario all vehicles in the vicinity of the intersection hear, and hence interfere with, each other. In other words, they form a *single interference domain*, as depicted in Figure 4.12. More precisely we do not simulate any building or other obstructions that would impair radio communication between individual vehicles. This allows us to analyze a rural intersection where no buildings obstruct the line of sight of any two vehicles and hence no shadowing effects of radio signals need to be considered. Even if there are no compact obstacles obstructing radio communications from the drivers' point of view, the line of sight might be still obstructed by bushes or trees as shown in Figure 4.12. Tchouankem et al. [137] have reported that even the vegetation at an intersection has an impact on radio communication. However, we employ this scenario to show the behavior of different communication strategies in a rural environment where all interfering vehicles are very close to the intersection; hence the signal attenuation in this scenario is modeled using the simple Free-space path loss model (described in Section 2.3.2.1). The densities of 40, 60, and 80 vehicles have been achieved by placing 10, 15, and 20 "ghost" vehicles in each road segment at a distance of 50 m from the intersection center.

The risk classification as well as the intersection collision probability have been evaluated by intersection crashes where randomly selected vehicles disregard traffic rules (as described in Section 3.1.2). This simulation technique, however, resulted only in a few vehicle collisions (less than 5 % of all situations), and in high speed collisions due to the fact that both vehicles cross the intersection with their right-of-way speed, which is usually quite high.

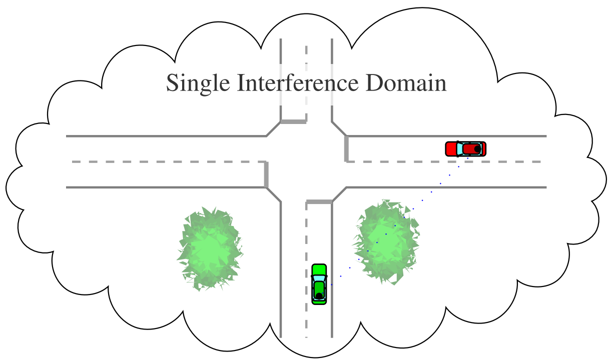


Figure 4.12 – Schematic overview of the *Rural Scenario* showing the two approaching vehicles that do not see each other yet due to visual obstructions by vegetation (e.g., bushes or trees). The additional vehicles, which are communicating in the background, are not depicted [154], © 2015 IEEE.

To evaluate IAS in a more realistic manner, we implemented an intersection approach model that is parameterized by the aggressiveness and discipline of the driver, as proposed in [152]. This allows to simulate arbitrary intersection approaches and vehicle collisions with different speeds and acceleration/deceleration behavior when right-of-way rules are disabled in the road traffic simulator SUMO.

With this technique, a wider range of intersection collision situations can be simulated. Moreover, the possibility to select driver behaviors precisely guarantees that every “run” of the simulation results either in a vehicle collision or an interesting (from the perspective of IAS) situation. This is very important, because simulations, specially when there are many vehicles crowding the communication channel, are computationally intensive and it is important to use the simulation time as efficiently as possible. The vehicles approach the intersection and cross it without turning. Additionally, the simulator guarantees that only two vehicles actually approach the intersection at the same time. The parameters for simulating the vehicle movements are summarized in Table 3.2. The intersection approach model is described in detail in Section 3.1.3.

For this scenario we simulated 480 intersection approaches and 352 of them resulted in a *Crash*. All our presented plots show only data points of intersection approaches that resulted in a *Crash*. The experiments only record the behavior

Table 4.2 – 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	33 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	Threshold $\mathcal{P}_{th}$	5 %
	Min. rate r_{min}	5 Hz
	Max. rate linear r_{linear}	100 Hz
	Max. rate cubic r_{cubic}	67.76 Hz
	Timeout t_{out}	1 s

of the cars and communications, without activating any countermeasure, so that the high number of *Crash* is not a failure of the proposal, but indeed is able to highlight the need for reliable communication to implement IAS.

All present vehicles (the two approaching, as well as all "ghost" vehicles) use either DynB or TRC (described in Section 2.2.6 and Section 2.2.5, respectively) as basic communication strategy. In addition, vehicles in dangerous situations (e.g., when the two approaching vehicles are close to the intersection and a crash becomes likely) make use of the situation-based rate adaptation algorithm (as described in Section 4.2.3) if it is enabled. In the following we refer to the communication strategies without situation-based rate adaptation as DynB w/o and TRC w/o. All communication related simulation parameters for physical layer, MAC, congestion control mechanisms, and the situation-based rate adaptation are listed in Table 4.2.

4.3.2 Initial Scenario Analysis

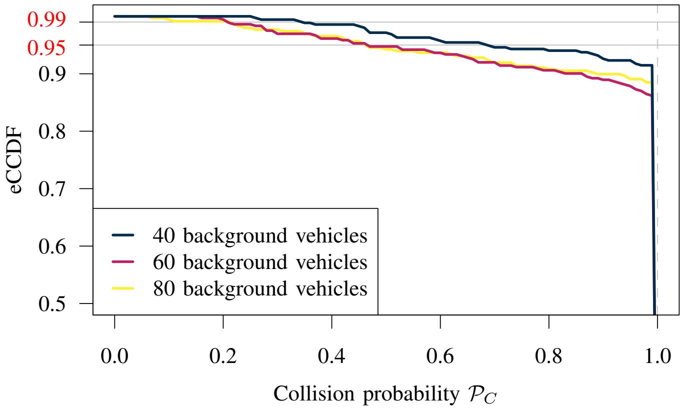
To gain first insights on the impact of different numbers of background communication vehicles we employ again the safety metric of the Last Before Unavoidable (LBU) beacons for this initial scenario analysis. Figure 4.13 shows the eCCDF of the intersection collision probability for the LBU beacons received when all nodes have been using DynB (cf. Figure 4.13a) and TRC (cf. Figure 4.13b).

Actually the difference between the different vehicle densities is marginal in these plots, but still a trend is visible: The more vehicles are trying to access the channel simultaneously the smaller the intersection collision probability will be for LBU messages. Moreover, it can be seen that when DynB is used as communication strategy, some vehicles experience very low LBU intersection collision probabilities (lower than 40 %).

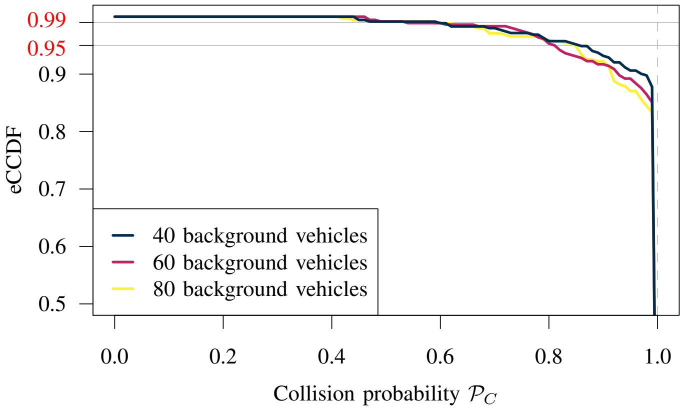
However, the LBU intersection collision probability analysis represents only a snapshot of the very last beacon before a crash becomes unavoidable. Hence the different communication situations of individual vehicles have a strong influence on the intersection collision probability. In particular, this snapshot of a single beacon for each approaching vehicle is not able to provide a complete picture of an entire intersection approach.

To overcome this limitation we analyze the single approaching vehicles with an application-specific communication analysis. In particular we carried out a worst-case update lag analysis as described in Section 3.4.2.

Figure 4.14 plots the eCDFs of worst-case update lags L_u^w per vehicle for DynB and all three simulated vehicle densities: 40, 60, and 80 vehicles communicating in the background. In order to highlight the influence of the vehicle density not the entire eCDFs are shown in this plot (Figure 4.14 shows only the eCDFs for



(a) DynB



(b) TRC

Figure 4.13 – eCCDF of the intersection collision probability for LBU beacons and approaches in group *Crash*.

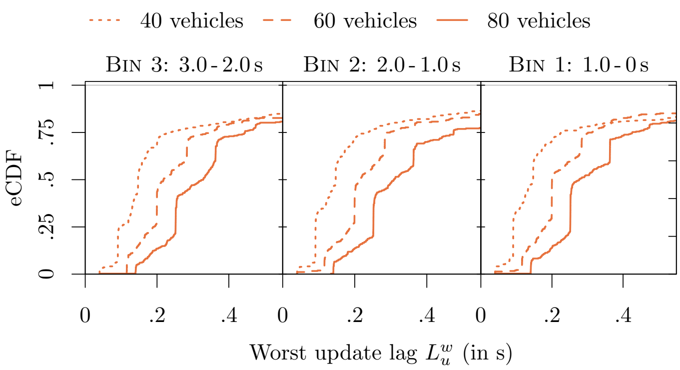


Figure 4.14 – eCDF comparing L_u^w of DynB w/o situation-based rate adaptation for different vehicle densities in the *Rural Scenario*.

$L_u^w \leq 550\,\text{ms}$). A clear trend can be spotted: The higher the vehicle density gets, i.e., the more crowded the wireless channel gets, the worse the experienced L_u^w gets for the individual vehicles. The difference is well visible and almost identical in all three plotted time to crash bins. Moreover, it can be already concluded that DynB is not able to satisfy strict update lag requirements in such crowded *Rural Scenarios*.

Interestingly, the investigated vehicle densities do not impose a notable difference of worst-case update lags for TRC (not shown for the sake of brevity). The reason for this finding is that most of the vehicles spend anyhow most of the time in the “active” state of TRC, which implies a rather high beacon interval of 500 ms. Nevertheless, the communication density must increase as the vehicle density increases if the majority of vehicles are in the “active” state. To verify this hypothesis Figure 4.15 plots the eCDF of experienced channel loads of the two monitored vehicles in the last three seconds before the crash has happened. Indeed, the channel load increases as presumed.

To conclude this initial scenario analysis with current congestion control mechanisms, we can note that the vehicle density has a different impact depending on the employed congestion control mechanism. For DynB the increase in vehicle density has a clear impact on the worst-case update lags. On the other hand almost no impact on the worst-case update lags is visible for TRC, because the majority of vehicles stay in the “active” state independently of the investigated vehicle densities. Therefore, the increase in vehicle density can only be seen by looking at the experienced channel load. Nevertheless, there exist certain vehicle densities where the impact of the density is also visible when looking at the update lags, i.e., when vehicles start adapting their congestion control state.

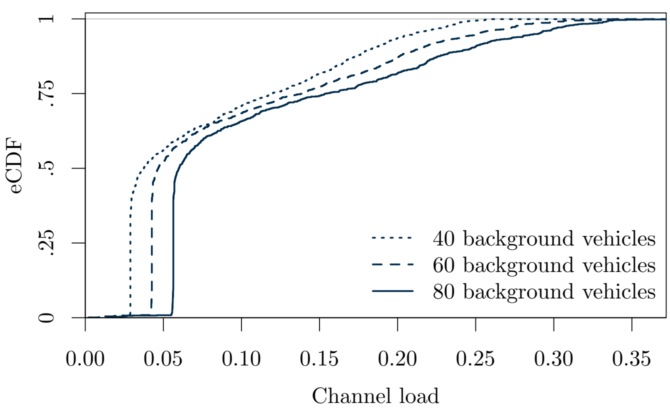


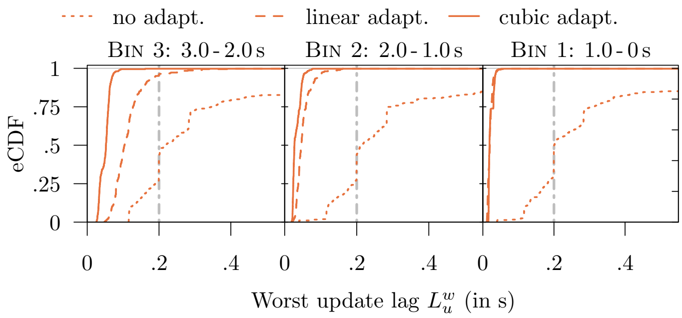
Figure 4.15 – eCDF comparing the experienced channel load of TRC w/o situation-based rate adaptation for different vehicle densities in the *Rural Scenario*.

4.3.3 Worst-case Update Lag Analysis

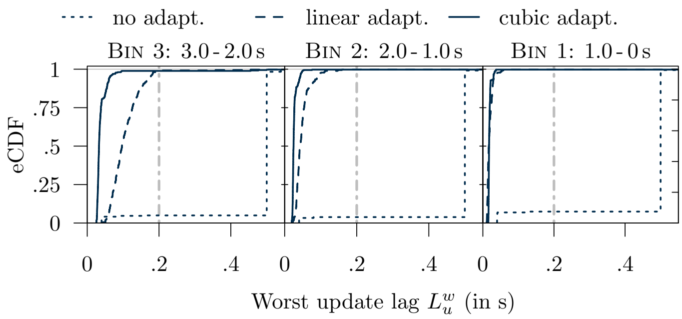
In this section, we study the benefits of using the situation-based rate adaptation in a *Rural Scenario* for two different congestion control mechanisms, namely DynB and TRC. To investigate the evolution of the different communication strategies we use the so-called worst-case update lag analysis as discussed in Section 3.4.2. Figure 4.16 presents the eCDFs of L_u^w for the *Rural Scenario* with 60 vehicles communicating in the background for all investigated communication strategies: DynB w/o adaptation, DynB linear adaptation, DynB cubic adaptation, TRC w/o adaptation, TRC linear adaptation, and TRC cubic adaptation.

Some eCDFs do not reach 100 % within the plotted range (0–550 ms). This is due to some CAMs being lost or longer beacon intervals caused by congestion control mechanisms.

We start with the results for DynB shown in Figure 4.16a. For DynB without adaptation it can be seen that L_u^w is for more than the half of vehicles above 200 ms, and in all three time-bins a non-negligible portion of more than 15 % has a worst-case update lag larger than 500 ms. When the situation-based rate



(a) DynB, 60 background vehicles



(b) TRC, 60 background vehicles

Figure 4.16 – eCDF comparing L_u^w for DynB and TRC with no, linear, and cubic adaptation for the *Rural Scenario* in the three 1 s time-bins before the crash.

adaptation is enabled, instead, Figure 4.16 shows that L_u^w never exceeds 500 ms (independently of the adaptation strategy). In addition, L_u^w has an upper bound of 200 ms for the last two seconds before a crash happened. Moreover, this upper bound is also valid for the vehicle densities of 40 and 80 vehicles (data not shown for the sake of brevity). For DynB with the cubic adaptation strategy this upper bound even holds for the entire last three seconds and hence is able to demonstrate the fact that situation awareness can be increased in particular for low intersection collision probabilities.

For TRC without adaptation (results for TRC depicted in Figure 4.16b) the eCDF shows clearly that more than 90 % of vehicles experience $L_u^w \geq 500$ ms in all bins. For some vehicles L_u^w even reaches 1 s (data not shown). The results for TRC with situation-based rate adaptation enabled, are almost identical to DynB for both adaptation strategies. The reported upper bound of 200 ms for DynB holds for TRC even for the linear adaptation for the entire last three seconds, but the cubic adaptation has a single outlier. We checked the outlier carefully and found that it is caused by an update happening at the beginning of Bin 3. In this case the intersection collision probability was still below the threshold $\mathcal{P}_{th}$ and hence the situation-based rate adaptation has been just enabled in Bin 3.

Finally, we want to point out that the situation-based rate adaptation works differently in the three depicted time to crash bins (cf. Figure 4.16). When using the linear adaptation, the following can be observed: The more dangerous the situation gets, the more often cars do get an update of the situation independently of the underlying congestion control mechanism. For the cubic adaptation, it can be seen that it further increases the situation awareness, in particular when the intersection collision probability is low.

4.3.4 Implications on Road Traffic Safety

The worst update lag L_u^w distribution (used in the previous Section) does not allow the assessment of the communication performance of individual vehicles for an entire intersection approach. In particular, the worst-case update lag analysis does not show whether an individual vehicle experienced multiple update lags in the different time to crash bins. Therefore, we carry out an analysis of the accumulated *unsafe time* t_{unsafe} per vehicle again for the last three seconds before the crash (detailed in Section 3.4.2). In this evaluation we assume a required update lag L_{req} of 500 ms, because the automated collision avoidance controller designed in [46] needs a reliable update frequency of 2 Hz. In the case of a non-automated system (e.g., an acoustic warning to a driver) this maximum update lag requirement might be tighter because of human reaction times. For this reason, we also study a required update lag of 200 ms.

In Figure 4.17 we plot the eCDF of the timespan that individual vehicles have spent in t_{unsafe} for the two mentioned required update lags for the *Rural Scenario* for 60 and 80 vehicles communicating in the background. To have a look at the results in detail, we concentrate again on the results of 60 background vehicles, shown here in Figures 4.17a and 4.17c.

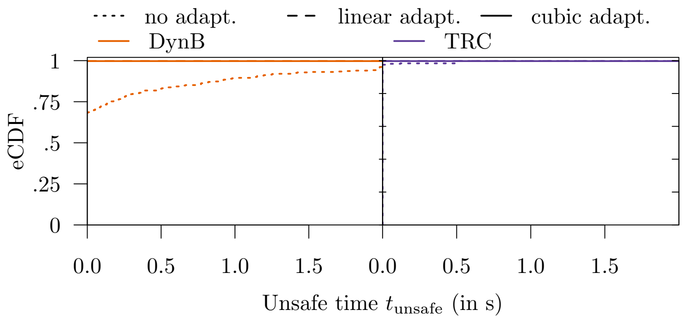
Starting with the required update lag ($L_{\text{req}} = 500\,\text{ms}$) depicted in Figure 4.17a, it can be seen that DynB without adaptation would not be able to satisfy the firm update requirements of an automated collision avoidance controller. In particular, DynB without adaptation is not able to provide timely updates for more than 28 % of vehicles in this medium dense road traffic situation. Moreover, the time that vehicles spend in an unsafe state is very long, i.e., more than 20 % of vehicles experience unsafe periods larger than 300 ms.

On the other hand TRC without adaptation is able to provide an update every 500 ms for more than 98 % of vehicles.This is possible, because most vehicles have been in the “active” state where they are allowed to send a CAM every 500 ms. Looking again at the results of situation-based rate adaptation strategies, we can observe that both protocols (DynB and TRC) and both strategies (linear and cubic) fulfill the update lag requirement of 500 ms to 100 % for the last three seconds before a crash. Figure 4.16 also confirms this fact by showing no worst-case update lags larger than 500 ms when using the situation-based rate adaptation.

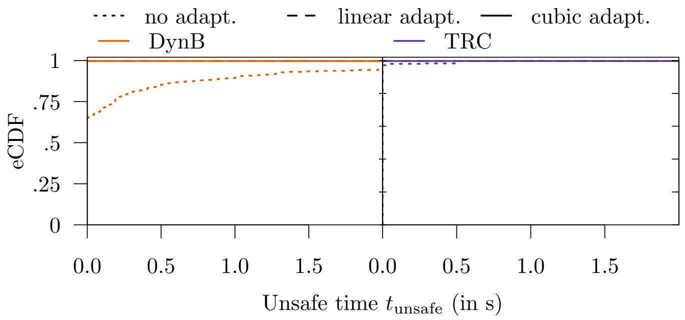
Figure 4.17c shows the eCDF for a required update lag of 200 ms when 60 vehicles are communicating in the background. As expected, the results are worse for both protocols without adaptation. When looking for the impact of higher vehicle densities for DynB without adaptation (discussed in Section 4.3.2), Figures 4.17c and 4.17d show how the experienced unsafe times increases when the vehicle densities is higher. This effect, however, is compensated by using the *situation-based rate adaptation* algorithm independently of the vehicle density and the adaptation strategy.

TRC is not able to provide frequent updates (as shown in the right part of Figure 4.17c). This is due to the fact that the majority vehicles stay most of the time in the “active” state where they use 500 ms as beacon interval. All vehicles spend at least 1.2 s in an unsafe state during the last three seconds before a crash. Also for this stricter update lag requirement, the situation-based rate adaptation is almost always able to provide all updates in time.

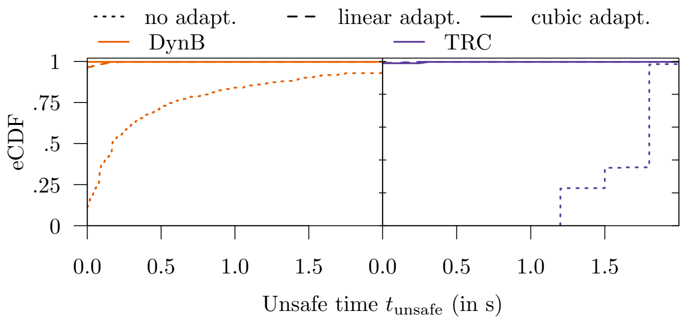
By comparing Figures 4.17a and 4.17b as well as Figures 4.17c and 4.17d it can be seen that the situation-based rate adaptation enables strict update requirements in a *Rural Scenario* for both protocols independent of the investigated vehicle densities. The results for a vehicle density of 40 are similar, but not depicted for the sake of brevity.



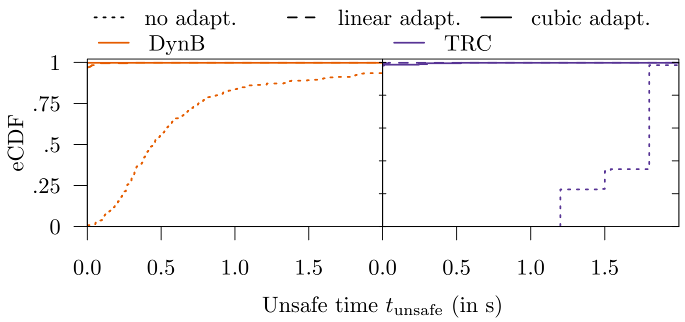
(a) $L_{\mathrm{req}} = 500\,\mathrm{ms}$, 60 background vehicles



(b) $L_{\mathrm{req}} = 500\,\mathrm{ms}$, 80 background vehicles



(c) $L_{\mathrm{req}} = 200\,\mathrm{ms}$, 60 background vehicles



(d) $L_{\mathrm{req}} = 200\,\mathrm{ms}$, 80 background vehicles

Figure 4.17 – eCDF showing the timespan that vehicles spent in an unsafe state during the last three seconds for the *Rural Scenario*.

4.4 Situation Awareness at Downtown Intersections

In order to get insights on IVC for Intersection Assistance Systems at downtown intersections, we simulated the real-world intersection depicted in Figure 4.18, which is located in Innsbruck, Austria. The geodata has been imported from OpenStreetMap[5] to integrate the exact road layout as well as the outlines of buildings into our simulation framework (described in Section 2.3.3). We use the layout of the intersection in Figure 4.18 to simulate two scenarios: the *Synthetic Downtown Scenario* and the *Realistic Downtown Scenario*. Both scenarios are used to investigate the behavior of the proposed situation-based rate adaptation in urban environments. The two scenarios differ by the number, placement, and movements of background communication vehicles.

By including shadowing effects of buildings, these scenarios consider two almost distinct interference domains. As shown in Figure 4.19, the two interference domains (red and green cloud) overlap in the intersection area. Therefore, the wireless communication of vehicles approaching the intersection is first influenced by vehicles on the same crossroad only. However, when entering the critical area for Intersection Assistance Systems they start to get influenced by both interference domains. This challenging communication scenario is caused by shadowing effects due to buildings, which are placed in the simulated urban environment as depicted in Figure 4.18.

[5] http://www.openstreetmap.org/

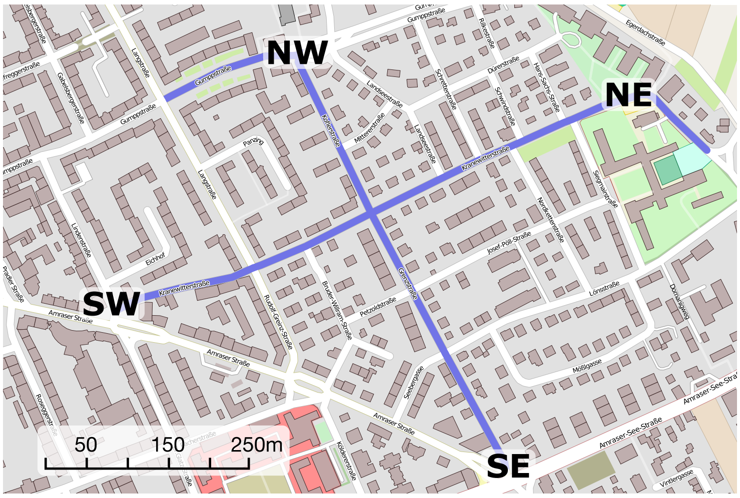


Figure 4.18 – Road map of the simulated intersection area in Innsbruck, Austria (N 47° 15' 50.0" E 11° 25' 2.5") [154], © 2015 IEEE.

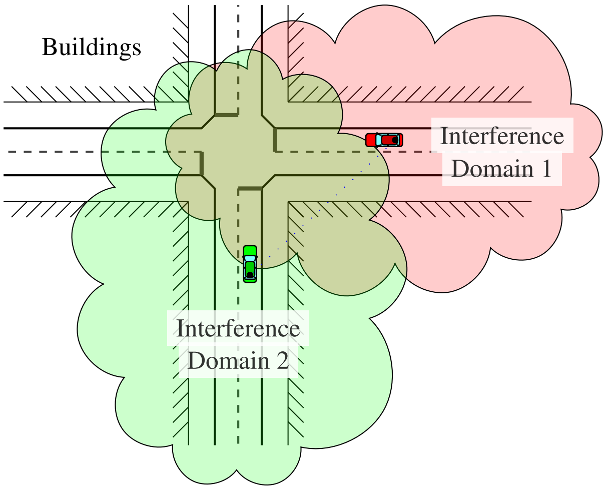


Figure 4.19 – Schematic overview of the *Synthetic Downtown Scenario* and *Realistic Downtown Scenario* showing two vehicles, which are about to enter the intersection area where the two interference domains overlap (effect caused by shadowing due to buildings) [154], © 2015 IEEE.

Table 4.3 – Additional physical layer parameters for the building shadowing model.

Parameter	Value
Shadowing model	Obstacle Shadowing [60]
Attenuation per wall [60]	$\beta = 9.0$ dB
Attenuation per m [60]	$\gamma = 0.4$ dB

Except for the shadowing model, all simulation parameters are identical as in the *Rural Scenario* and listed in Table 4.2. The additional parameters for the building shadowing model are listed in Table 4.3.

4.4.1 *Synthetic Downtown Scenario*

In this scenario, we use again "ghost" vehicles (similar as in the *Rural Scenario* in Section 4.3), which generate only additional network traffic by using the same communication strategy as the two vehicles under analysis. These background communication vehicles are simulated only in the network simulator and not in the road traffic simulator SUMO.

To study different kinds of shadowing effects, the approaching vehicles are alternating their starting place (i.e., NE, SE, SW, NW—cf. Figure 4.18). The densities of 20, 28, and 40 background communication vehicles are obtained by placing the "ghost" vehicles at a distance of 50 m to the intersection center on the crossroads. In the different experiments the vehicles always use the same communication strategies as the two approaching vehicles under analysis.

4.4.1.1 Initial Scenario Analysis

We start again with an initial safety metric analysis of the scenario by investigating the intersection collision probability of Last Before Unavoidable (LBU) beacons. Figure 4.20 depicts the eCCDF of the calculated intersection collision probability of the received LBU beacons. For DynB a considerable difference between the three different densities is visible in Figure 4.20a. In particular when 40 vehicles are communicating and hence cause interference, there is a major impact on the intersection collision probability of LBU beacons visible.

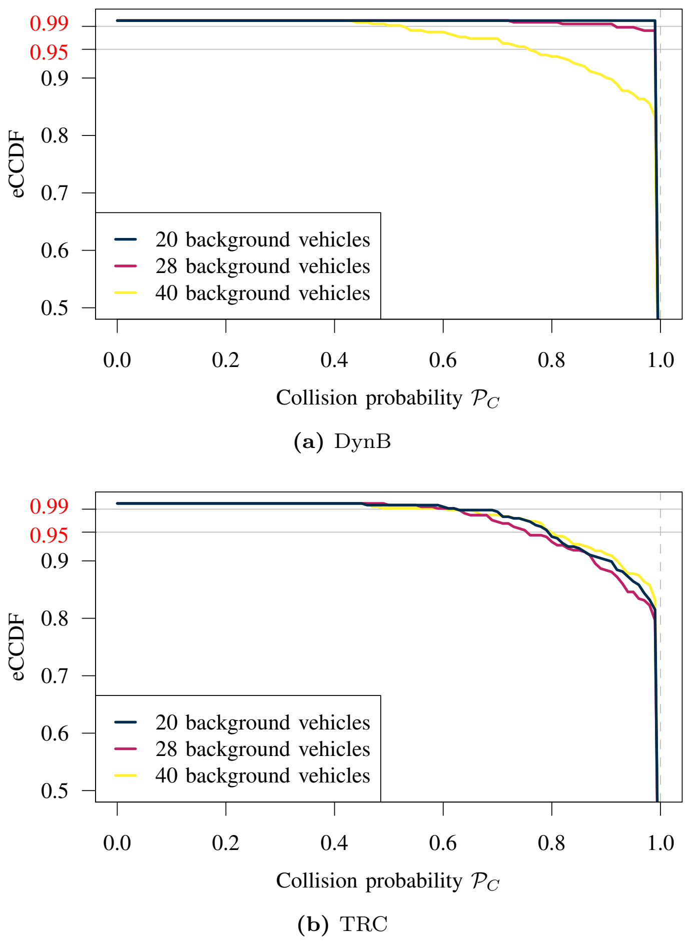


Figure 4.20 – eCCDF of the intersection collision probability for Last Before Unavoidable (LBU) beacons and approaches in group *Crash*.

Interestingly, there is almost no difference between the different vehicle densities visible for TRC. However, the fact that in this scenario DynB performs better is undeniable and specifically pronounced for the vehicle densities of 20 and 28.

Nevertheless, this safety metric analysis provides only a first understanding of how the different communication strategies affect the very last beacon before a crash becomes unavoidable. Therefore, we now carry out an initial worst-case update lag analysis (described in Section 3.4.2) for both congestion control mechanisms (DynB and TRC) of the last three seconds before a crash has happened.

Starting with DynB, Figure 4.21 plots the eCDFs of the worst-case update lag L_u^w for all investigated vehicle densities (20, 28, and 40 vehicles communicating in the background). Similar as in the *Rural Scenario*, a clear impact of higher vehicle densities can be seen (cf. Section 4.3.2). In addition, another interesting observation can be made: There is a notable difference of the worst update lag distributions in the plotted time to crash bins visible. Starting with, the highest vehicle density of 40 vehicles we can notice that the update lags get longer shortly before the crash, i.e., when vehicles are already very close to the intersection center. This finding can be explained by the scenario environment. Due to shadowing effects of the buildings, DynB is highly sensitive to the additional channel load generated by the interfering vehicles on the crossroad which is experienced only very close to the intersection.

However, the experiment with 20 vehicles shows a slightly contrary trend DynB: The distribution of L_u^w gets better in Bin 2 and in Bin 1. In order to better understand this unexpected behavior we plotted the eCDFs of the channel load for the entire last three seconds for this scenario in Figure 4.22.

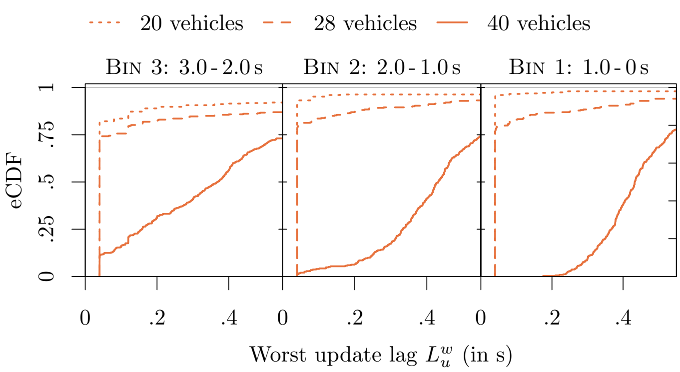


Figure 4.21 – eCDF comparing L_u^w for DynB and different vehicle densities in the *Synthetic Downtown Scenario*.

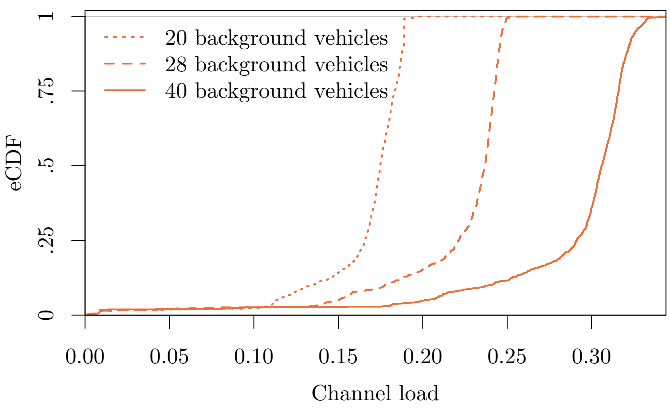


Figure 4.22 – eCDF comparing the channel load for DynB and different vehicle densities in the *Synthetic Downtown Scenario*.

In the *Rural Scenario* the measured channel load of DynB is always very close to the desired channel load of 25 % independent of the vehicle density. However, for the *Synthetic Downtown Scenario* we can notice a completely different behavior which is caused by shadowing effects of buildings and the lower vehicle densities. For low vehicle densities (20 and 28) the channel load in the two distinct interference domains is clearly below the desired channel load and even when the two approaching cars enter the overlapping area of the two interference domains, the channel load stays below. Therefore, there is no rate reduction by the congestion control protocol DynB necessary. Indeed, the vehicles are more likely to successfully transmit a CAM for this low vehicle densities if they are in range of both interference domains, because their transmissions will be successful with a higher probability. This is the reason why the worst-case update lag distribution gets slightly better for this low vehicle densities when the cars are very close to the intersection (cf. Bin 2 and Bin 1 in Figure 4.21).

Moreover, Figure 4.22 shows that DynB in this scenario for 40 vehicles communicating in the background is not able to keep the channel load at the desired level of 25 %. In detail the background vehicles in the two distinct interference domains continue sending with the minimum beacon interval, because the channel load sensed by them is still clearly below 25 %. But for the two approaching vehicles the channel load increases as they get in the range of both interference domains and hence DynB restricts their beacon interval exactly when communication is of utmost importance for IAS.

To complete this initial analysis of the *Synthetic Downtown Scenario*, the worst-case update lag distributions for TRC and different vehicle densities are depicted in Figure 4.23. Also for TRC, we split our analysis by vehicle densities. Starting with the low vehicle densities (20 and 28), it can be seen that the

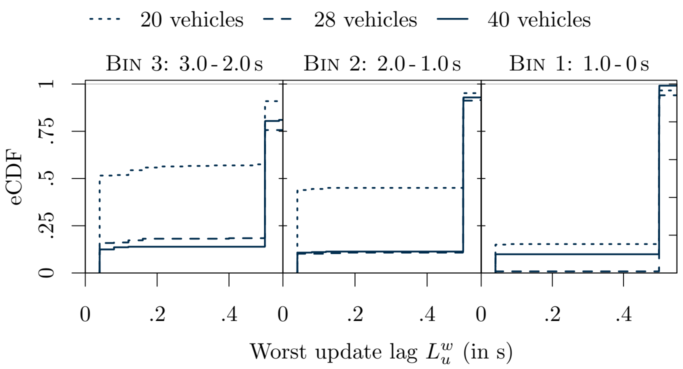


Figure 4.23 – eCDF comparing L_u^w for TRC and different vehicle densities in the *Synthetic Downtown Scenario*.

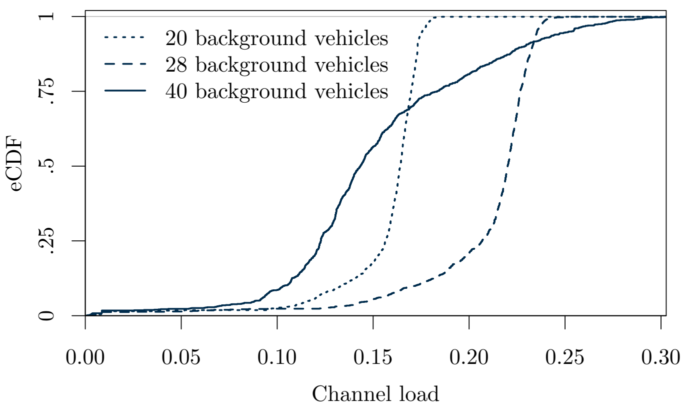


Figure 4.24 – eCDF comparing the channel load for TRC and different vehicle densities in the *Synthetic Downtown Scenario*.

worst-case update lag distribution gets worse if the vehicles get in range of both interference domains. As depicted in Figure 4.24, the experienced channel load is for most of the two approaching vehicles larger than 15 % and hence they will more likely switch to the "active" state where a beacon interval of 500 ms is configured (cf. Section 2.2.5). The reason for the high channel load is again that the vehicles in the two distinct interference domains continue sending with lowest beacon interval, because they do not sense a channel load above 15 %.

Coming to the high density of 40 vehicles, almost no difference of the L_u^w distributions in the plotted time to crash bins is notable. This can be explained by the fact that within the two interference domains some vehicles were already in the "active" state and hence the overall channel load is lower for this vehicle density (cf. Figure 4.24). Nevertheless, most of the approaching vehicles spend a major portion of the intersection approach as well in the "active" state and in some cases the experienced channel load reaches almost 30 %.

To conclude this initial analysis, we can note that DynB and TRC show a very different behavior for the investigated vehicle densities. Therefore, the aggressiveness of congestion control mechanisms plays not only a major role when two large clusters of vehicles meet (as investigated in [97, 99]), but also when two "distinct" interference domains as in this scenario are present and single vehicles are exposed to both of them.

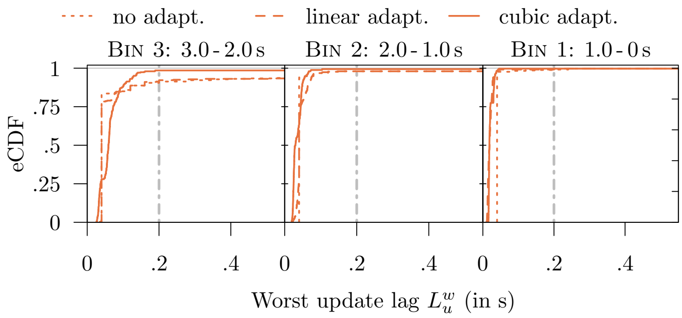
4.4.1.2 Worst-case Update Lag Analysis

Figure 4.25 depicts the L_u^w distribution for the *Synthetic Downtown Scenario* for two vehicle densities (20 and 40). Starting with the results for 20 background vehicles (Figures 4.25a and 4.25b concentrating on Bin 3) it can be seen that the linear adaptation helps to improve the update lags, but for DynB the improvement is marginal, because all approaching vehicles were sending CAMs every 40 ms and the channel is not much congested (cf. Figure 4.22). Using the cubic adaptation, the L_u^w distributions can be improved substantially, because it enforces higher beacon rates even if the intersection collision probability is low (for both congestion control mechanisms).

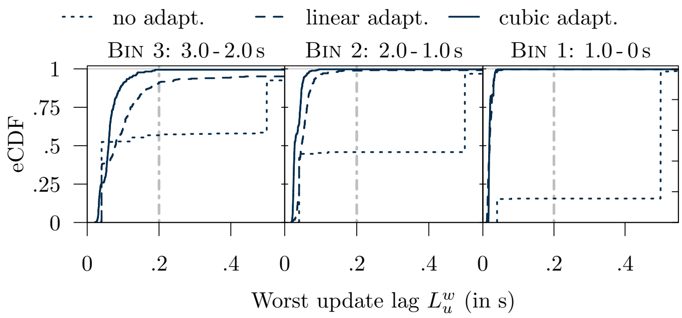
In detail, both congestion control mechanisms w/o adapatation are able to provide better L_u^w than with the adaptation algorithm in place for a small fraction of vehicles, but are clearly not able to meet the threshold of 200 ms: only in 56 % and 90 % of the cases the deadline is met for TRC and DynB w/o adaptation, respectively. The cubic adaptation strategy is able to meet the 200 ms threshold in 100 % of the cases (for both congestion control protocols) whereas the linear adaptation is only able to achieve the required update lags for 91 %. In Bin 2 and Bin 1 all, but TRC without adaptation, perform almost identically for this low vehicle density.

Looking at the results for a vehicle density of 40 in Figures 4.25c and 4.25d, similar results for the adaptation strategies can be observed: Only the cubic adaptation is able to provide frequent updates ($\leq$ 200 ms) independently of the congestion control mechanism for 98 % of vehicles in Bin 3 and 100 % in Bin 2. The linear adaptation works slightly worse in Bin 3 in this scenario; meeting the threshold with DynB only for 77 % and with TRC for 85 % of vehicles.

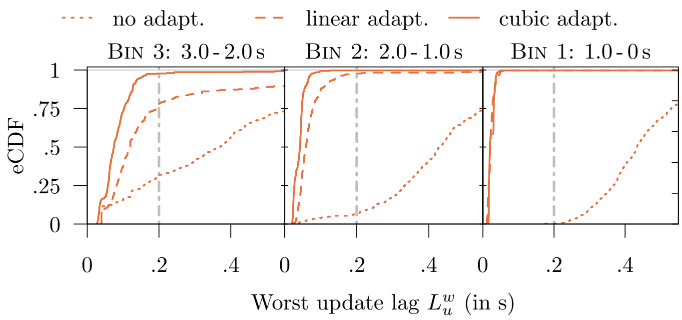
Finally, we want to highlight one important characteristic of the situation-based rate adaptation: Although the worst update lag distribution is getting worse in Bin 2 and Bin 1 for TRC without adaptation with a low vehicle density (cf. Figure 4.25b) and for DynB for the higher density (cf. Figure 4.25c), both adaptation strategies are able to completely eliminate these effects, which are caused by the two overlapping interference domains.



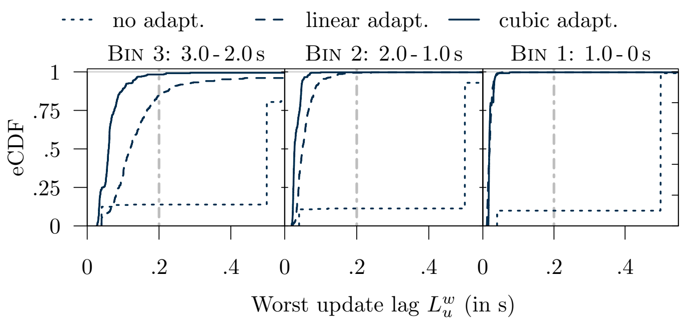
(a) DynB, 20 background vehicles



(b) TRC, 20 background vehicles



(c) DynB, 40 background vehicles



(d) TRC, 40 background vehicles

Figure 4.25 – eCDF comparing L_u^w for DynB and TRC with no, linear, and cubic adaptation for the *Synthetic Downtown Scenario* in the three 1 s time-bins before the crash.

4.4.1.3 Implications on Road Traffic Safety

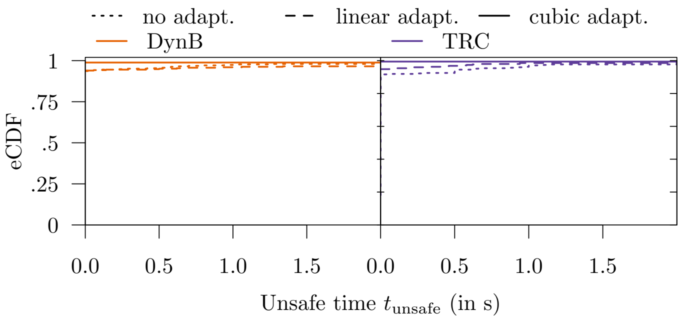
To understand how much time individual vehicles spent in an uninformed state, we also carry out a safe time analysis of the last three seconds before the crash has happened. A detailed explanation of the computation of the unsafe time t_{unsafe} can be found in Section 3.4.3. Again, we analyze the required update lags of 500 and 200 ms for automated reaction controllers and warning systems, respectively (as outlined in Section 4.3.4). Figure 4.26 shows the eCDFs of the timespan that vehicles have spent in an unsafe state during the last three seconds before the crash.

First, we discuss the impact on road traffic safety for a required update lag of 500 ms, depicted in Figures 4.26a and 4.26b. As anticipated for a vehicle density of 20, only very few vehicles do not receive a CAM within the required update lag when no situation-based rate adaptation is enabled. However, it is alarming that exactly these few vehicles are staying a long time in an unsafe state (in some cases even 1.5 s). The number of vehicles and the timespan in an unaware state increase with the vehicle density, yielding to more than 50 % of vehicles experiencing an unsafe time when using DynB and more than 20 % for TRC.

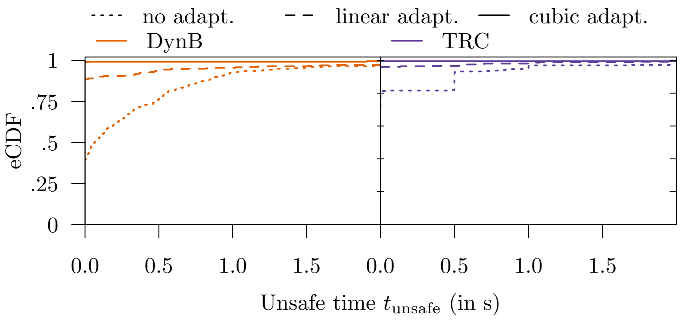
When the situation-based rate adaptation is enabled, we can observe the following: The linear adaptation is not able to provide full situation awareness for high vehicle densities (more than 40 vehicles communicating in the background). The cubic adaptation is able to meet the required update frequency during the entire last three seconds for all vehicles independently of the vehicle density and congestion control mechanism.

Second, looking at the results for a required update lag of 200 ms (shown in Figures 4.26c and 4.26d), it can be noticed that in particular TRC without adaptation is not able to provide the required update lag to almost any vehicle. On the other hand DynB only struggles for the higher vehicle density of 40 and shows better results than TRC.

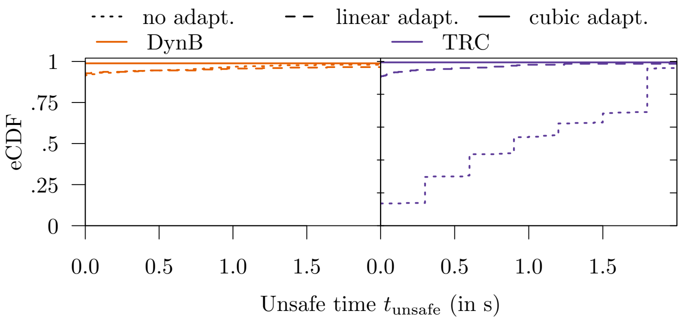
In any case, the situation-based rate adaptation reduces the unsafe time for almost all experiments. As pointed out in the previous section, the linear adaptation for DynB helps only if a vehicle density is reached where DynB increases the beacon interval. Again, the difference between the linear and the cubic adaptation strategy is not negligible, showing a clear advantage for the cubic adaptation. The cubic adaptation is almost always able to provide updates in time, only in 2 % of the cases the vehicles stay for a very short period ($\leq$ 100 ms) uninformed. Nevertheless, it needs to be mentioned that this advantage is only caused by the fact that the linear adaptation slowly adapts its rate at the beginning and hence is not able to provide frequent updates in Bin 3 (cf. Figure 4.25).



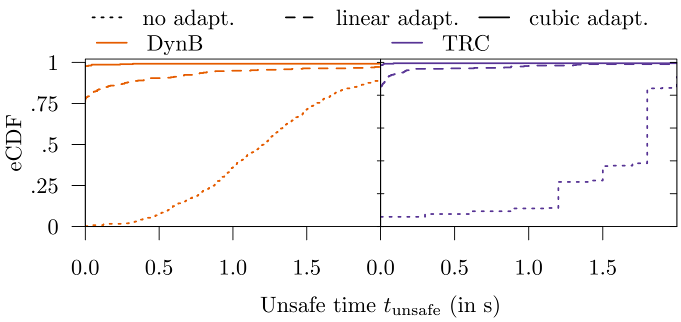
(a) $L_{\text{req}} = 500\,\text{ms}$, 20 background vehicles



(b) $L_{\text{req}} = 500\,\text{ms}$, 40 background vehicles



(c) $L_{\text{req}} = 200\,\text{ms}$, 20 background vehicles



(d) $L_{\text{req}} = 200\,\text{ms}$, 40 background vehicles

Figure 4.26 – eCDF showing the timespan that vehicles spent in an unsafe state during the last three seconds for the *Synthetic Downtown Scenario*.

4.4.2 *Realistic Downtown Scenario*

So far we have studied the situation-based rate adaptation in scenarios where the background communication nodes were not moving. This allowed us to investigate current congestion control mechanisms for different vehicle densities without causing a traffic jam at the intersection, which would obviously influence the vehicle dynamics of the approaching vehicles under analysis. In addition, we were able to obtain an in-depth understanding of the situation-based rate adaptation for various vehicle densities in two different environments. However, such a static simulation setup does not reflect the reality in vehicular networks. In particular, in an urban environment where shadowing effects of buildings are predominant, a comparison with a realistic scenario is essential for the credibility of the entire simulation study.

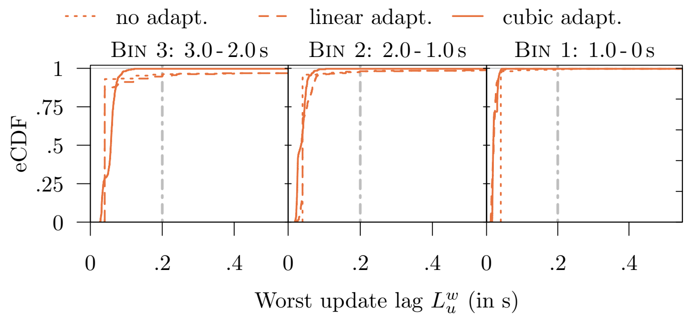
To ensure that the evaluation also holds for a scenario where all vehicles are actually participating in the road traffic, we created the *Realistic Downtown Scenario*. This scenario is similar to the *Synthetic Downtown Scenario* (cf. Figure 4.19). The only difference is that instead of adding "ghost" vehicles, all vehicles are simulated in the road traffic simulator SUMO as well and hence are moving along the crossroads. In order to investigate the communication performance of the two vehicles in a dangerous situation, we paid attention that none of the other vehicles is influencing their road traffic behavior. In contrast to the *Rural Scenario* and the *Synthetic Downtown Scenario*, where the vehicles have alternated their starting points, in this scenario all observed vehicles were starting from SE and NE (cf. Figure 4.18). This was necessary to ensure non-interaction with other vehicles.

Since this scenario uses an unregulated single lane intersection, we could not simulate a high density of background vehicles. Moreover, the periodic injection of vehicles with different speeds in SUMO results in a varying distribution and slightly changing vehicle density. On average, 20 vehicles have been driving in the scenario. Therefore, the results are mostly comparable to *Synthetic Downtown Scenario* with 20 vehicles communicating in the background. All simulation models and parameters are identical as in Section 4.4.1. However, we want to stress that the vehicle parameters (distribution of minimum/maximum acceleration and speed) listed in Section 3.1.3 apply in this scenario to all vehicles.

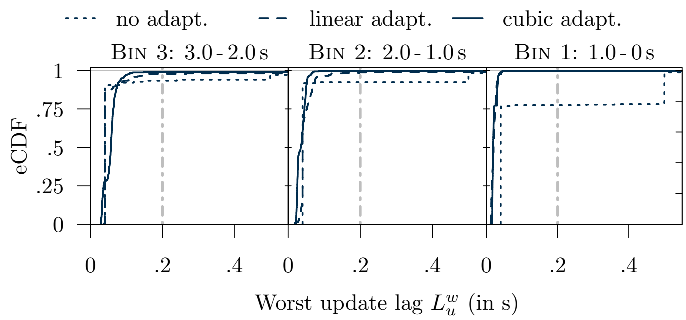
For this scenario we also simulated 480 intersection approaches, where 314 of them resulted in a *Crash*. The presented plots are composed only by data points of intersection approaches that finally resulted in a *Crash*.

4.4.2.1 Worst-case Update Lag Analysis

Figure 4.27 plots the eCDF of L_u^w for the *Realistic Downtown Scenario*. Starting with DynB we can notice that it performs very similarly as in the *Synthetic Downtown Scenario* with 20 background vehicles. However, it can be seen that TRC without adaptation is performing much better in this dynamic scenario compared to the *Synthetic Downtown Scenario* with similar vehicle density (cf. Figure 4.25b). This can be explained by the fact that the two vehicles in question do not experience the additional channel load of the crossroad interference domain at once, but rather incrementally, due to the different positions of vehicles on the crossroad. Moreover, all vehicles close to the intersection are aware of both interference domains and hence adapt their beacon rate accordingly as well. When looking at the situation-based rate adaptation results, it can be noticed that the results are comparable with the *Synthetic Downtown Scenario*, again showing that the cubic adaptation strategy is performing better in BIN 3.



(a) DynB



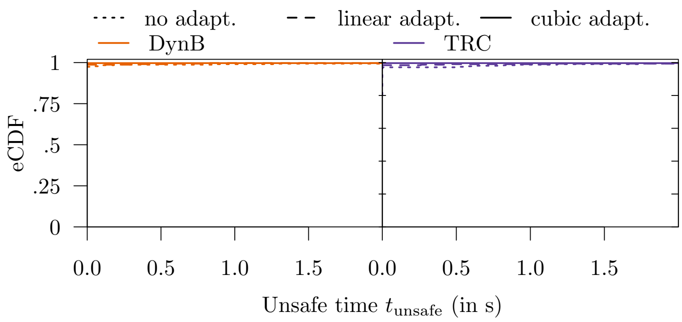
(b) TRC

Figure 4.27 – eCDF comparing L_u^w for DynB and TRC with no, linear, and cubic adaptation for the *Realistic Downtown Scenario* in the three 1 s time-bins before the crash.

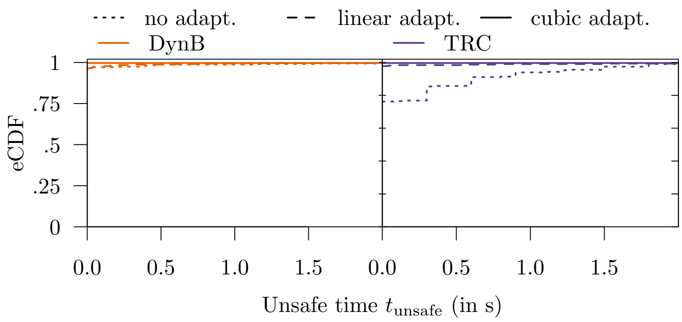
4.4.2.2 Implications on Road Traffic Safety

To conclude the evaluation of the situation-based rate adaptation algorithm, Figure 4.28 presents the impact of the investigated protocols on the situation awareness of individual vehicles during the last three seconds before a crash. Focusing on the result of a required update lag of 500 ms in Figure 4.28a, it can be seen that all investigated communication strategies are able to provide updates in time for almost all vehicles. Nevertheless, the cubic adaptation strategy accomplishes the best results also in this scenario.

In Figure 4.28b the results for a required update lag of 200 ms show similar findings as reported for the *Synthetic Downtown Scenario* in Figure 4.26c: TRC without adaptation is not able provide the needed update frequency for more than 22 % of vehicles, and DynB is not able to meet these stricter real-time requirements for more than 4 % of vehicles. The linear adaptation strategy is only able to improve situation awareness for TRC, but not for DynB. In this realistic scenario the cubic adaptation allows 99 % of vehicles to receive all updates in time.



(a) $L_{\text{req}} = 500\,\text{ms}$



(b) $L_{\text{req}} = 200\,\text{ms}$

Figure 4.28 – eCDF showing the timespan that vehicles spent in an unsafe state in the last three seconds for the *Realistic Downtown Scenario*.

The presented simulation results for the *Realistic Downtown Scenario* prove that the situation-based rate adaptation is able to provide timely updates in realistic, but uncrowded road traffic situations. Nevertheless, it can be expected that in large cities the downtown scenarios easily reach higher vehicle densities (i.e., more than 20 vehicles close to the intersection). Therefore, we want to stress that the situation-based rate adaptation works also for crowded road traffic situations as investigated in *Synthetic Downtown Scenario*, because the situations cover even unrealistically bad conditions, i.e., the additional channel load by the crossroad interference domain is experienced exactly when reliable communication for IAS is essential.

4.5 Conclusion

By analyzing static beaconing approaches with the two proposed safety metrics—the *risk classification* and the *intersection collision probability*—we were able to draw first conclusions on the communication demands of Intersection Assistance Systems. The analysis of the risk classification already revealed that communication needs to be more frequent than 2 Hz in order to trigger all warning levels. In addition, this requirement is confirmed when looking for reasonable reaction/warning thresholds for IAS with the intersection collision probability. Only with a beacon interval lower than 100 ms, thresholds that guarantee to support 95 % or 99 % of approaching vehicles are in a feasible range. Although these findings with the help of safety metrics and static beaconing approaches are valid and demonstrate the need for frequent updates for IAS, the applicability of static beaconing approaches in reality has been disproved already [96, 99].

To handle possible channel congestion, which might be caused by static beaconing, different congestion control mechanisms have been proposed (e.g., DynB and TRC, described in Sections 2.2.5 and 2.2.6, respectively). However, until now no congestion control mechanism is taking the individual situation of vehicles into account. Hence current congestion control mechanisms are not able to provide frequent communication opportunities to satisfy the requirements of vehicular safety applications. Based on the analysis of the intersection collision probability we have proposed the *situation-based rate adaptation* algorithm in Section 4.2, which allows vehicles in dangerous situations to get a temporary exception from congestion control restrictions and to adapt their information dissemination rate based on the situation criticality. For this algorithm we established and evaluated two different adaptation strategies—namely linear and cubic adaptation—of the information dissemination rate.

We investigated the six communication strategies (i.e., DynB and TRC each without, and with linear as well as cubic adaptation) in two different scenario environments (rural and downtown). For the *Rural Scenario*, we can conclude that communication for IAS suffers from significant concurrent (i.e., more than 40 vehicles) communication when using state-of-the-art congestion control mechanisms. Surprisingly, the impact of more communicating vehicles is not that clearly visible for TRC due to its congestion control behavior. However, for DynB the impact on IAS is clearly visible, because the protocol adapts its beacon interval to the channel conditions more aggressively.

The worst-case update lag analysis demonstrated that the linear situation-based rate adaptation is not only able to positively influence DynB, but also provides reasonable update lags when using TRC as congestion control mechanism. Moreover, the cubic adaptation strategy enables shorter update lags in particular when the intersection collision probability is low. The analysis of the unsafe time (the time that vehicles had to deal with out-dated information) confirmed the positive impact of the situation-based rate adaptation. In addition, massive problems of both congestion control mechanisms, DynB and TRC w/o adaptation, have been pointed out when there is a need for low update requirements, such as 200 ms. To conclude the results of the *Rural Scenario*, we can note that with increasing vehicle density the effective update lags grow, but it can be limited for endangered vehicles by allowing them to adapt their information dissemination rate to the situation with the proposed rate adaptation strategies. In detail the situation-based rate adaptation is able to provide similar performance independently of the vehicle density and the adaptation strategy. This is possible, because non-endangered vehicles lower their beacon interval (caused by the congestion control mechanism in place) and hence indirectly promote the communication reliability of vehicles in dangerous situations.

The *Synthetic Downtown Scenario* represents a particularly challenging environment for IVC (caused by shadowing effects of buildings) for Intersection Assistance Systems: The interference domains of the crossroads usually overlap exactly in the region where two approaching vehicles need to communicate frequently. Therefore, already very low vehicle densities—from 20 to 40 in the entire scenario—can lead to massive update lags when using state-of-the-art congestion control mechanisms, because the endangered vehicles are forced to adapt their rate based on both interference domains.

The initial scenario analysis has revealed interesting aspects concerning the two overlapping interference domains in this scenario: DynB shows the expected behavior for a moderate vehicle density of 40, yielding to worse communication performance shortly before the crash. On the contrary, TRC shows for this density equally bad performance independently of the time to crash, but is badly influenced by overlapping effects for lower vehicle densities. Besides showing bad communication characteristics for IAS, these two facts demonstrate that downtown intersection scenarios need to be carefully evaluated when investigating new or improved congestion control mechanisms for vehicular networks.

The worst-case update lag investigation has revealed that the situation-based rate adaptation is able to completely eliminate these effects of DynB and TRC for all reviewed vehicle densities. Nevertheless, only the cubic situation-based rate adaptation is effectively keeping the update lags in a useful range for IAS for the entire last three seconds before a crash.

In the *Rural Scenario* the synthetic scenario setup (i.e., background vehicles are not moving along the crossroads) has no influence on the results, because all vehicles are located within a single interference domain. However, due to shadowing effects of buildings and the resulting two distinct interference domains, we wanted to verify the validity of the results of the *Synthetic Downtown Scenario* by simulating the *Realistic Downtown Scenario* where all vehicles are moving along the crossroads. We can confirm that the results of the *Realistic Downtown Scenario* are very close to the ones reported for *Synthetic Downtown Scenario* with a total vehicle density of 20. Hence we can conclude that the situation-based rate adaptation works also in scenarios where all vehicles are moving and channel conditions are even more dynamic.

To conclude this chapter, we can note that the situation-based rate adaptation is able to provide full situation awareness in conjunction with current congestion control mechanisms. The only precondition is that the situation-based rate adaptation can only be performed if initial communication is available between the two approaching vehicles. This precondition cannot always be guaranteed, especially in urban environments where shadowing effects by buildings might harm communication substantially. For this reason, we have built-in the self-collision probability, which provides an adaptation fall-back if no CAM has been received recently.

In short this chapter addressed the following scientific problems: We showed with the safety metrics (developed in Chapter 3) that beacon intervals larger than 500 ms are not sufficient to support IAS. Current congestion control mechanisms might use such long beacon intervals, because they neglect that vehicles might be in different situations and hence have diverse communication requirements. We addressed this problem by introducing the situation-based rate adaptation algorithm, which is independent of the underlying congestion control mechanism. The situation-based rate adaptation is a good opportunity to make congestion control mechanisms (which are mainly built to achieve communication fairness) reconcilable with vehicular safety application requirements, which require biased channel access favoring vehicles in dangerous situations.

In general, the situation-based rate adaptation algorithm might be used for other vehicular safety applications that rely on frequent broadcast based updates.

The detailed analysis also reveals that beacon rates can be adapted to meet the demands of vehicular safety applications. Finally, the situation-based rate adaptation algorithm could become part of future congestion control mechanisms for vehicular networks and enable more frequent and reliable communication when required by applications.

Chapter 5

Cooperative Communication

In the previous chapter we have demonstrated that it is beneficial to use an application-specific metric in addition to channel metrics to adjust the information dissemination frequency. The proposed *situation-based rate adaptation* algorithm allows us to prevent communication failures due to excessive channel usage of vehicles which are not in a dangerous situation and hence have not that frequent communication needs. This communication strategy has been designed with the idea in mind that the endangered vehicles are in communication range of each other. Moreover, the current ETSI standard defines the communication strategy of CAMs as follows [88]: "The CAM shall be transmitted only from the originating ITS Station (ITS-S) in a single hop to the receiving ITS-Ss located in the direct communication range of the originating ITS-S. A received CAM shall not be forwarded to other ITS-Ss."

However, it has already been shown by several measurement campaigns (e.g., [28, 29]) that communication between vehicles at intersections, specifically in cities, can suffer from radio signal shadowing by buildings and lead to excessive communication outages. Hence standard compliant beaconing might be insufficient to satisfy communication demands of vehicular safety applications under NLOS conditions. It is obvious that especially IAS are exposed to NLOS communication situations. Therefore, this chapter aims to investigate the benefits of cooperative communication for IAS.

One possibility to enable cooperative communication is to place infrastructure (an RSU/SSU) at every intersection. To omit these costly investments the usage of parked cars has been proposed in [155], and of course every vehicle driving on the roads can help to make cooperative communication possible.

As concluded in the previous chapter, the situation-based rate adaptation can only provide full situation awareness if frequent direct (one-hop) communication is feasible, i.e., no communication outages due to shadowing effects are present.

Specifically it might fail to provide sufficient communication under NLOS conditions when direct communication is scarce or even impossible. Figure 5.1 depicts such a situation at an intersection where the two approaching vehicles (the green and the red one) are in two distinct interference domains because of shadowing effects by buildings. Obviously, the blue car could help to improve the situation, because it can overhear CAMs of both cars and hence it is able to forward information cooperatively.

When looking in detail at one-hop communication strategies two main drawbacks can be discovered: First, they are simply not able to support *situation awareness* if direct communication between approaching vehicles is not available. Second, approaching vehicles cannot distinguish a potentially dangerous situation where direct communication has failed and a safe situation where no other vehicles are approaching the intersection. Since awareness is needed whether communication is currently working or not, we refer to this second aspect as *communication awareness*.

Improvements of situation awareness are desirable and enable better and more efficient IAS, but communication awareness is the essential feature for IAS. Therefore, this chapter explores if and under what circumstances situation awareness at intersections can be improved by cooperative communication and to what extent communication awareness is enabled by cooperative communication.

This chapter starts with an initial study on simple relaying of all periodic CAMs by parked cars close to the intersection. This study explores a best case

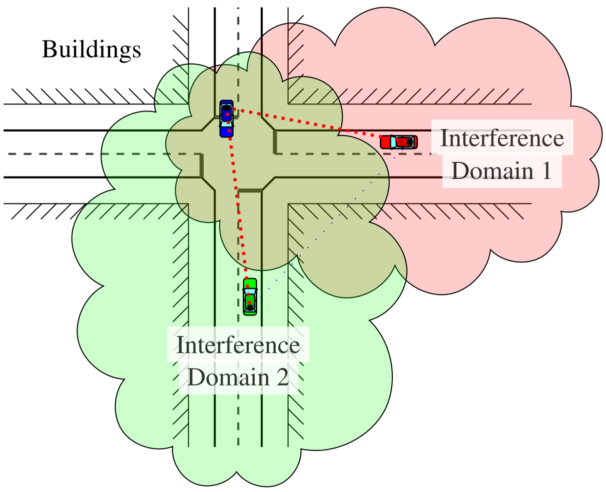


Figure 5.1 – Schematic overview of an exemplary intersection approach showing two vehicles (the green and the red one) that are not able to communicate directly and hence cooperative communication would help to improve the situation.

regarding channel usage, because only the two approaching vehicles attempt to transmit CAMs. Nevertheless, the combination of static beaconing intervals and precautionary rebroadcasts of all CAMs by a parked car would lead to excessive channel usage already for low vehicle densities.

To overcome this limitation, we propose in Section 5.2 a cooperative communication strategy, which combines the idea of situation-based communication for approaching vehicles and third-party vehicles that are able to rebroadcast CAMs. Specifically, all vehicles along the crossroads are considered as possible relays, but only a single vehicle should actually rebroadcast information if necessary. Therefore, several communication mechanisms are proposed to keep the additional channel load as low as possible. The presented approach does not only allow to improve situation awareness, but also communication awareness.

The approach is evaluated in various scenarios (described in Section 5.3.1) using the same intersection layout as basis, but investigating different speed profiles and traffic densities. Section 5.3 provides a detailed analysis of the proposed cooperative communication strategy regarding different aspects: First, the benefits of the proposed self-organizing and infrastructure-free cooperative approach are shown by comparing it to a similar but infrastructure-based approach. Second, we check by investigating the channel usage of the different communication strategies that the design goal of keeping communication overhead low is achieved. Finally, we explore in detail how and if the individual vehicles can always deduce whether their intersection approach is safe.

This chapter contains results of the following publication:

- S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, "To Crash or Not to Crash: Estimating its Likelihood and Potentials of Beacon-based IVC Systems," in 4th IEEE Vehicular Networking Conference (VNC 2012). Seoul, Korea: IEEE, Nov. 2012, pp. 25–32. This chapter presents the results on simple relaying of the static beaconing using the risk classification which have been collected by myself.

5.1 Initial Study on Simple Relaying

Due to the radio shadowing effects of buildings, two approaching vehicles might not be able to communicate sufficiently for IAS. Basically any form of cooperative communication can help to improve communication in NLOS conditions, but here we study simple relaying mechanisms with the risk classification described in Section 3.2. This initial study reveals the benefits that cooperative communication strategies are able to provide under optimal communication conditions.

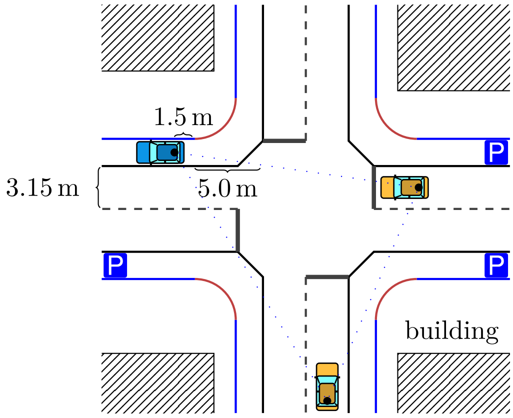


Figure 5.2 – Schematic view of the X intersection scenario when simple relaying is enabled [69], © 2012 IEEE.

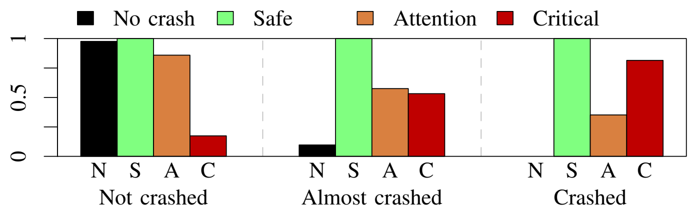
In particular, we follow the ideas in [155, 156] to use parked vehicles as relays, because it can be expected that some cars might be parked at useful positions close to an intersection. When a parked car overhears a CAM (the message is decoded and handed over to the application layer), it immediately rebroadcasts the received message without any modification (the application layer sends the CAM to the corresponding MAC queue and it gets transmitted when it successfully contended). The parked car is placed at the optimal position for its relaying task and also the communication conditions represent a best-case scenario where only the two approaching vehicles disseminate CAMs.

In detail, the parked cars in our scenario are placed as depicted in Figure 5.2. A minimum distance of 5 m to the intersection corner is required by Austrian law. We add additional 1.5 m to account for the fact that the antenna on vehicles is not placed at the very back or front of the car, but most likely somewhere on the roof. The resulting 6.5 m represent a reasonably and almost optimal case, allowing us to illustrate the benefits of relaying when using parked cars. This concept can of course also be replaced using RSUs or SSUs installed at the traffic light but at much higher operational costs.

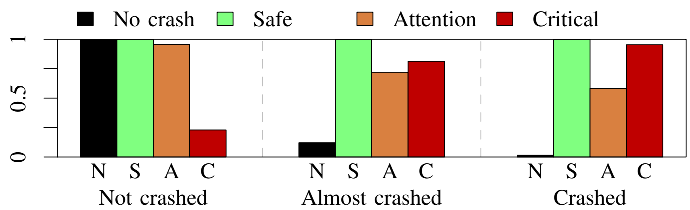
We always let only two vehicles approach the intersection and simulate critical situations by disabling safety checks. Static beaconing is carried out with a rate ranging from 1–10 Hz for the two approaching vehicles and is implemented on top of a IEEE 802.11p PHY/MAC. As described before, we use a vehicle parked close to the intersection as a relay node. This parked car does not broadcast CAMs, because it is not moving. Nevertheless, the parked car uses the same physical layer and MAC as the two approaching vehicles for its relaying purposes. A full description and the list of parameters can be found in Section 3.2.2.1.

5.1.1 Evaluation with Risk Classification

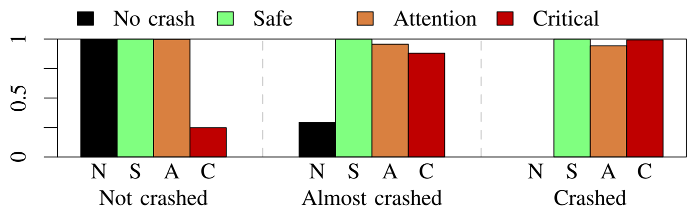
In Figure 5.3 we plot the percentage of approaches which triggered a certain warning level at least once. When relaying by parked vehicles is enabled, this leads to 100 % of the vehicles receiving messages also during the time window when messages are still classified as SAFE. Interestingly, this observation holds for all beacon intervals and different crash situations. The reason for triggering the class SAFE at least once for every approach independently of the beacon



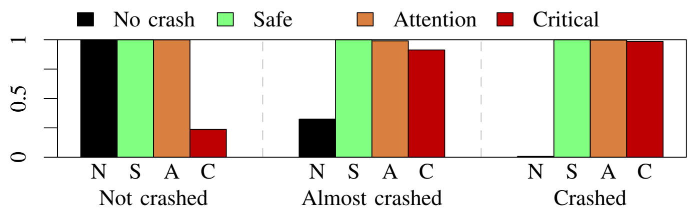
(a) Relay, Beacon interval 1 s [69], © 2012 IEEE



(b) Relay, Beacon interval 0.5 s



(c) Relay, Beacon interval 0.1 s

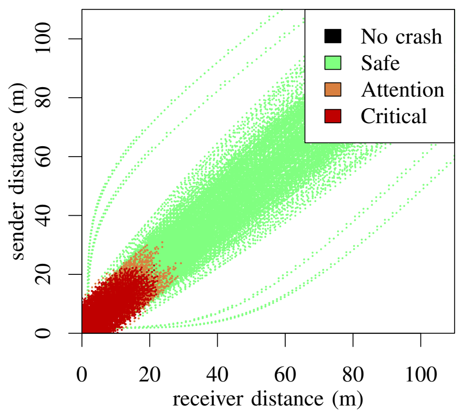


(d) Relay, Beacon interval 0.04 s

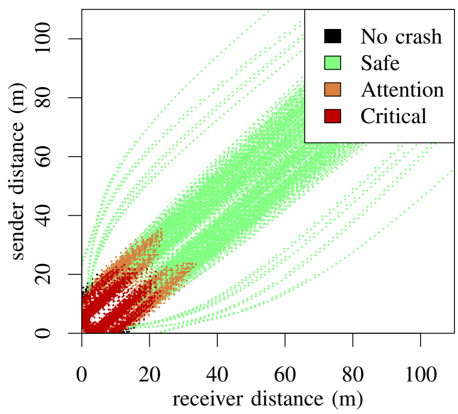
Figure 5.3 – Rate of approaches during which a certain warning level was triggered for relaying with different beacon intervals.

interval lies in the fact that all approaches spent a reasonable long time, i.e., the time from the first communication possibility until it changes to ATTENTION or NO-CRASH, in this class.

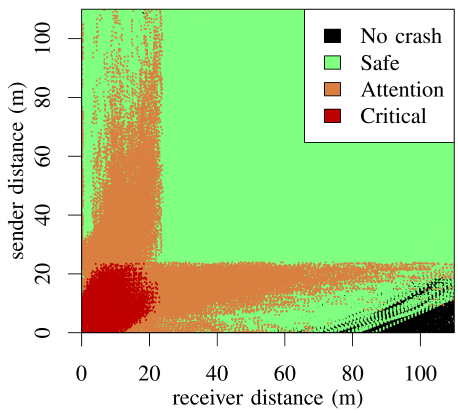
With a beacon interval of 1.0 and 0.5 s, however, even the relay cannot help closing the gap between SAFE and CRITICAL, in particular for *Crash* situations. The results for smaller beacon intervals confirm that beaconing with intervals smaller than 0.1 s and relay lead to smooth transitions between SAFE and CRITICAL beacon classifications. Hence, this simple relaying approach cannot improve situation awareness if the basic information dissemination rate is too low.



(a) Crashed situations



(b) *Near Crash* situations



(c) Not crashed situations

Figure 5.4 – Risk classification of every received beacon including relayed beacons based on the received and own trajectory; subdivided by the resulting intersection situation [69], © 2012 IEEE.

However, the use of relays clearly increases cooperative awareness of all vehicles, in particular when none of the vehicles is in the vicinity of the intersection yet. This observation is in line with findings presented in [155]. Cooperative communication can thus become a very important factor for IAS since it enables the vehicles to trace the movements of others much earlier than they could do otherwise.

Figure 5.4 shows the risk classification of every received beacon based on the received and own trajectory when a relaying car is parked at the intersection. It can be seen that in *Crash* and *Near Crash* situations the single approaches can get traced much further away (cf. Figure 3.5). Moreover, beacons at any combination of sender/receiver distance are received in *No Crash* situations and the majority gets classified as SAFE (cf. Figure 5.4c).

This initial study showed that in idealistic communication conditions parked cars can help to substantially improve situation awareness when all overheard CAMs are precautionary relayed. However, this simple relaying mechanism does not allow us to draw conclusions on situation awareness of current state-of-the-art communication strategies for IAS.

5.2 Cooperative Communication Strategy

In the previous section we have explored the potential of cooperative communication under idealistic communication conditions. Indeed, relaying of all received CAMs by a parked car close to the intersection or an RSU/SSU at the intersection increases situation awareness when the vehicles are not able to directly communicate. However, under realistic conditions where possibly hundreds of vehicles contend for the wireless channel, such simple relaying mechanisms would quickly congest the channel. Even if no rebroadcasts are considered the beacon rate needs to be adjusted by congestion control mechanisms such as DynB and TRC.

In the previous chapter we have shown that including an application metric (in the case of IAS, the intersection collision probability) helps to improve situation awareness at intersections for current congestion control mechanisms. If such an application specific metric is integrated in the rebroadcast decision, it might be feasible to limit rebroadcasts to situations that benefit of rebroadcasts from an application point of view. By integrating this aspect, the channel load caused by cooperative communication can be decreased substantially. This first aspect will be referred to as *situation-based rebroadcast*.

Another approach to reduce the number of rebroadcasts would be to determine whether other vehicles would profit from a rebroadcast, i.e., they would be able gain information. In general, situation awareness of vehicles on the road can be increased if a pair of vehicles, which is not able to communicate directly, exists within communication range of the rebroadcasting node. This idea will be referred to as *useful rebroadcast* and mainly addresses the issue of rebroadcasting only if it is beneficial from a communication point of view. To determine, which vehicles are in communication range of each other, additional information needs to be transmitted, i.e., the one-hop neighbor information. In addition to this increased transmission needs, the rebroadcasting node will need to keep the one-hop neighbor information temporarily. In combination with the previous idea of situation-based rebroadcast this should lead to an optimal number of rebroadcasts from an application and a communication point of view.

The two presented cooperative aspects are able to handle crowded communication conditions, but both of them would only work if a single node is responsible for rebroadcasting (e.g., an RSU/SSU is installed at an intersection). As pointed out in [155,156], the installation of RSUs/SSUs would cause additional costs, but can be saved by including parked cars. Nevertheless, there might be no parking cars in close vicinity to the intersection center.

Basically any vehicle can act as relay for urgent information. If no rebroadcast suppression method is implemented, many vehicles might overhear CAMs and decide to rebroadcast and hence rebroadcasts might be redundant. Hence, the broadcast storm problem [78] could emerge even if only useful and situation-based rebroadcasts are carried out. As a consequence, these redundant rebroadcasts cause contention among rebroadcasting vehicles and eventually collisions of such rebroadcasts. Therefore, if not only a single "static" node is responsible for the rebroadcast decision, a suitable rebroadcast suppression technique needs to be integrated. We propose to rely on an election process, which tries to select a single node dynamically. In the following this aspect is called *infrastructure-free* cooperation.

As pointed out in the introduction of this chapter, communication awareness is another important aspect, which can be improved by cooperative communication. Fortunately, the two rebroadcast mechanisms (useful and situation-based rebroadcasting) provide already a good basis for enabling communication awareness: The rebroadcasting node can infer which vehicle is able to communicate directly with which subset of vehicles in communication range of it. In addition, the rebroadcasting node can provide information, which vehicles should have received rebroadcasts. Hence, every vehicle receiving this information is able to deduce its current communication status. In general, it would be difficult to transmit all necessary information, but once more the necessary amount of data is already reduced by the first two rebroadcast aspects, i.e., useful as well as situation-based rebroadcasts.

To summarize, we identified four important aspects of cooperative communication mechanisms for IAS:

- **Situation-based rebroadcasts**, i.e., useful from a road traffic point of view.
- **Useful rebroadcasts**, i.e., useful from a communication perspective.
- **Infrastructure-free** approach which tries to select a single vehicle which takes care of rebroadcasting.
- **Communication awareness** allows any vehicle to deduce its current communication state during an intersection approach.

To integrate all four aspects, our approach relies on a so-called *intersection coordinator*, i.e., the node which is responsible for rebroadcasting CAMs. This role can be taken by any vehicle. To enable this decentralized, self-organizing, and infrastructure-free approach of cooperative communication, the *coordinator selection* is one of the main tasks, which needs to be performed by every vehicle. In addition, all vehicles can assess their current communication awareness by checking received CAMs, rebroadcasts and received information of the current intersection coordinator.

The vehicle that is currently the intersection coordinator has the following additional tasks: To reduce the amount of rebroadcasts, the intersection coordinator tracks the current communication state of all vehicles within its communication range and performs a situation assessment. Moreover, it is responsible to transmit periodic announcements, which are used by the individual vehicles to perform the coordinator selection as well as the assessment of communication awareness.

In the following, we first start with the tasks that need to be performed by all vehicles, independent whether they are an intersection coordinator or not. Then, the intersection coordinator tasks are described in detail.

5.2.1 All Vehicle Tasks

Algorithm 5.1 lists all event triggers and sketches what all vehicles need to perform for enabling our cooperative approach. Since our approach wants to optimize channel usage and avoid unnecessary rebroadcasts of CAMs, we add a feedback possibility by integrating the list of current one-hop neighbors. Given that CAMs should be reasonable small, because their transmission should be short, limitations regarding neighbor information need to be considered. However, we do not investigate these limitations, because there exist already potential solutions to minimize the overhead of neighbor information (e.g., bloom filters [80]).

When a CAM is received (ReceivedCAM, line 2), it needs to be added to the list of received CAMs where per vehicle only the latest message needs to be stored. For our approach it is important to keep the entire CAM and not only the one-hop neighbor information, because the actual content is needed to compute the intersection collision probability in case the node is or becomes the coordinator of an intersection. Whenever a CAM is sent by a vehicle, it adds one-hop neighbor information which is extracted from the recently received CAMs (timeout $t_{\text{neighbor}} = 1\,\text{s}$). The remaining part of this procedure needs only to be executed by vehicles which are currently the coordinator of an intersection and hence are described later in detail.

Compared to the normal CAM structure, the list of current one-hop neighbors is added as depicted in Figure 5.5. The necessary information per neighbor consists of a unique identifier and either the last sequence number or a timestamp. Our approach makes use of a timestamp and hence the size of a CAM would grow per neighbor entry by 12 B.

```
1:  procedure ReceivedCAM                              ▷ called when CAM received
2:      receivedCAMs ← receivedCAMs + CAM
3:      if currentlyCoordinator then
4:          call CheckRebroadcast                      ▷ see Algorithm 5.3
5:      end if
6:  end procedure
7:
8:  procedure ReceivedICM                              ▷ called when ICM received
9:      coordinatorPresent ← true
10:     if currentlyCoordinator then
11:         call SelectCoordinator                     ▷ see Algorithm 5.2
12:     end if
13:     call CheckCommunicationState                   ▷ see Algorithm 5.2
14: end procedure
15:
16: procedure PeriodicCoordinatorCheck                 ▷ called every 100ms
17:     if currentlyCoordinator then
18:         call SendICM                               ▷ see Algorithm 5.3
19:         call SelectCoordinator
20:     else
21:         if coordinatorPresent = false then
22:             call SelectCoordinator
23:         end if
24:     end if
25:     coordinatorPresent ← false
26: end procedure
```

Algorithm 5.1 – Overview of event triggers for the cooperative communication strategy.

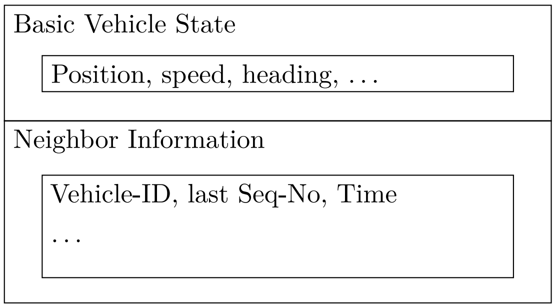


Figure 5.5 – Extended structure of a CAM for supporting cooperative communication.

The procedures ReceivedICM and PeriodicCoordinatorCheck in Algorithm 5.1 are used for both—the coordinator selection as well as the communication awareness assessment. Both mechanisms rely on so-called Intersection Coordinator Messages (ICMs) which are transmitted periodically by the intersection coordinator.

5.2.1.1 Coordinator Selection

The intersection coordinator can be an RSU/SSU at an intersection (the coordinator selection will always select it) or a vehicle, ideally the one closest to the intersection center. This ensures that the node which is most likely to have communication possibilities with vehicles on both crossroads takes the coordinator role. Compared to other works, which are built upon the assumption that at any time only a single entity is responsible for some critical tasks, our cooperative communication strategy does not have that high demands. Therefore, we do not need to rely on a complex election process as for example outlined in [157]. In particular, it does not harm our approach if, for a short period of time, more than one vehicle performs the coordinator tasks.

The coordinator selection is outlined in Algorithm 5.1 and is based on ICMs: When a vehicle receives an ICM, the procedure ReceivedICM is triggered (line 8) and it can deduce that a coordinator is present for a particular intersection. If a vehicle which currently holds the coordinator role of the same intersection receives an ICM, it calls the procedure SelectCoordinator to ensure that it only keeps the coordinator role if it is the better coordinator, i.e., the one closer to the intersection center. The final call of the CheckCommunicationState procedure enables the assessment of the communication awareness, which is described in detail later.

To ensure that a vehicle takes the coordinator role if it is the vehicle closest to the intersection center, every vehicle needs to perform the following periodic check. The procedure PeriodicCoordinatorCheck (line 16) is executed by all vehicles every 100 ms (t_{check}). If the vehicle is currently the coordinator of an intersection, it first sends an ICM and then rechecks its coordinator role by calling the procedure SelectCoordinator. Non-coordinator vehicles only reassess their non-coordinator status if there is currently no coordinator present. Finally, the flag which keeps track whether a coordinator is currently present or not, needs to be reset.

The selection of the coordinator is performed in the procedure SelectCoordinator (Algorithm 5.2, line 1). When this procedure is executed, the node can conclude that the communication state is COORDINATOR_UNCLEAR. Then it checks all recently received CAMs (time frame is twice the current beacon interval). If any vehicle is closer to the intersection center, it can conclude that it is not the coordinator of this intersection.

Please note that this coordinator selection might elect more than a single coordinator for one intersection. In the context of IAS it is more important to provide best possible communication between vehicles which have an urgent need to communicate with each other. Hence, the additional communication overhead caused by two concurrent coordinators for a short time during hand-over is acceptable.

5.2.1.2 Communication Awareness Check

The communication awareness check is carried out in two stages: The first stage checks whether an intersection coordinator is present, whereas the second stage examines the communication to the coordinator as well as rebroadcasts.

The first stage is carried out in the procedure SelectCoordinator (Algorithm 5.2). Whenever this procedure is called by a vehicle—independent of currently being a coordinator or not—it can conclude that the current communication state is COORDINATOR_UNCLEAR. In the following situations this procedure gets called: In procedure ReceivedICM (Algorithm 5.1, line 8), a coordinator receiving an ICM by another vehicle should definitely conclude that its communication state is COORDINATOR_UNCLEAR. In addition, the procedure PeriodicCoordinatorCheck (Algorithm 5.1, line 16) calls the SelectCoordinator procedure if the vehicle is currently coordinator (line 19) or a vehicle detects that no coordinator was present in the last period (line 22).

The second stage (CheckCommunicationState in Algorithm 5.2) is called to assess the current communication situation, when an ICM is received (Algorithm 5.1, line 13). By keeping track of the last received CAM per vehicle and by using the ICM of the intersection coordinator, the vehicle can deduce the current communication state.

```
1: procedure SelectCoordinator
2:     communicationState ← COORDINATOR_UNCLEAR
3:     currentlyCoordinator ← true
4:     for all receivedCAMs do
5:         if sendtime ≥ time − 2 ∗ curBeaconInterval
6:           and distance ≤ myDistance then
7:             currentlyCoordinator ← false
8:         end if
9:     end for
10: end procedure
11:
12: procedure CheckCommunicationState(ICM)
13:     communicationState ← SAFE
14:     reliable ← call CheckCommunication(
15:             lastCAMofCoordinator, lastCAMbeforeCoordinatorCAM)
16:     if Not reliable then
17:         communicationState ← TO_COORD_FAILED
18:     end if
19:     for all endangeredPairs in ICM do
20:         if In pair and not received CAM since ICM then
21:             communicationState ← REBROADCAST_FAILED
22:         end if
23:     end for
24: end procedure
25:
26: procedure CheckCommunication(newMsg,oldMsg)
27:     for all neighbors in newerMsg do
28:         if neighbor.id = oldMsg.id and neighbor.time = oldMsg.time then
29:             return true
30:         end if
31:     end for
32:     return false
33: end procedure
```

Algorithm 5.2 – Detailed methods for enabling coordinator selection as well as communication awareness.

In Algorithm 5.2 the procedure CheckCommunicationState (line 12) outlines this communication check. It starts with the assumption that the communication state is *safe* and gets altered if one of the following checks fails. First, it checks if the coordinator was able to receive CAMs from the node itself. This is done by calling the procedure CheckCommunication with the last CAM of the current coordinator and the own CAM that has been sent before the one of the coordinator.

The procedure CheckCommunication, which is outlined in Algorithm 5.1 starting from line 26, determines first which message is newer, because the newer message should acknowledge the older one. Then it checks if the older

CAM is included in the neighbor list of the newer CAM by checking the vehicle identifier and the timestamp. In this case it checks whether the last CAM of the coordinator acknowledges the own CAM right before that one. If the communication from the node itself to the coordinator was not reliable, the communication state TO_COORD_FAILED is assigned.

As a second step, it checks if a possible rebroadcast of a CAM has been received. All rebroadcasts by the coordinator are listed in the ICM in the list of *endangeredPairs*. If the own vehicle identifier is included in a pair, the vehicle needs to check whether it has received a CAM from the other vehicle since the last ICM. If this check fails, the communication state is REBROADCAST_FAILED.

5.2.2 Coordinator Tasks

The coordinator of an intersection needs to perform two tasks outlined in Algorithm 5.3: First, it is responsible to rebroadcast overheard CAMs if it is necessary and second it needs to transmit the ICM periodically.

5.2.2.1 Rebroadcast of CAMs

The intersection coordinator is responsible to check whether any received CAM needs to be rebroadcasted by executing the procedure CheckRebroadcast (line 1). This procedure gets called if a vehicle currently has the coordinator role (as listed in Algorithm 5.1, line 4).

```
1: procedure CheckRebroadcast(recvCAM)
2:     for all CAM in recently receivedCAMs do                         ▷ recently means 1s
3:         if collisionProbability ≥ threshold then
4:                                                       ▷ includes check if collision possible
5:             if NOT call CheckCommunication(recvCAM, CAM) then
6:                 endangeredPairs ← endangeredPairs + curPair
7:                 rebroadcast cumulativeCAM
8:             end if
9:         end if
10:    end for
11: end procedure
12:
13: procedure SendICM
14:    periodicMessage ← endangeredPairs
15:    send periodicMessage
16:    endangeredPairs ← ∅
17: end procedure
```

Algorithm 5.3 – Summary of coordinator tasks.

To determine whether a rebroadcast might be helpful or not, the coordinator calculates the intersection collision probability of the vehicle from which the currently received CAM originates with all recently received CAMs ($t_{\text{rebroad}} = 500\,\text{ms}$). If a collision is possible and the collision probability exceeds a certain threshold (in our case we use the same threshold $\mathcal{P}_{th}$ as for the situation-based rate adaptation), the coordinator checks whether the communication between the two vehicles was successful in the recent past. In particular, a detailed check of communication is performed in the procedure CheckCommunication, which has been explained before in detail and is listed in Algorithm 5.2. If communication was not successful in the recent past, the coordinator rebroadcasts a cumulative CAM, which includes the latest CAM of both vehicles. The pair of vehicles is also added to the list of $endangeredPairs$, which gets included in every ICM.

5.2.2.2 Periodic Transmissions of Intersection Coordinator Messages

The second task, the periodic transmission of ICMs, is triggered during the PeriodicCoordinatorCheck in Algorithm 5.1 and is detailed in the procedure SendICM (line 13). Basically, the ICM is a signal to all other vehicles that a coordinator is present and it enables the communication awareness check by providing the list of endangered vehicle pairs since the last ICM has been sent. To enable the communication awareness check the list of $endangeredPairs$ is first added to the ICM and reset after the ICM has been sent already.

5.3 Evaluation

In the following the proposed cooperative communication approach for IAS is evaluated in order to answer the following two questions:

- "How much can situation awareness be improved when using the dynamic cooperative communication strategy?"
- "Is it possible to assess the state of communication correctly at any time during an intersection approach?"

5.3.1 Scenario Setup

The simulation scenario is similar to the one used for evaluating the situation-based rate adaptation at downtown intersections in Section 4.4: To make the results more comparable, we use the exact same road layout and building outlines as depicted in Figure 4.18. To enable studies of the proposed cooperative communication strategy, we need to simulate the movements of all vehicles.

Hence, the scenarios are almost identical to the *Realistic Downtown Scenario* in Section 4.4.2, which has been used to show benefits of the situation-based rate adaptation in a realistic scenario when all vehicle movements are simulated.

To study the impact of traffic density on the cooperative communication strategies we simulate different densities. In addition, we want to analyze the impact of speed on situation awareness and hence three different speed profiles of vehicles are considered. There are two reasons to use high speed profiles: First, higher speed profiles allow us to study NLOS situations at intersections without changing the environment (i.e., building outlines or their shadowing characteristics) which causes such effects. Second, the high speed profiles of approaching vehicles are also the ones which are challenging from a communication point of view.

By taking the *Baseline Scenario* and combining two different vehicle densities with two speed profiles we end up with the following five scenarios (detailed scenario parameters are listed in Table 5.1):

1. ***Baseline Scenario*** uses the exact same scenario setup as outlined in Section 4.4.2 and hence is comparable to *Realistic Downtown Scenario*. The average speed of colliding vehicles the last 5 s before a crash $\bar{v}_{[0,5]\mathrm{s}}$ is 9.2 m/s.

2. ***Medium Speed Scenario*** uses higher speed profiles than the *Baseline Scenario* and hence the average speed before a collision $\bar{v}_{[0,5]\mathrm{s}}$ is 20.3 m/s. The traffic density is reduced to a medium level.

3. ***Medium Speed + High Density Scenario*** simulates a higher vehicle density which is similar to the one in *Baseline Scenario*, but the speed profiles is the same as in *Medium Speed Scenario*.

4. ***High Speed Scenario*** uses very high speed profiles at the intersection ($\bar{v}_{[0,5]\mathrm{s}} = 21.6\,\mathrm{m/s}$), but a comparable medium traffic density as in *Medium Speed Scenario*.

5. ***High Speed + High Density Scenario*** uses higher vehicle density, but the same speed profile as in *High Speed Scenario*.

For every scenario 440 different approaches have been simulated using the crash situation model described in Section 3.1.3. Please note that not only the two vehicles under analysis behave differently for every approach, but also the position of possible intersection coordinators as well as uninvolved vehicles varies. Table 5.2 lists the mean speed during the last five seconds before a crash as well as the mean traffic density and the total number of crashes for each scenario.

Table 5.1 – Detailed overview of road traffic simulation parameters.

Scenario	Maximum speed $v_{\max}$ [m/s]	Crossing speed v_{cross} [m/s]	Time delta t_δ [s]
Baseline	$\sim \mathcal{N}(13.9, 2.9)$	$\sim \mathcal{U}(3, 12)$	$\sim \mathcal{U}(0.1, 1.0)$
Medium Speed	$\sim \mathcal{N}(23.9, 2.9)$	$\sim \mathcal{U}(10, 25)$	$\sim \mathcal{U}(0, 1.0)$
Medium Speed + High Density	$\sim \mathcal{N}(23.9, 2.9)$	$\sim \mathcal{U}(10, 25)$	$\sim \mathcal{U}(0, 1.0)$
High Speed	$\sim \mathcal{N}(25.9, 2.9)$	$\sim \mathcal{U}(18, 28)$	$\sim \mathcal{U}(0, 0.5)$
High Speed + High Density	$\sim \mathcal{N}(25.9, 2.9)$	$\sim \mathcal{U}(18, 28)$	$\sim \mathcal{U}(0, 0.5)$

Table 5.2 – Overview of measured scenario behavior.

Scenario	Mean speed $\bar{v}_{[0,5]\text{s}}$ [m/s]	Mean traffic density	Total number of crashes
Baseline	9.2	19.9	276
Medium Speed	20.3	14.0	288
Medium Speed + High Density	20.3	21.5	226
High Speed	21.6	13.3	334
High Speed + High Density	21.6	20.1	319

These numbers are not parameters, but are measured values during simulations and hence give insights on the comparability of individual scenario results.

For sake of brevity this chapter analyzes only DynB as underlying congestion control mechanism. The situation-based rate adaptation as proposed in Section 4.2 is used for all presented communication strategies, but the self-collision probability feature has been disabled. The self-collision probability is disabled, because it has been added to increase the beacon rate even if no initial communication is possible due to NLOS communication. Moreover, the situation-based rate adaptation makes use of the superior adaptation strategy, i.e., *cubic* with the same maximum dissemination rate $r_{\text{cubic}} = 67.76\,\text{Hz}$. Table 5.3 summarizes all communication related parameters.

To summarize, the following three communication strategies will be evaluated:

- **Non-cooperative**: uses only the situation-based rate adaptation in addition to the congestion control mechanism DynB.

- **Dynamic cooperation**: uses all cooperative communication mechanisms described in Section 5.2.

- **SSU cooperation**: uses also all cooperative communication mechanisms although the coordinator selection will always select the SSU.

Table 5.3 – Network and congestion control protocol parameters.

	Parameter	Value
PHY & MAC	Path loss model	Free-space ($\alpha = 2.0$)
	Shadowing model	Obstacle Shadowing [60]
	Attenuation per wall [60]	$\beta = 9.0$ dB
	Attenuation per m [60]	$\gamma = 0.4$ dB
	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 CAM	AC_VO
	CAM size	193 B
	Transmit power	33 dbm
DynB	I_{des}	0.04 s
	b_{des}	0.25
Adaptation	Threshold $\mathcal{P}_{th}$	5 %
	Min. rate r_{min}	5 Hz
	Max. rate cubic r_{cubic}	67.76 Hz
	Timeout t_{out}	1 s
Cooperative	Timeout neighbor t_{neighbor}	1 s
	Periodic check t_{check}	100 ms
	Rebroadcast calculation t_{rebroad}	500 ms
	Access category ICM	AC_VI
	Access category rebroadcasts	AC_BE

5.3.2 Situation Awareness

In this section the question “How much can situation awareness be improved when using the dynamic cooperative communication strategy?” will be discussed.

Similarly, to the previous chapter this evaluation is based on a worst-case update lag analysis as described in Section 3.4.2. Since there was no interesting behavior visible for Bin 1 in the plots presented in the previous chapter, we decided to include Bin 4 instead. Moreover, Bin 4 is of particular interest, because countermeasures to prevent a crash in high speed situations need to be taken much earlier.

Figure 5.6 depicts the eCDFs of the worst update lags L_u^w in *Baseline Scenario* for three different communication strategies: non-cooperative, dynamic cooperation and SSU cooperation. The non-cooperative communication strategy uses only the situation-based rate adaptation without self-collision probability. This self-collision probability feature is exactly the reason why the non-cooperative communication strategy has a slightly worse performance in Bin 3 than in Figure 4.27a.

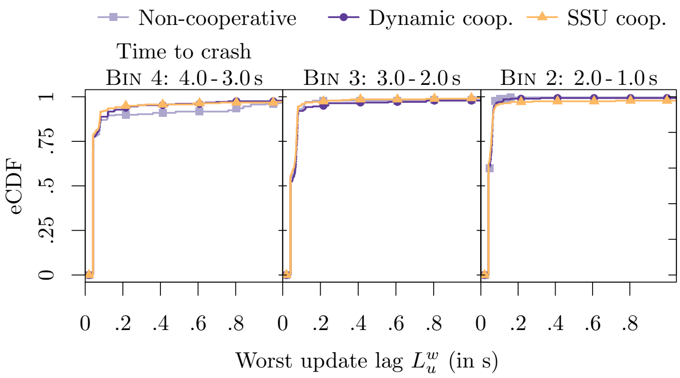


Figure 5.6 – eCDF comparing the worst-case update lag L_u^w per bin for DynB without cooperation as well as dynamic and SSU cooperative communication in the *Baseline Scenario*.

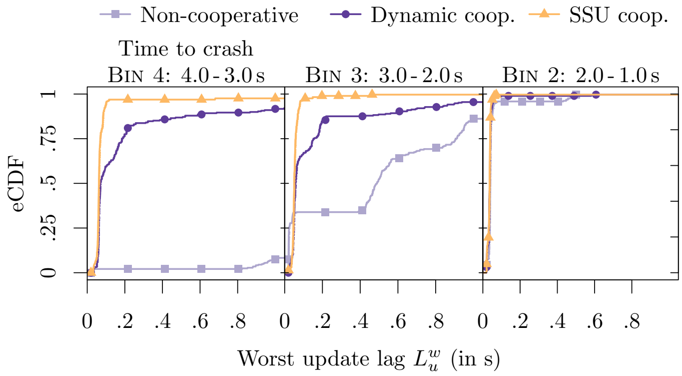
When looking at the cooperative communication strategies, it can be seen that both of them have slightly better performance in Bin 4 than the non-cooperative. Nevertheless, the advantage of using a cooperative communication strategy is marginal in such a scenario, because during most approaches the vehicles under analysis are already in communication range of each other.

As mentioned earlier, we increased the speed of approaching vehicles to require them to communicate already when direct communication is still blocked by shadowing effects of buildings. Figure 5.7 shows the eCDFs for the *Medium Speed Scenario* and the *High Speed Scenario*. As expected, the non-cooperative approach achieves worse performance if the speed of approaching vehicles is higher.

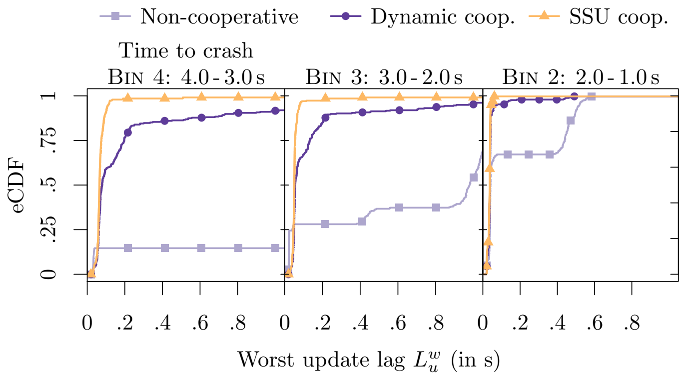
In the *Medium Speed Scenario* more than 50 % of vehicles experience update lags larger than 500 ms in Bin 3. The situation gets worse if the speed is increased further as the results for the *High Speed Scenario* show: Even in Bin 2 more than 25 % of vehicles experience such unacceptable update lags.

The two cooperative communication strategies are able to substantially improve situation awareness. Starting with the SSU cooperative approach, it can be seen that it reaches almost 100 % for these two scenarios independently of the speed. Some vehicles do not achieve full situation awareness, because the CAMs of approaching vehicles might still collide at the SSU. The reason for such collisions in the air is that vehicles on the two crossroads are in distinct interference domains as long as they are far away from the intersection center.

Looking at the results of the dynamic cooperative communication strategy, it can be noticed that the performance compared to an SSU is worse for both scenarios. Nevertheless, also the dynamic approach delivers a substantial increase in situation awareness in Bin 3 and Bin 4. In addition, its performance



(a) *Medium Speed Scenario*



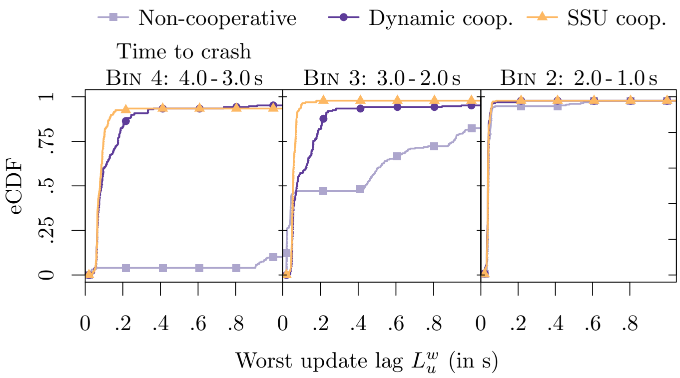
(b) *High Speed Scenario*

Figure 5.7 – eCDF comparing the worst-case update lag L_u^w per bin for DynB without cooperation as well as dynamic and SSU cooperative communication (*Medium Speed Scenario* and *High Speed Scenario*).

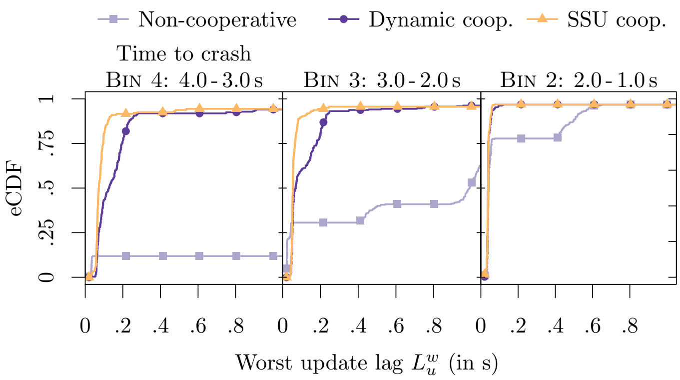
improvement is not influenced by the speed of approaching vehicles (this can be seen by comparing the eCDFs for the dynamic cooperation in Figure 5.7a and Figure 5.7b).

The gap between the SSU cooperation and the dynamic cooperation might get closer if an intersection coordinator is almost always available. By increasing the vehicle density in the scenario, we can control how likely it is to have a useful coordinator available while two vehicles are approaching the intersection. Figure 5.8 shows the results for higher vehicle densities and the two different speed profiles.

Compared to the results in Figure 5.7, which are gathered in low vehicle density conditions, it can be seen that the dynamic cooperation is almost as successful as the SSU cooperation. Only around 25 % of vehicles experience longer worst update lags in Bin 4 and Bin 3. These slightly longer worst update lags can be caused by having no coordinator available or a coordinator handover.



(a) *Medium Speed + High Density Scenario*

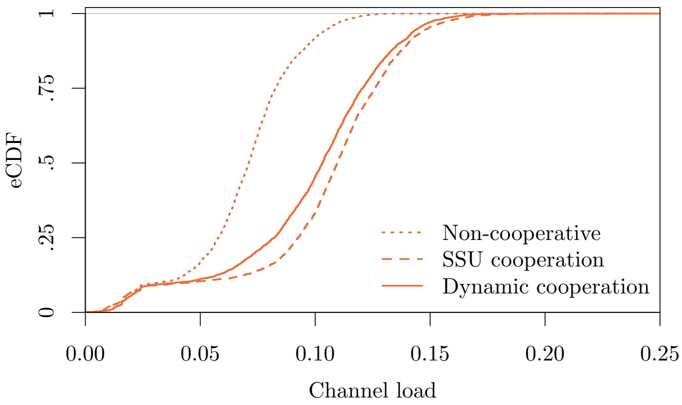


(b) *High Speed + High Density Scenario*

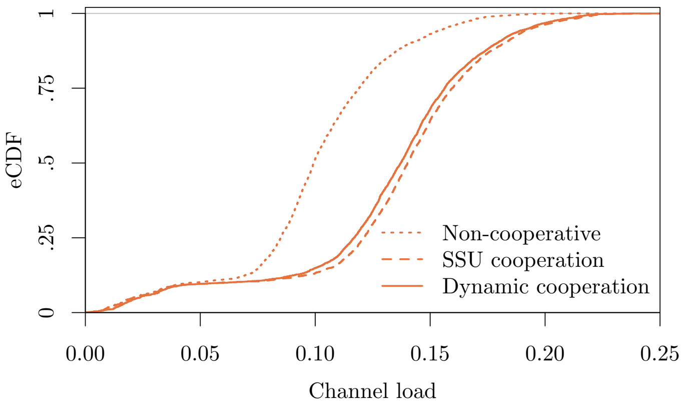
Figure 5.8 – eCDF comparing the worst-case update lag L_u^w per bin for DynB without cooperation as well as dynamic and SSU cooperative communication (*Medium Speed + High Density Scenario* and *High Speed + High Density Scenario*).

In the following we are going to analyze the channel load of the different scenarios in order to understand some effects better. By paying close attention to the results of the SSU approach and comparing them with the results in Figure 5.7, it can be noticed that the SSU approach works slightly worse in high density situations. Looking at BIN 4, the SSU approach is able to provide L_u^w smaller than 200 ms for around 98 % in low density situations compared to only around 92 % in high density situations.

To further examine this decrease of situation awareness in dense road traffic situations we had a look at the channel load for BIN 4 and BIN 3. And yet it turned out that the reason for this worse behavior is the increased channel load in the *Medium Speed + High Density Scenario* and the *High Speed + High Density Scenario*.



(a) *Medium Speed Scenario*



(b) *Medium Speed + High Density Scenario*

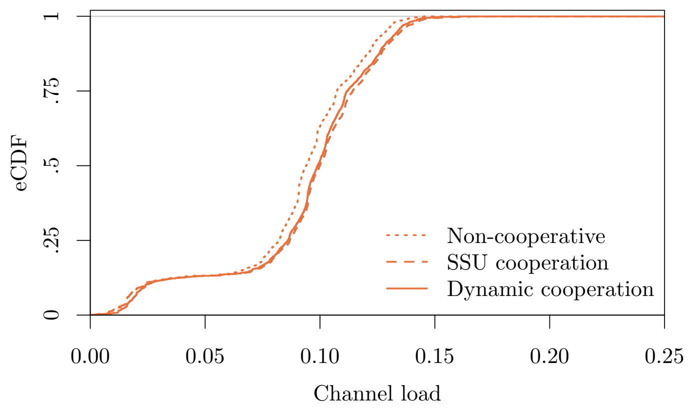
Figure 5.9 – eCDF comparing the channel load for DynB without cooperation as well as dynamic and SSU cooperative communication for Bin 4 and Bin 3.

For sake of brevity only a comparison of the *Medium Speed Scenario* and the *Medium Speed + High Density Scenario* is plotted in Figure 5.9. When comparing the different cooperation approaches, it can be seen that the channel load is higher in the *Medium Speed + High Density Scenario* and hence the likelihood of packet collisions at the SSU or the intersection coordinator increases.

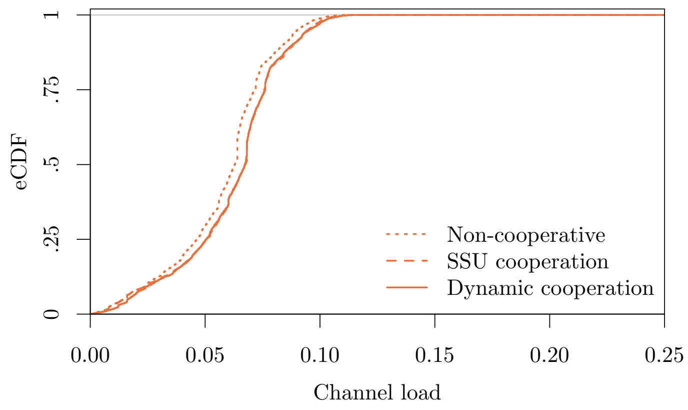
Moreover, the experienced channel load is higher if an SSU is placed at the intersection center, because there is always a coordinator available and hence more rebroadcasts are executed. This finding is also confirmed by the fact that the difference of channel load between the SSU and the dynamic approach is larger in the *Medium Speed Scenario* than in the *Medium Speed + High Density Scenario*.

To estimate the overhead of the proposed cooperative communication strategy in *Medium Speed Scenario* when no rebroadcasts are issued, Figure 5.10 plots the eCDFs for two time frames: Figure 5.10a shows the experienced channel load in Bin 1, when no rebroadcasts are issued, because the approaching vehicles can communicate directly. Figure 5.10b depicts the channel load during a time frame where neither the situation-based rate adaptation nor the cooperative communication strategy are active.

Compared to Figure 5.9a it can be seen that in both figures the difference between non-cooperative and cooperative strategies is much smaller if no rebroadcasts are issued. In addition, the SSU and dynamic cooperative communication strategies yield to almost the same channel usage when no rebroadcasts are



(a) Time to crash Bin 1: 1.0–0 s



(b) Time to crash: 10.0–7.0 s

Figure 5.10 – eCDF comparing the channel load for DynB without cooperation as well as dynamic and SSU cooperative communication for the *Medium Speed Scenario*.

issued. Finally, one can observe in Figure 5.10a a much higher channel load for all communication strategies. This shift is caused solely by the situation-based rate adaptation, which is heavily influencing the dissemination rate during the last second before a crash.

The channel load analysis of all scenarios revealed that the idling overhead of both cooperative communication strategies is marginal, i.e., an increase of less than 0.5 %. During the time frame when rebroadcasts are issued, the channel load significantly increases in all scenarios and for both cooperative communication strategies. For the SSU assisted cooperative communication it is ranging from 3.8–4.2 % and for the dynamic approach the increase lies between 3.2–3.9 %.

Please note that the additional channel load caused by cooperative communication will not be added to the overall channel load, but comes at the expense of all vehicles in communication range decreasing their dissemination rate due to congestion control mechanisms.

5.3.3 Communication Awareness

The ability to detect whether communication is currently able to provide a full picture of the road traffic situation at the intersection is of utmost importance for IAS. If approaching vehicles are aware of possible communication failures, they can approach the intersection in an appropriate manner and/or use additional sensors to enable safe intersection crossings. Therefore, we are going to check in the following whether and how vehicles can make use of the proposed cooperative communication strategy to achieve this goal.

With a non-cooperative communication strategy, such as adaptive beaconing or the situation-based rate adaptation algorithm, only communication outages can be detected. In particular a vehicle approaching an intersection can never conclude that there is no other vehicle driving on the crossroad towards the intersection. To compensate this possible lack of (initial) information we used the *self-collision probability* for the situation-based rate adaptation to improve its behavior in exactly this stage of the intersection approach [114, 154] when no CAMs have been received yet.

As stressed in the cooperative communication strategy in Section 5.2, our approach should not only provide communication between potential collision partners even if there is no direct one-hop communication possible, but also allow to detect whether communication is able to provide a full picture or not. In more detail it should be even feasible to detect which part of the cooperative communication strategy has failed.

Using the proposed cooperative communication strategy, a vehicle can detect the following possible situations where communication might not work and hence additional countermeasures for preventing accidents have to be taken:

1. **Coordinator unclear**: it means that either a new coordinator overtook the role and hence might not yet have the full picture, or that no coordinator is available and the vehicle itself becomes coordinator (cf. Algorithm 5.2, COORDINATOR_UNCLEAR).
2. **Communication to coordinator failed**: since the coordinator acknowledges the reception of CAMs in his own CAM, every vehicle can check whether the coordinator was able to receive their CAMs (cf. Algorithm 5.2, TO_COORD_FAILED).
3. **Rebroadcast failed**: the coordinator has rebroadcasted the CAM, but it was not received (cf. Algorithm 5.2, REBROADCAST_FAILED).

To ensure that our cooperative communication strategy can be used to build fail-safe IAS we checked all situations where vehicles did not receive updates in time, i.e., the required update lag of 200 ms has been violated. All received messages of approaching vehicles as well as their online determined communication state have been recorded. Whenever an update lag has exceeded the acceptable boundaries, we investigate the recorded communication states within the update lag time.

Figure 5.11 depicts a situation where the update lag $L_{u_{n+1}}$ is larger than 200 ms. Since the recorded communication state is still evaluated positive if an update from the potential collision partner has been received within the last 100 ms, a positive communication state reflects still valid information during this period. The requirements for a valid communication awareness check for an update lag $L_{u_{n+1}}$ larger than 200 ms are the following:

1. No positive recorded communication state during the time frame marked red in Figure 5.11, i.e., there might be a positive record in the green and red hatched area.
2. At least one negative recorded communication state during the entire update lag $L_{u_{n+1}}$.

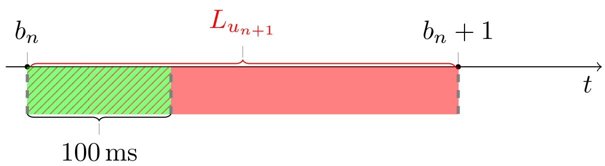


Figure 5.11 – Check of communication awareness.

The check of all situations, where even the dynamic cooperative communication mechanism could not help to improve situation awareness fully, revealed that the approaching vehicles could deduce their communication state, i.e., the received information via IVC does potentially not provide a full picture. Hence, we were able to show that all vehicles were able to assess the state of communication correctly at any time during their intersection approaches. By integrating this communication awareness aspect in future IAS, fail-safe systems with the help of communication, but without the need of dedicated infrastructure, are feasible.

Besides the feasibility of the communication awareness check, we have also analyzed the gathered communication state information in detail. Figure 5.12 provides an overview of communication failures that have been recorded for all approaches during the last 4 seconds before a crash. It can be seen that the likelihood that communication can be considered *safe* is higher in *Medium Speed + High Density Scenario* and *High Speed + High Density Scenario* where more vehicles are driving on the crossroads. Again, higher vehicle density yields to a higher probability of having a useful coordinator available at the intersection.

Since the proportions in Figure 5.12 include also the situations where the vehicles are already very close to or in the intersection area, the proportions of failed communication need to be put into perspective: The seemingly high proportions for coordinator failures (more than 40 % and 23 % for normal and high density scenarios, respectively) comprise situations shortly before the crash has happened and hence the probability that one of the two colliding vehicles is the closest to the intersection center is high. Moreover, the worst-case update lag analysis has revealed that depending on the vehicle density, the dynamic cooperation is well able to improve situation awareness (cf. Figure 5.7 and

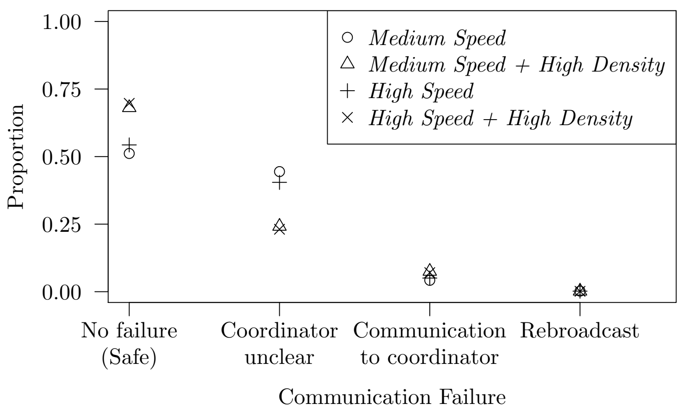


Figure 5.12 – Distribution of the communication states during the last 4 seconds before a *Crash*.

Table 5.4 – Overview of the communication failures during the last 4 seconds before a crash.

Scenario	Coordinator unclear	Comm. to coord.	Rebroad-cast
Medium Speed	44.4 %	4.2 %	0.2 %
Medium Speed + High Density	24.2 %	7.5 %	0.2 %
High Speed	40.5 %	5.0 %	0.2 %
High Speed + High Density	23.1 %	7.1 %	0.1 %

Figure 5.8). It is hardly visible in Figure 5.12, but there is also a difference between the scenarios if the communication to the coordinator failed, as listed in Table 5.4. The probability that communication to the coordinator fails is higher in the high density scenarios, because there are more vehicles contending for the wireless channel.

5.4 Discussion

The previous section showed that cooperative communication is able to increase situation awareness at intersections significantly if direct communication between approaching vehicles is blocked. Moreover, it has been shown that vehicles can deduce whether communication is able to provide full situation awareness or not. This communication awareness will allow to build fail-safe IAS in future. However, the presented cooperative communication strategy and its evaluation should be seen as a proof-of-concept. Several aspects have not been studied in detail yet, because they are out of scope of this thesis. In the following, we are going to discuss all discovered aspects which need further attention.

As already pointed out in Section 5.2.1.1, the coordinator selection does not ensure that always only a single coordinator is active. Therefore, we checked how many coordinators have been active concurrently. It turned out that at most two coordinators and at least one coordinator are active at the same time. The duration of these two coordinator situations were mostly caused by coordinator handover. However, we also found situations where two coordinators coexist for a longer period. The reason for these longer periods is that two coordinators driving on different crossroads further away from the intersection center might not be able to communicate with each other. This could even lead to a situation where two approaching vehicles have a valid coordinator, but since the coordinators cannot overhear messages from the crossroad, no rebroadcasts are issued and, even worse, the communication awareness check could reveal that the situation is currently *safe*.

Hence, we introduced the additional communication awareness rule that only trusts coordinators which are in close vicinity to the intersection center. A 10 m radius turned out to be sufficient for our scenarios. This vicinity parameter could be determined for every intersection by vehicles themselves. Another solution would be to use another communication link which does not rely on direct communication between coordinator vehicles. For example, a heterogeneous vehicular network (e.g., [84, 158]) would be able to address this issue.

One prerequisite of the proposed cooperative communication strategy is the need for *periodic* ICMs by a coordinator for every intersection. Since these periodic messages also cause additional channel load, but are exempt from congestion control mechanisms, it could happen that these messages congest the wireless channel. This could especially be an issue if many intersections are in close vicinity of each other. Ideas to circumvent such problems could use, for example, different transmit power levels to reduce the transmit range, but still reach all affected vehicles. So interference at neighboring intersections could be reduced. The current coordinator selection might be not appropriate for intersections with many parallel lanes, because this would likely lead to many coordinator changes. So the coordinator selection could be improved in order to support such multi-lane scenarios.

Finally, we want to discuss the impact of traffic density on situation awareness at intersections. Figure 5.13 sketches the situation awareness of different communication strategies for IAS depending on the traffic density. Please note, that this figure does not depict absolute values, but rather should provide an idea of how cooperative communication can improve situation awareness. In

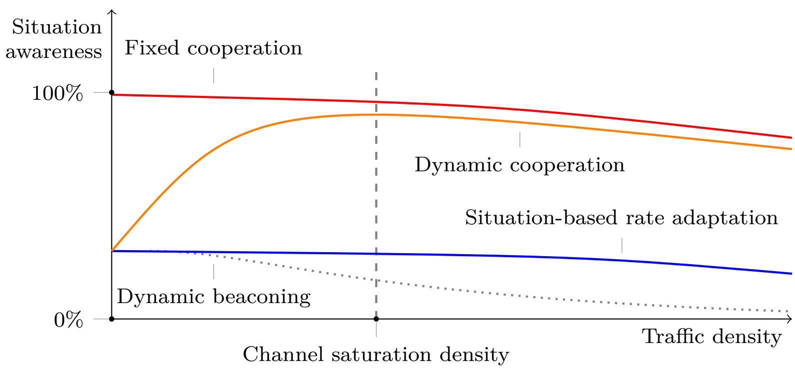


Figure 5.13 – Situation awareness depending on traffic density of different communication strategies for IAS.

addition, we need to emphasize that the curves themselves and their position might vary depending on the intersection environment (e.g., shadowing effects of buildings).

Starting with dynamic beaconing approaches (such as DynB and TRC, explained in Section 2.2.2), we can notice that although the channel load is kept in an efficient range, they fail to provide frequent updates for potential collision partners if the traffic density increases. By using the situation-based rate adaptation we were able to substantially increase situation awareness for IAS, especially for higher vehicle densities (demonstrated in Section 4.4). As mentioned earlier, one-hop CAMs are not able to provide situation awareness if direct communication between approaching vehicles is not possible. Hence, full situation awareness is only feasible with cooperative communication strategies.

Cooperative approaches can be split into two groups: The first group—*fixed cooperation*—uses only not moving communication nodes at the intersection, such as RSUs, SSUs or parked vehicles [156], to rebroadcast relevant information. The second group—*dynamic cooperation*—uses all vehicles as potential relays and hence can provide situation awareness without expensive road-side infrastructure or parked vehicles. Consequently, this group can provide only situation awareness when there is a third vehicle close to the intersection acting as a relay (as depicted in Figure 5.1). Since this availability depends on the traffic density, such approaches can provide better situation awareness for higher vehicle densities as shown in Section 5.3 and depicted by the converging orange line in Figure 5.13.

Furthermore, it needs to be considered that the benefit of using IVC slightly decreases if the traffic density becomes very high and hence the wireless channel congested. The degradation of communication depends on the employed congestion control mechanism, but unless additional channel resources are added the gained situation awareness will start to degrade at a specific traffic density, which we marked in Figure 5.13 as *channel saturation density*.

Chapter 6

Conclusion

In this thesis, we investigated means for improving safety at intersections with the help of Inter-Vehicle Communication (IVC). In the first part of the work we showed that it is vital to analyze exactly the moment when information is needed, i.e., a few seconds before a crash at an intersection. Therefore, we started with an intuitive risk classification, which already allowed us to gain a first understanding when communication needs to be reliable. However, the results also showed that a classification based on binary decisions is not able to provide adequate analysis prospects for Intersection Assistance Systems (IAS).

Consequently, we introduced the intersection collision probability—a continuous safety metric, which allows us to estimate the likelihood of a collision for two vehicles at an intersection. Since its calculation is based solely on data that can be exchanged via Cooperative Awareness Messages (CAMs), it can not only be used to analyze crash situations afterwards, but also to assess the current situation of individual vehicles. For this reason, the basic concept of this safety metric can be applied and further researched in the following domains:

- Warning systems within IAS,
- Controller for automated or semi-automated collision avoidance in IAS,
- Evaluation as well as improvements of communication strategies for IAS (explored in this thesis).

Independent of the research domain further enhancements of the intersection collision probability are conceivable: The two used acceleration distributions are a good starting point for showing the applicability and validity of the intersection collision probability. However, there is a huge potential for further investigations on driver behavior and the deducible acceleration distributions. For example, when a driver is currently braking, it is not feasible to apply full acceleration instantaneously, because first of all the driver needs to switch the pedal and second the engine needs some time to provide full acceleration. Another aspect is that acceleration and deceleration are not treated equally likely, because usually the maximum deceleration rate of a vehicle is much larger than the maximum acceleration. Unfortunately, there are no studies that provide such acceleration distributions for crash situations based on real-world data available in literature.

Since the goal of this thesis was to improve intersection safety with IVC, we decided to use the intersection collision probability metric as input for a new communication strategy that strengthens communication exactly when it is needed. By integrating a safety metric in the communication strategy, i.e., influencing the information dissemination rate, vehicles in dangerous situations are allowed to communicate more frequently than others. In essence this approach is enabled by vehicles in normal situations, which still comply to the deployed congestion control mechanism, and hence reduce their dissemination rate in favour of vehicles in dangerous situations. This situation-based rate adaptation achieves an indirect prioritization of messages by individual vehicles and provides a decentralized, self-organizing solution.

The study of this situation-based rate adaptation revealed that it is able to provide frequent updates even if the vehicle density close to an intersection is very high. In addition, we showed that even in inner city scenarios (which are very challenging due to shadowing effects of buildings) it is still able to provide timely updates. Thus, reliable communication can be provided by situation-based rate adaptation in very dense road traffic situations as well as unrealistically crowded communication conditions.

Although we demonstrated the benefits of situation-aware communication only for IAS, the basic concept can be applied to any vehicular safety application if a practical safety metric can be found. Moreover, we studied situation-aware communication only in the context of Dedicated Short-Range Communication (DSRC)-based communication, but it might well be applicable to other communication technologies and concepts. For example in cellular communication networks decisions about broadcasting cooperative awareness information could also be based on the road traffic situation. Furthermore, heterogeneous vehicular networks could use situation-aware decisions to foster communication for vehicular safety applications.

The study on situation-aware communication was based on one-hop communication, which is currently suggested by IVC standards. However, the major drawback of one-hop communication is that it cannot provide situation awareness to vehicles if direct communication between them is obstructed. Several measurement campaigns have shown that direct communication between approaching vehicles might be not available in Non Line of Sight (NLOS) situations at intersections. Therefore, we aimed to improve situation awareness at intersections further by integrating cooperative communication mechanisms.

The two main design goals of the cooperative communication strategy are that it should add minimal communication overhead and it does not depend on costly infrastructure at the intersection (e.g., Roadside Units (RSUs) or Stationary Support Units (SSUs)). The first design goal was achieved by taking the situation into account for the rebroadcast decision, i.e., situation-aware communication, and by integrating a communication check between potentially endangered vehicles. The second goal is accomplished by using a selection algorithm that determines the vehicle, which has the best possible communication conditions, to be in charge of rebroadcasting messages.

During development of a suitable cooperative communication strategy for IAS, we recognized that the implemented mechanisms are not only helpful for increasing situation awareness, but almost allow vehicles to deduce whether the received information is complete. The missing information can be added to the periodic messages of the intersection coordinator. The ability to detect whether IVC is able to provide the full picture or not implies the following on future IAS: IAS will obviously make use of other sensors whenever possible, but if endangering vehicles are not in visual range of each other, IVC might be the only option. When integrating cooperative mechanisms as outlined in our proposal, IAS can rely to 100 % on the information provided by IVC if the communication awareness check reveals that all necessary information has been received. If IVC is not working correctly, IAS need to take appropriate countermeasures.

The analysis of the cooperative communication strategy revealed that the additional communication overhead caused is marginal compared to the one caused by situation-aware communication. By using a situation-based rebroadcast decision we were also able to demonstrate that situation-aware communication is not only beneficial in the context of current IVC strategies, i.e., one-hop broadcasts, but also for cooperative communication strategies.

In the field of cooperative IVC we identified interesting research questions regarding the coordinator selection algorithm. It could be for example refined by integrating multiple communication technologies or considering complex intersection layouts. In addition, there is huge potential to increase situation awareness by cooperative communication also for other vehicular safety applications.

In conclusion, this thesis is a step towards application-tailored communication strategies in the context of vehicular safety applications. In particular, it shows how IVC can be tailored towards the needs of IAS. With the help of cooperative communication, fail-safe IAS are only a stone's throw away from becoming reality. By integrating practicable countermeasures IAS will be able to save human lives and decrease the number of accidents in near future.

List of Acronyms

Acronyms

AC Access Category

ACC Adaptive Cruise Control

ADAS Advanced Driver Assistance System

AIFS Arbitrary Inter-Frame Space

AIMD Additive Increase Multiplicative Decrease

ATB Adaptive Traffic Beacon

BSM Basic Safety Message

BSS Basic Service Set

C2C Car-to-Car

C2I Car-to-Infrastructure

C2X Car-to-X

CAM Cooperative Awareness Message

CCA Clear Channel Assessment

CCH Control Channel

CSMA Carrier Sense Multiple Access

DCC Decentralized Congestion Control

DCF Distributed Coordination Function

DSRC Dedicated Short-Range Communication

DynB Dynamic Beaconing

eCCDF empirical Complementary Cumulative Distribution Function

EDCA Enhanced Distributed Channel Access

IAS Intersection Assistance System

ICM Intersection Coordinator Message

IDM Intelligent-Driver Model

ITS Intelligent Transportation System

ITS-S ITS Station

IVC Inter-Vehicle Communication

LBU Last Before Unavoidable

LOS Line of Sight

MAC Medium Access Control

MANET Mobile Ad Hoc Network

NLOS Non Line of Sight

OFDM Orthogonal Frequency-Division Multiplexing

PRNG Pseudo Random Number Generator

QoS Quality of Service

RSU Roadside Unit

SCH Service Channel

SSU Stationary Support Unit

SUMO Simulation of Urban Mobility

TRC Transmit Rate Control

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

V2X Vehicle-to-X

VANET Vehicular Ad Hoc Network

WAVE Wireless Access in Vehicular Environments

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