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Communication and Networking Techniques for Traffic Safety Systems

by

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Abstract

Accident statistics indicate that every year a significant number of casualties and extensive property losses are recorded due to traffic accidents. Consequently, efforts are directed towards developing passive and active safety systems that help reduce the severity of crashes, or prevent vehicles from colliding with one another. To develop these systems, technologies such as sensor systems, computer vision and vehicular communication have been proposed. Safety vehicular communication is defined as the exchange of data between vehicles with the goal of providing in-vehicle safety systems with enough information to permit detection of traffic dangers. Inter-vehicle communication is a key safety technology, especially as a complement to other technologies such as radar, as the information it provides cannot be gathered in any other way. However, due to the specifics of the traffic environment, the design of efficient safety communication systems poses a series of major technical challenges.

In this thesis we focus on the design and development of a safety communication system that provides support for active safety systems such as collision warning and collision avoidance.

We begin by providing a method for designing the support system for active safety systems. Within our study, we investigate different safety aspects of traffic situations. For performing traffic investigations, we have developed ECAM, a temporal reasoning system for modeling and analyzing accident scenarios.

Next, we focus on the communication system design. We investigate approaches that can be applied to implement safety vehicular communication, as well as design aspects of such systems, including networking techniques and transmission procedures. We then propose a new solution for vehicular communication in the form of a distributed communication protocol that allows the vehicles to organize themselves in virtual clusters according to their common interest in traffic safety. To disseminate the information used for organizing the network and for assessing dangers in traffic, we develop an anonymous context-based broadcast protocol that requires the receivers to determine whether they are the intended destination for sent messages based on knowledge about their current situation in traffic. This communication system is then augmented with a reactive operation mode, where warnings can be issued and forwarded by vehicles. A vehicular communication platform that provides an implementation framework for the communication system, and integrates it within a vehicle, is also proposed. Experiments have been conducted, under various conditions, to test communication performance and the system's ability to reduce accidents. The results indicate that that the proposed communication system is able to provide a reliable and timely exchange of safety information between vehicles.

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My primary thanks are directed to my supervisor, Professor Nahid Shahmehri, for introducing me to research work in the area of vehicular communication and giving me the opportunity of performing the work presented in this thesis. Her support and guidance were always available and were crucial for the outcome of the work.

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Ioan Chisăliță (Nanu)

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Contents

1. Introduction

This introductory chapter presents the motivation behind our work, the formulation of the research problems for which we propose solutions, and our contributions. The chapter also includes an overview of the thesis.

1.1 Motivation

The automobile is arguably one of the most important inventions of the twentieth century [Jon01]. The development of society has been profoundly influenced by the expansion of the road system and the resulting increase in freedom of movement. However, it has always been the case that wherever there are cars, there are traffic accidents. This is not a minor issue: with more than one million people worldwide dying on the roads every year, and billions of US$ in accident-related property losses, traffic safety continues to be a serious and difficult problem [Eva04, CARE04].

The statistics underscore the seriousness of the situation. For instance, although traffic fatalities in the European Union have consistently gone down over the past ten years (see Figure 1.1), there were still more than 42.000 fatalities in the European Union alone in 2004. In addition to loss of life and limb, the financial impact of traffic accidents is enormous: for example, in 2003 the total of accident-related losses reported in the U.S. was more than $230 billion USD [NCSA03].

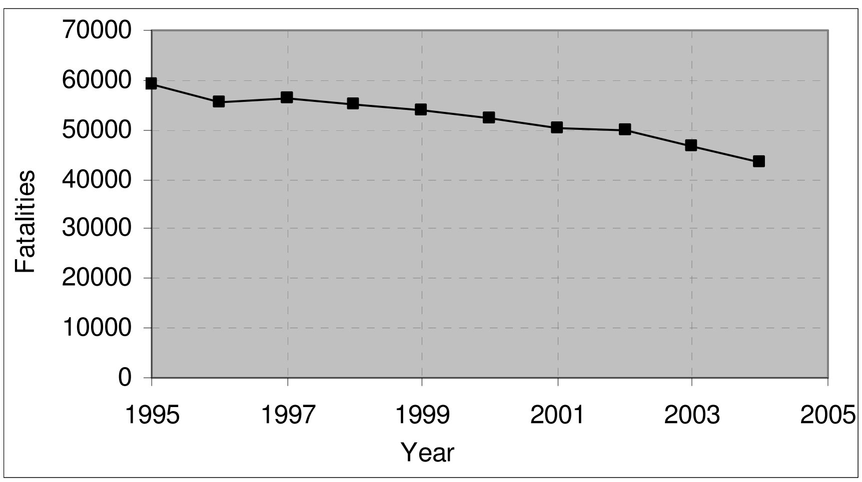

Figure 1.1 EU fatalities 1995-2004
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In an effort to improve traffic safety, extensive investigations into the causes of accidents and crash countermeasures have been conducted over the course of the last decade [USDT99, Bis00, Bre00]. Many of these studies identified driver error as the major cause of crashes (i.e. 90%). Consequently, a great deal of effort has been directed towards helping drivers and reducing operator error. Work has been done both on improvement of the road infrastructure (e.g. using roundabouts at crossroads) and integration of support systems into vehicles. Such in-vehicle systems have great potential for reducing the number of accidents. Thus, research in traffic safety has indicated that reduction rates up to 70% may be possible for particular types of accidents [USDT99, AHR01, MH02]. However, accidents vary tremendously in the way they happen, and developing a system that is efficient in every traffic situation is challenging. For instance, rear-end accidents are defined as situations when a vehicle strikes the rear end of the vehicle situated immediately in front of it. Intersection accidents are defined as angle collisions that occur at crossroads. Lane change accidents are defined as lateral crashes due to the unsafe movement of a vehicle into an adjacent lane. The algorithms used for detecting the possibility of accident are usually dependent on the accident type, and so are the actions that are taken when hazards are detected. Consequently, current prototype systems address only one type of collision, and focus on the most common accidents (e.g. rear-end).

Two main lines of development have been undertaken for safety systems that can be installed in vehicles. The first approach addresses the development of *passive safety systems* that react when dangerous situations happen, and try to reduce the consequences of inevitable accidents. Examples of systems that have already proved their efficiency are anti-lock brakes, pre-tensioned seatbelts, and smart airbags [Bre00, Jon01]. The second approach addresses the development of *active safety systems*, which are intended to prevent vehicles from colliding with each other. If this is not possible due to the specifics of the traffic situation, these systems should at least reduce the consequences of accidents [Jon01]. For instance, in the case of rear-end collisions, active systems should at least assure a reduction of the velocity of the vehicle in back at the moment of impact. Two representative examples of active systems are collision warning and collision avoidance [ECT99]. These systems notify the driver of potential dangers in traffic, and may employ automatic actions such as emergency braking or steering on behalf of the driver [Jon02]. The major difference between passive and active systems lies in the level of support they can provide to drivers. Thus, *passive safety systems* are oriented towards protecting the driver when a dangerous situation is already underway. They are certainly essential for making traffic safer, but due to their reactive mode of operation they cannot provide a high level of improvement in traffic safety on their own [Jon01]. *Active safety systems* take an active role in preventing traffic situations from developing into accidents. They have the ability to predict the possibility that a hazard will happen, and thus are able to act well in advance to avoid its occurrence [Jon01].

Two approaches were considered for developing active safety systems. The first approach addresses the development of *autonomous systems* that collect and analyze information from the local environment of a vehicle [AVN00]. These systems usually employ technologies such as radar (e.g. millimeter-wave or light-based), and machine vision (e.g. video cameras and image processing) for acquiring information about obstacles situated in front of, next to, and behind a vehicle [Pie98, Bis00]. One limitation of systems of this type is that this information may not be accurate enough [KTT+02]. Also, complex traffic situations can require knowledge about vehicles and obstacles that cannot be detected by sensors integrated into autonomous systems [AVN00]. The second approach is the development of *collaborative systems* that employ the wireless exchange of information among vehicles and possibly between vehicles and servers located on the roadside [AF96]. These systems require the development of *vehicular communication networks.* Collaborative systems function similarly to autonomous systems, but they use both data collected by sensors and data received via communication from other vehicles when assessing dangers in traffic. This fusion of information can provide a vehicle with an accurate view of its current situation in traffic [AF96]. Using communication, collaborative systems allow vehicles to acquire information that cannot be provided by sensors such as radar. Therefore, these systems are able to overcome limitations associated with autonomous systems such as their unilateral perception of the environment that surrounds a vehicle [WH98a, AVN00, KTT+02]. Previous research has indicated the potential of collaborative active safety systems for improving traffic safety, e.g. [AF96, WH98a, WH00, Bis00, AVN00, MSN00, AHR01, XHS+02, KTT+02, LO03]. Consequently, vehicular communication is considered one of the key technologies for developing efficient safety systems.

Systems that provide exchange of safety data among vehicles require specific functionality and features that are not provided by ordinary communication systems [AF96, WH98b, BV01]. Also, the adaptation of current communication techniques for supporting traffic safety systems is considered to be impractical [Win96, Per99, AVN00, MKA+00, MIK01, KBS+01].

Collaborative systems are a promising solution for improving traffic safety. For these systems to become a reality, communication systems that can provide efficient exchange of safety data among vehicles must be developed. Therefore, we focus in this thesis on the design of communication and networking techniques for vehicular safety communication.

1.2 Problem description

Key requirements for safety communication among vehicles are low latency, reliability and high throughput. In addition, the vehicular environment has properties that pose very specific requirements on communication. For example, vehicles constantly change their position, travel in areas with different levels of interference, and can join and exit the traffic in a relatively random manner. Additionally, vehicles can travel at high speeds and follow well-defined patterns (i.e. the roads), they usually move with respect to well-defined (traffic) rules, and they perform maneuvers with regard to maneuvers executed by nearby traffic participants.

Simply providing vehicles with a means of communication and letting them communicate without supplying a means of organization would not lead to improvements in traffic safety [CC05]. Such uncoordinated communication cannot fulfill the requirements of safety applications, and cannot guarantee that vehicles will eventually receive the necessary safety information. Furthermore, the bandwidth will rapidly be saturated if vehicles frequently send and relay data in an uncoordinated manner. Even if a number of vehicles receive some data, its relevance could be low. Even worse, the received information could be misleading, which in turn might induce unexpected maneuvers and produce accidents. Additionally, due to the properties of the traffic environment, the communication needs to provide support for highly dynamic management of the links. Forwarding of information must also be implemented, as vehicles that are outside each other's communication range may still need to exchange data. Information filtering is also necessary, as the receivers may not be aware of which vehicles should provide them with safety data. Therefore, organizing the vehicular network and the communication is crucial.

To conclude, network techniques and communication procedures that fulfill the requirements imposed by the vehicular environment and by traffic safety applications must be developed.

1.3 Contributions

This thesis contributes to the area of vehicular communication and networking for traffic safety systems. The main issues addressed are presented below:

- How to organize the vehicles into a network and how to manage this network?
- How to transfer safety data in a timely and reliable manner among vehicles?

We address these issues by proposing two techniques for controlling safety communication among vehicles. First, we propose an organization of vehicles into virtual clusters, which allows for the definition of manageable groups of vehicles. These clusters are defined and maintained according to the vehicles' current interest in traffic safety. Second, we design a context-based protocol for delivering and forwarding data among vehicles. Within this protocol, the vehicles broadcast safety data and the receivers are responsible for determining if they are the intended destination for the data, and if the received data should be forwarded. These operations are performed based on vehicles' knowledge about their situation in traffic.

The detailed contributions of this thesis include:

▪ A method for designing the support system for active safety systems. This contribution includes a set of analyses and a temporal reasoning system for investigating traffic scenarios. The set of analyses includes a requirements analysis, an analysis of the applicability of communication-based safety systems to accident avoidance, an analysis of approaches for developing safety communication systems, and analyses of components of the communication system. The reasoning system helps to investigate the time development of traffic scenarios, and also helps identify requirements for technologies that can be used for avoiding accidents.

▪ A safety-oriented vehicular communication system. This contribution includes techniques for organizing and managing the vehicular network, and a proposed communication protocol that fulfills the requirements imposed by the vehicular environment and traffic safety applications. Finally, a vehicular communication platform, intended to provide a framework for realizing and integrating the communication system within a vehicle, is proposed.

▪ System evaluation under a range of conditions. This contribution includes a dedicated testing environment consisting of traffic simulators and a network simulator. Comprehensive investigations of the performance of the communication system, and the system support for traffic safety systems under various conditions, are presented. The testing environment allows realistic simulations, both from communication and traffic dynamics points of view.

Parts of the work reported in this thesis have been presented in a number of publications: [CS02a], [CS02b], [CS02d], [CS04a], [CS04b], [CSL04], [SCA+04] and [Chi04].

New communication methods have been proposed in [CS06a] and [CS06b]. Considerations regarding the communication system design and analysis have been addressed in [CS06c] and [CS06d].

Related research results have been published in [CS02c], [NAM+04] and [SCA06].

1.4 Thesis outline

The rest of the thesis is organized as follows:

Chapter 2 gives an overview of in-vehicle safety systems and presents a method for designing the support system for safety systems. A reasoning system for modeling and analyzing traffic scenarios is also introduced here.

Chapter 3 presents analyses of communication systems for exchange of safety data among vehicles. A requirement analysis and an analysis of design components of safety communication systems are presented. The design choices that we have made for developing a new system are also introduced in this chapter.

Chapter 4 provides a description of the techniques proposed for organizing and managing the vehicular network, and for exchanging safety data between vehicles. An overview of a vehicular communication platform is also presented.

Chapter 5 presents an evaluation of the proposed communication system. The evaluation goals, method and settings are first introduced. Further on, evaluation results are presented and discussed.

Chapter 6 discusses related work in the area of vehicular communication.

Chapter 7 summarizes the work and presents final remarks. This chapter also includes future research directions.

2. Designing the support system for active safety systems

In this chapter we discuss active safety systems and propose a design method for development of the support system for vehicular safety systems. We introduce the component elements of this method and then propose a modeling system for temporal analysis of traffic scenarios.

2.1 Active safety systems

2.1.1 Background

Active safety systems are intended to proactively prevent vehicles from colliding with each other or with other objects. They collect and analyze information extracted from the environment surrounding a vehicle to identify dangers in traffic [Bis00, AVN00]. These systems are designed to provide assistance to the driver for better completion of driving tasks. They also contribute to the increase of the driver's situational awareness by providing information about traffic situations. Active safety systems act towards avoiding accidents by alerting the driver to a potential danger, and might eventually employ automatic actions such as emergency braking or steering. An example of early active safety systems is the Adaptive Cruise Control (ACC) system that uses radar sensors to help drivers maintain a safe distance between vehicles [Jon01]. Active safety systems can also be connected with passive safety systems. Examples include systems that offer support to passive systems by anticipating an imminent collision using radar technology. Based on this data, the passive systems (e.g. seat belt, airbag) can be activated in advance, which can lead to a reduction of the severity of injuries that the vehicle's occupants may suffer. An example of such passive-active system is the Toyota Pre-crash Safety System [Toy02].

The proposals for active safety systems can be categorized according to the type of support provided to the driver as [Jon02]:

- *Information delivery systems*: control the content and the presentation of notifications. These systems present the driver with information that can increase his/her situation awareness and let the driver take the appropriate measures.
- *Automatic control systems:* delegate driving tasks to the driver and to the vehicle. These systems aim at providing more support to the driver by employing automatic actions on the part of the vehicle. However, attention needs to be given to the transfer of tasks from humans to vehicles, since unknown problems may arise.

2.1.2 Technologies for developing active safety systems

Many research areas such as sensors, kinematics, positioning, information systems, and communication networks can contribute to the development of efficient active safety systems. We discuss in the following three technologies that were considered the most promising for implementing safety systems: radar and laser sensor systems, computer vision, and communication systems [Jon01].

Sensor systems

Since the ultimate goal of active safety systems is to keep vehicles from colliding with each other and with other objects, vehicles can be equipped with devices that can identify the presence of nearby obstacles. Such devices are usually radar sensors or lidar sensors (i.e. sensors based on laser) that can detect obstacles that exist around a vehicle and may interfere with its traveling path [Bre00, Jon01]. Standard radar systems use sensors that send narrow microwave beams that are reflected by objects and received back by the radar system [Wol95]. Based on this information, the relative position and speed of other objects can be determined. Lidar systems use light beams for the same purpose.

The major limitation associated with sensor systems is their local perception [AVN00]. This is due to the fact that sensor systems usually require a line-of-sight (LOS) for object detection [MH02]. They cannot detect distant or hidden objects (i.e. objects that are not in the LOS), and therefore may not be able to provide information about more complex traffic situations.

Several other problems arise with the utilization of sensor systems, both with regard to their operation modes and the state of the art of the technology. For example, lidar sensors are considered less appropriate because rain and snow affect their functionality. The accumulation of dust and mud may even make them unusable [Jon01]. Issues such as cost, sensor integration within vehicles (i.e. this may require modification of the car body), and regulatory aspects addressing frequency spectrum also need to be considered when developing sensors for vehicles. For instance, radar systems on 76 -77 GHz, which were initially used in adaptive cruise control systems, are currently considered less appropriate due to their high cost. Consequently, proposals for new radar systems on 24 GHz have been made [IST02]. However, due to their smaller operation range, radar systems on 24 GHz may not be so effective in cases that require the detection of more distant obstacles.

Computer vision

Another technology that has been considered for improving traffic safety is computer vision. One important safety application addresses collision avoidance where vehicles use vision to detect obstacles such as pedestrians and other vehicles that may interfere with the traveling path of a vehicle [FH02a]. Another important type of application using computer vision addresses the monitoring of vehicle movement based on elements characteristic to roads, such as lane markers [NSG+04, NDM+05]. In these applications, stereo cameras are used to monitor the environment around a vehicle and image processing is employed to determine the occurrence of dangerous situations, such as when a vehicle approaches the lateral side of a road unsafely [CAC02]. These systems then alert the driver to such situations.

However, as with the utilization of sensor systems, limitations related to the local perception of vehicles (e.g. LOS object detection and monitoring) can also apply to active safety systems based on computer vision.

We note that computer vision can also be used to monitor driver condition. In such an application, video cameras analyze the driver by monitoring behavior-related features such as eye movement. This gives indications about the driver's capacity for paying attention to road conditions and successfully fulfilling driving tasks. An application that has received much attention is the determination of the state of drowsiness of a driver [USDT99, HMS+02].

Vehicular communication systems

Relying on data from local sensors is an inherent weakness of active safety systems based on sensors and computer vision. Local sensors have limited utility in detecting objects that are not in the line of sight, such as vehicles entering an intersection [MH02]. One solution to these limitations is to equip vehicles with communication capabilities, allowing the exchange of traffic safety information. Using communication, a vehicle can then obtain data about vehicles that are not detected by sensors (e.g. radar) or by computer vision systems. Consequently, the information gathering ability of a vehicle is extended. Considering this advantage, it was predicted that vehicular communication would have a major impact on the development of active safety systems that could effectively reduce the number and severity of crashes [AF96, Jon01]. Additionally, it was envisioned that a variety of safety services, such as collision warning, collision avoidance, or traffic jam notifications could be provided to the driver when vehicles have communication capabilities [WH98a, AVN00, MSN00, KBS+01, AMF+02].

We note that communication networks for vehicles can be formed only by vehicles, or by vehicles and servers located on the roadside. Thus, two types of vehicular communication were defined [MKO00]:

- *Vehicle-to-Road Communication (VRC):* exchange of data between vehicles and communication servers located on the roadside. Even if data needs to be exchanged between two vehicles, this is performed via a roadside server (fig 2.1).
- *Inter-Vehicle Communication (IVC):* direct exchange of data between vehicles (fig 2.2).

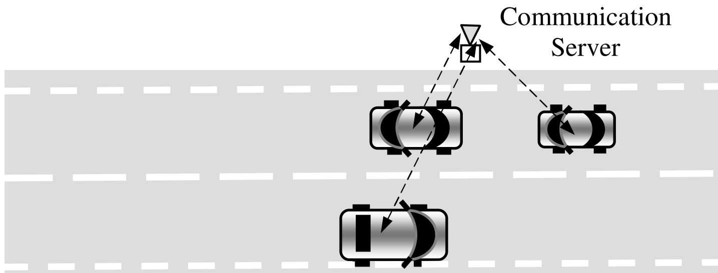


Figure 2.1 Vehicle-to-Road Communication example

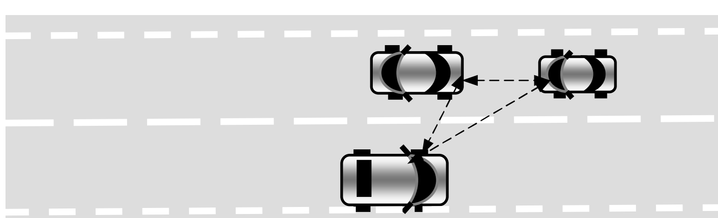


Figure 2.2 Inter -Vehicle Communication example

2.1.3 Collaborative active safety systems

The concept of collaborative safety communication is illustrated in figure 2.3. We use an example with two vehicles, the concept being similar when more vehicles interact with one another. The collaborative active safety systems contain a communication system for data exchange between vehicles, a traffic database (i.e. the Traffic Data component), a knowledge base for traffic scenarios patterns (i.e. the Traffic Scenario Knowledge component), and a processing unit.

The communication system is used to exchange safety information such as front-end data characterizing vehicles (e.g. velocity, position, heading), and data describing the road (e.g. slipperiness coefficient). This information is registered in the traffic database.

The knowledge base for traffic scenarios contains patterns of potential accidents, which are used to detect the occurrence of dangerous situations in traffic. This information is quasi-static and may need to be updated. This can be done statically, e.g. during regular vehicle check-ups, or dynamically, e.g. using a vehicular communication system.

The processing unit uses the collected data and the traffic knowledge to assess whether threats might occur in traffic. If a threat is detected, the system can perform actions such as giving a notification to the driver or initiating an automatic maneuver such as emergency braking [MH02, KFC+03].

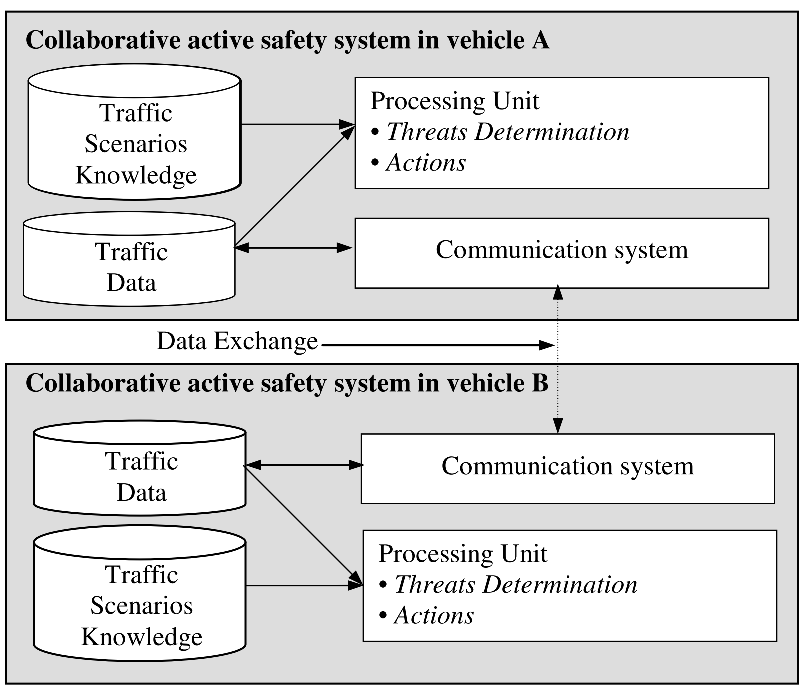


Figure 2.3 Collaborative communication concept

2.2 Design method for realizing the support system

This section introduces a generic design method that we propose to realize the support systems for active safety systems. This method focuses on the important aspects of supporting a vehicular safety system, which leads to an in-depth design of the support system. The designer is thus able to specify the relevant set of requirements, identify appropriate solutions for the system components, and analyze limitations of the system. In this thesis the method was applied when designing the communication system that is part of a collaborative safety system.

Figure 2.4 provides a graphic representation of the components that we identified as essential to analyze, and how the results of the analyses were used.

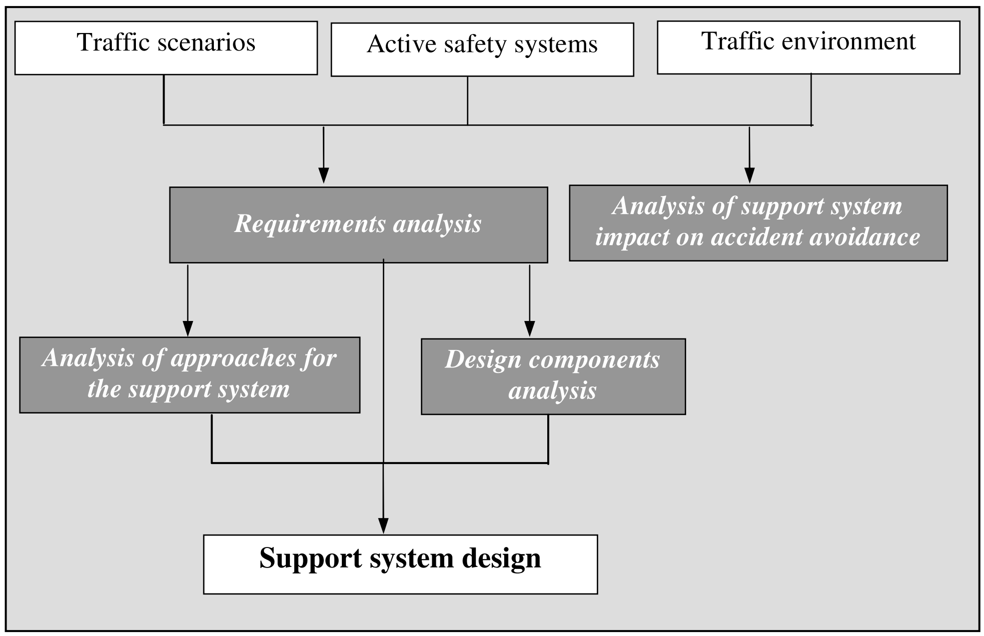


Figure 2.4 Design method

We analyzed traffic scenarios to determine accident dynamics and identify when dangerous situations might occur. The accidents patterns that we addressed here are similar to those that should be recorded in the component Traffic Scenarios Knowledge of collaborative active safety systems (i.e. in figure 2.3). Requirements on exchange of traffic data (i.e. data registered within the Traffic Data component) such as delivery latency, information content and size were derived from these analyses. The spatial and temporal relevance of data were also investigated, e.g. the set of vehicles that have data of interest for a subject vehicle, or when relevant information needs to be provided to a vehicle to increase the odds of avoiding a collision. We further investigated how accidents could be avoided by applying specific actions in traffic, and we also evaluated whether an active safety system using communication can be used to induce these actions. To perform these analyses we developed a temporal reasoning system that allows investigation of the time development of traffic scenarios and the effect of inter-vehicular communication on accident avoidance. This system is presented in the last section of this chapter.

The vehicular environment imposes certain unique constraints on the reliable exchange of safety information. We defined requirements specific to this environment for data exchange between vehicles and for network management. Examples of these requirements include information dissemination latency, service area size, and frequency of providing traffic data.

The next aspect that we focused on was the operation mode of active safety systems. We used currently proposed systems for defining a general set of requirements and analyzed how they applied to systems using communication. Generic requirements such as on system availability, data exchange properties (e.g. reliability, latency) and communication cost were then defined.

We underline that the requirements on vehicular communication derived from our analyses addressed not only communication performance (e.g. data rate, latency), but also functional aspects (e.g. service area, system availability), and economic aspects (e.g. operation and deployment costs). These requirements were used to assess the applicability of current communication approaches to develop a safety communication system. Systems based on satellite networks, cellular networks, infotainment infrastructures deployed on the roadside and systems using direct data exchange were investigated. The requirements were also used to analyze design components of communication systems such as operation modes, networking techniques or data transmission procedures. Based on these analyses, we have selected several features to be integrated within a proposal for a safety communication system.

We note that the proposed design method can help realize other support systems for active safety systems, e.g. radar systems. In these cases, the analyses need to be changed or extended, but some of the results presented here can be reused.

In the following, we introduce the reasoning system developed for traffic scenarios analyses. Details on the other analyses defined within the design method are presented in the following chapters.

2.3 Accident modeling and vehicular communication

The analysis of accidents helps in identifying elements that affect traffic conditions, the relations between these elements, and how they may contribute to the occurrence of dangerous situations [NSS+03]. Based on the results of such analyses, more efficient crash countermeasures can be developed. Descriptions of accidents are usually provided in the form of official reports compiled by public safety agencies such as the police. Enhanced versions of such reports, where the information is reorganized, are provided for research purposes by governmental organizations such as the U.S. National Highway Transport Administration [USC05]. Such official reports usually contain detailed descriptions of accidents and include narratives and sketches of accidents. They also include information about the consequences of crashes in terms of injuries and property damage. Usually, the reports also include characteristics of the involved vehicles (e.g. size, airbag status, type of brake) and the description of pre-crash environmental and driver-related data (e.g. roadway profile, driver distraction). Although these reports are extensively used for statistically describing traffic aspects, they can be difficult to use for deriving causal relations that provide indications about how an accident occurred, and what actions can be taken to avoid it [MST01, USC03]. This method of describing accidents is also static, and allows only a limited investigation of the patterns related to the dynamics of crashes. Consequently, there is a need for organizing and dynamically analyzing the information contained by the above-mentioned reports. Thus, it is necessary to develop a means for identifying preconditions that describe how a traffic situation develops into an accident [USDT99, IST02, NSS+03]. It is also important to be able to investigate what data should be provided to safety systems located in vehicles for these to efficiently act to avoid possible collisions. Furthermore, it should be possible to investigate when and how this information should be delivered [KLP+99, TCE+00, PAO01, MH02].

One way to dynamically analyze accidents is the simulation of scenarios using classical traffic simulators. Examples of simulators that integrate advanced vehicle dynamics and driving behaviors are presented in [SBH97, RO99, ER01]. However, high-performance simulators are usually not accessible for public use. Common open-source simulators have several drawbacks that make their utilization less appealing. First, many of them are difficult to modify and are resource extensive. Other simulators include algorithms that cannot represent exactly the states within time-developing situations, such as in specific accidents. For example, some of these simulators work with fixed time steps for updates (e.g. typically 1-second intervals) [BBA98]. Several event-based simulators are also available for use [BBA98]. However, those that we tried to employ (e.g. SIMNET and FLEXSIT-II) were dedicated to other types of analyses, and could not be easily adapted for studying traffic scenarios involving crashes.

Considering the difficulties above, we decided to use formal logic to create an easy-to-use and efficient reasoning system that can integrate elements given in official reports of accidents. This system was designed to perform dynamical accident analyses for identifying relationships that are of particular interest in developing safety systems. The modeling of accidents using a formal logic also provides the possibility of formal verifications.

2.3.1 ECAM - Event Calculus for Accident Modeling

Selected formalism

The sequence of traffic-related events, the relationships between them, and the relationships between consecutive traffic situations determine if a collision takes place or not. Therefore, a formal system for modeling traffic scenarios needs to offer the possibility of specifying relations between traffic situations and actions that occur in traffic (e.g. driving maneuvers). The formalism used by such a system should then allow temporal reasoning about situations and changes. It should also allow the representation of preconditions for events to happen, the specification of when they happen and how they affect a traffic situation. Since events can occur simultaneously, concurrency should be considered. A formal system for modeling accidents should also be able to model a wide variety of aspects and conditions related to traffic situations.

Given these requirements, we selected Event Calculus (EC) [KS86, Sha99] as the logic for our reasoning system. Event Calculus is a logical framework for temporal reasoning about situations, events, and changes that has the capacity to model event-based systems with time-specific behavior [CM00, EFD+02]. The time development of traffic situations under certain conditions can be seen as such a system. Event Calculus allows the easy specification of time relations between situations and events, which is essential for describing traffic accidents. Furthermore, the development of accidents is driven by events, and Event Calculus integrates by default the eventing mechanism. The specification of concurrent actions is also possible. Event Calculus is also general enough to specify any type of event-based system [CM00].

Event Calculus has been successfully applied for developing systems in diverse applications areas. An example is the use of Event Calculus for specifying a patient monitoring system [CMD+94]. Systems for defining policies for adaptive mobile communication systems [EFD+02], and systems for policy analyses were also proposed [BLR03]. Event Calculus was also used for system description and control [CM00, CBC01]. However, the systems presented in these works were strongly dependent on the specific application area. For instance, the system in [CM00] describes the operation of a gas heater by modeling its components and possible states (e.g. *lighter*, *warm up* state). Consequently, we could not adapt previous systems for modeling accidents.

Other logical formalisms can be considered for developing systems similar to the one proposed by us. An example is the Situation Calculus that allows reasoning about actions and their effects on the world [RN95, PR99b]. However, this formalism specifies a sequential occurrence of actions and does not allow the specification of the moment when an action takes place or the specification of the development of a situation under concurrent actions [McC02]. In the development of a collision, the time when a certain event occurred is important. Also, numerous events may take place at the same time. Therefore, formalisms such as Situation Calculus did not serve our purpose well enough. The logic framework of Features and Fluents, proposed in [San94] could also be the basis for constructing a system for modeling and analyzing accident scenarios. For instance, such a system may be constructed using the Fluent Calculus [Bra98] that was developed using the above-mentioned framework. The formalism specified in the Features and Fluents framework is similar in many aspects to Event Calculus [Bra98, Sha99]. However, it provides a representation of continuous changes that is more complex than in Event Calculus [Sha95]. Since we aimed at constructing an easy-to-use system for modeling and analyzing accident scenarios, we decided to base the development of the system on Event Calculus. The use of a formalism based on the Features and Fluents framework can be subject to future investigations.

Event Calculus entities

We introduce below the entities defined within the specifications of Event Calculus (based on [Sha99]):

- *Events*: actions that occur at a moment in time or during a time interval.
- *Fluents*: entities that modify their state as the result of the occurrence of actions. Examples are the value of a quantity such as the velocity of a vehicle, or a proposition such as "vehicle **x** is braking". The modification of the state of a fluent is due to events. Thus, a fluent has time duration and is *initiated* and *terminated* by events. A fluent holds when it is true (e.g. a

proposition is correct). A fluent does not hold at the time the event that initiates it happens, but holds at the time the event that terminates it happens.

- *Predicates*: entities that specify when events take place or indicate the state of fluents at different time points. Event Calculus provides a basic set of predicates and allows the definition of new predicates.
- *Constraints (state constraints, effect constraints,* and *causal constraints):* entities that define, using predicates, diverse relations between fluents, and between fluents and events. For example, the occurrence of two events at the same time that determines a modification of the state of a fluent can be described using constraints.

ECAM – a modeling system based on Event Calculus

The reasoning system

The reasoning system that we propose for describing and analyzing traffic scenarios provides an Event Calculus-based logical framework for time-developing situations. The set of predicates and domain independent axioms provided by Event Calculus that we used in our work are presented in figure 2.5. Throughout this chapter, we use ∧, ∨, ¬ for *And*, *Or* and *Negation*. Notations such as **=, <, >, +, -, *** and **/** denote equality, inequality, and calculus relations.

Predicates:

- *InitiallyP(f)* – fluent **f** holds from time 0 (i.e. the initial moment).
- *Happens (e ,t)* – event **e** occurs at time **t**.
- *Initiates (e, f, t)* – fluent **f** is initiated by event **e** at time **t** and starts to hold immediately after **t**.
- *Terminates (e, f, t)* – fluent **f** is terminated at time **t** by event **e** and ceases to hold immediately after **t**.
- *t1<t2* – time point **t1** is before time point **t2** (temporal order).
- *HoldsAt (f, t)* – fluent **f** holds at time **t**.
- *Clipped (t1,f,t2)* – fluent **f** is terminated at some time **t** between times **t1** and **t2**, where t1<t<t2.
- *Trajectory (f1,t1,f2,dt)* – if fluent **f1** is initiated at time **t1**, then fluent **f2** becomes true at time **t1+dt**.

Axioms:

- *HoldsAt (f, t1)* <- InitiallyP(f) ∧ ¬Clipped (0, f, t1).
- *HoldsAt (f, t2)* <- Happens (e, t1) ∧ Initiates(e, f, t1) ∧t1<t2 ∧ ¬Clipped (t1, f, t2).
- *HoldsAt (f2, t2)* <- Happens(e, t1) ∧ Initiates(e, f1, t1) ∧ t1 < t2 ∧ t2 = t1 + d ∧ Trajectory (f1, t1, f2, d) ∧ ¬ Clipped (t1, f1, t2).
- *Clipped (t1, f, t2)* <- Happens(e, t) ∧ t1<t<t2 ∧ Terminates(e,f, t).

Figure 2.5 ECAM - Predicates and Axioms

We should mention that the original specifications of Event Calculus (e.g. [KS86]) are able to provide only a discrete representation of changes. Therefore, in our work we have used the extension of Event Calculus proposed by Shanahan [Sha90, Sha99]. This provides the possibility of representing not only discrete, but also continuous changes, such as the variation of the speed of a vehicle. Thus, in our approach the varying entities (e.g. speed, acceleration, distances) take values from a one-dimensional quantity space (e.g. speed can take values from 0 to 200 km/h), and they are quantitatively represented when modeling traffic scenarios.

The system that we developed is called ECAM, which stands for **E**vent **C**alculus for **A**ccident **M**odeling. This reasoning system inherits the properties presented by Event Calculus and provides a convenient way of analyzing a wide variety of elements from traffic scenarios. By using Event Calculus, ECAM is able to represent the relations between different elements of a traffic scenario, and is able to model the changes that take place when events happen in a traffic situation. Also, ECAM is able to accommodate the description of various accident types. Event Calculus allows the determination of the validity of fluents, the determination of the occurrence of events, and the determination of the moments in time when events occurred [Sha99, EFD+02]. Consequently, ECAM can be used to determine if certain traffic conditions related to vehicles involved in a traffic scenario are valid at some moments in time. ECAM can be also used to determine whether and when certain events occurred within the development of a scenario. For example, it can be determined if a collision between two vehicles took place and when the crash occurred. ECAM can be used to investigate the impact of certain actions on the development of scenario. For instance, it can be examined whether an action (e.g. braking) can lead to the avoidance of an accident, and when such action needs to take place. We present below the conceptual model of ECAM and an overview of a logic programming implementation of the system. In the following sections, we illustrate the utilization of the system for modeling and analyzing accident scenarios. ECAM is represented in figure 2.6 and contains three components:

- ***K**nowledge **B**ase for **E**vent **C**alculus (KBEC):* contains the elements that describe the Event Calculus formalism and its logic. These are the concepts of events, fluents, predicates, and constraints, the basic set of predicates and the domain independent axioms.
- ***W**orld **R**epresentation (WR):* contains the fluents and events used for describing the time development of the scenario under consideration. It also contains the constraints that define specific relations between fluents and events.
- ***T**emporal **E**volution of the **S**cenario (TES):* contains the initial status (i.e. at the moment the scenario begins) of various fluents encoded using InitiallyP predicates. It also contains the time-ordered sequence of explicit events in the scenario (i.e. events with the exact moment of occurrence specified beforehand), encoded using Happens predicates.

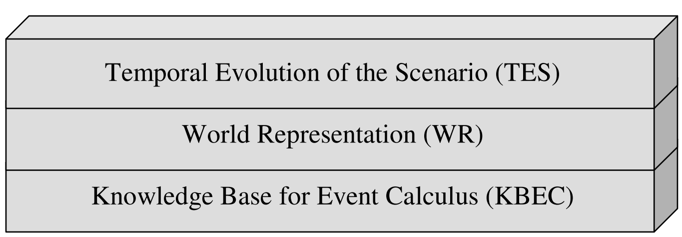


Figure 2.6 Conceptual architecture of the ECAM system

The initial description of traffic scenarios is usually given using natural language. We provide below a step-based method for modeling the development of such scenarios using ECAM:

Step 1. Complete the initial description of the scenario with elements needed for dynamic modeling. For instance, the kinematic equations used for describing the movement of vehicles, or specific assumptions such as the driver reaction time, need to be specified.

Step 2. Translate the scenario description into ECAM elements. This implies the definition of fluents and events of importance for describing the scenario and for performing analyses.

Step 3. Define the initiation and termination map of fluents, i.e. define which events start and terminate which fluents.

Step 4. Define constraints describing specific relations between events and fluents.

Step 5. Define the narrative of the scenario in terms of initial conditions and the time-ordered sequence of explicit events.

Step 6. Create an implementation of the model and perform analyses of interest.

An overview of a logic programming implementation of ECAM

We present below an overview of a Prolog [Bra01] implementation of the ECAM system. We implemented ECAM using Prolog because this language constitutes a flexible programming framework that allows the easy specification of relations between objects. Prolog also integrates a powerful reasoning mechanism about such relations. We note that most of the other programming languages (e.g. C) do not provide such a mechanism, which needs to be developed if such languages are used for implementing ECAM. Moreover, Prolog provides a highly expressive declarative style of programming, which is an advantage for representing the relations between the component elements of traffic scenarios.

We note that for modeling accident scenarios we considered that all the required information is present in the system and no intervention from the outside world is possible (i.e. closed world assumption). Thus, if the validity of an entity in the model (e.g. a fluent) could not be proven, it was considered not to hold. We should mention that we were interested in when conditions related to traffic, such as if a vehicle is braking or the value of the speed of a vehicle, are valid at different points in time.

The Event Calculus predicates were represented as Prolog predicates. Within this implementation, we kept the original Event Calculus predicates with the exception of the *Initiates* and *Terminates* predicates. These were encoded as *Init* and *Initiate* and respectively *Term* and *Terminate* (i.e. as proposed in [CM00]), where the events, fluents and time moments were separated. This separation simplifies the definition of the relations between fluents and the events that initiate and terminate them. The fluents and events used for describing traffic scenarios were represented as Prolog data objects. The set of Prolog predicates that we used in our implementation is presented in Figure 2.7. The Prolog predicates *holdsAt*, *initiate*, *terminate,* and *clipped* were defined in a common way as presented in Figure 2.8. Predicates such as *happens* and *initiallyP* were used to implement the time development of the scenario under consideration. We note that predicates such as *trajectory* or *holdsAt* may be subject to specific definitions for certain fluents and events in different scenarios. These additional definitions are needed to implement the constraints that define specific relations between fluents and events within the modeling of the scenario. New predicates may be also needed to implement aspects related to a scenario. Such additional predicates are usually support functions used for various calculations (e.g. speed of vehicles, distance between vehicles, various timers).

Prolog predicates:

happens (E, T): event E occurs at time T.

initiallyP (F): fluent F holds from time T=0 (i.e. initial moment).

init (E, F): event E starts fluent F.

initiate (F, T): fluent F is initiated at time T.

term (E, F): event E terminates fluent F.

terminate (F, T): fluent F is terminated at time T.

clipped (F, [T1, T2]): fluent F is clipped within the time interval [T1,T2].

holdsAt (F, T): fluent F holds at time T.

trajectory (F1, T1, F2, DT): if fluent F1 is initiated at time T1, then fluent F2 starts to hold at time T1+DT.

Figure 2.7 Prolog predicates

holdsAt predicate:

```
holdsAt(F, T):-     initiallyP(F), \+clipped(F,[0,T]).
holdsAt(F, T2):-    initiate(F, T1), T1 < T2, \+clipped(F, [T1, T2]).
holdsAt(F2, T2):-   happens(E,T1), init(E,F1), T1<T2, D is T2-T1, trajectory(F1, T1, F2, D),
                      \+clipped(F1,[T1,T2]).
```

initiate, terminate and clipped predicates:

```
initiate(F, T):- init(E, F), happens(E, T).
terminate(F, T):- term(E, F), happens(E, T).
clipped(F, [T1, T2]):-  terminate(F, T), T1 < T, T < T2.
```

Figure 2.8 Common definitions for Prolog predicates

The advantages of the Prolog programming language recommended it for implementing the ECAM system. Also, this implementation preserves the characteristics provided by ECAM. However, several limitations apply when using Prolog. Thus, it may be possible that some of the clauses defined within the accident modeling cannot be directly implemented due to the occurrence of infinite loops in Prolog [Sha90]. Such relations need then to be modified in order to be implemented, which can limit the flexibility of representing the results of the occurrence of events on fluents for specific traffic scenarios. We illustrate this type of problem and present a solution to it when discussing the implementation of a case study in the next section. For scenarios where such modifications should not be made because they unrealistically alter the time development of the traffic situation or make it difficult to perform analyses, we see the use of constraint logic programming (CLP) as a possibility for overcoming some of the limitations imposed by the Prolog implementation. Finally, we should note that the ECAM implementation in Prolog may be complex for scenarios that involve a large number of vehicles or a large number of relations between the component elements of the considered scenario.

2.3.2 ECAM – case study

We have modeled and analyzed various accident scenarios using the ECAM system. These scenarios were selected from the most representative types of accidents, i.e. the accidents that appear most frequently in traffic (e.g. [USDT99, SITC01]). These types of accidents were:

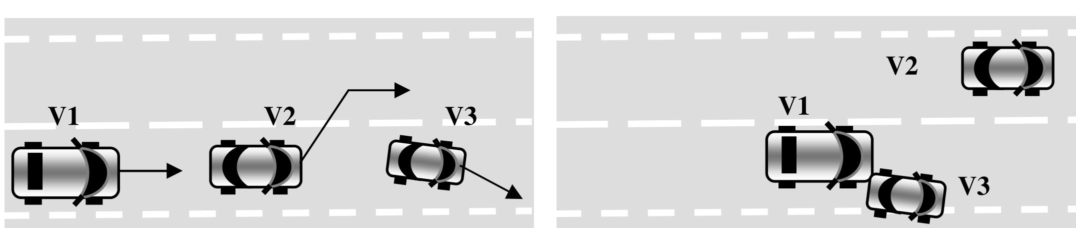
- *Rear-end accidents,* e.g. crashes implying a vehicle driven by an inattentive or distracted driver that strikes the rear end of another vehicle.
- *Intersection accidents,* e.g. angle crashes at cross-roads due to vehicles that run "stop" or "give way" signs.
- *Lane change accidents,* e.g. crashes due to a change lane maneuver executed by a vehicle that does not notice the presence of another vehicle in the lane it moves into.

When modeling accidents with ECAM we used the descriptions of collisions given in research addressing crash analyses (e.g. [KLP+99, NSS01, MH02, SSN03, KCF+03]). We illustrate in the following the development of the ECAM system by the use of an example. Thus, we model and analyze a rear-end accident scenario.

View obstruction followed by tailgate scenario (VOTS)

VOTS - Scenario Description (Step 1)

In the following we provide an example of the use of ECAM for modeling an accident scenario classified as rear-end. This scenario can be categorized as view obstruction followed by tailgate (VOTS) [KLP+99]. The scenario involves 3 vehicles, V1, V2, and V3 as presented in Figure 2.9. The development of events is as follows. At time t0 the vehicles follow each other at a distance considered safe, as presented in Figure 2.9 a. Vehicle V1 is considered not to be aware of V3 since its view is blocked by vehicle V2. At some time t1 vehicle V3 suffers a breakdown and starts to pull over. At time t2 after t1, V2 realizes the problem facing V3 and executes an evasive maneuver to avoid V3 (indicated by the arrow in Figure 2.9.a). This maneuver is considered successful. At time t3 after this maneuver, V1 starts to realize the situation of V3 and tries to execute an emergency braking. Due to the short separation distance between V1 and V3, the maneuver is unsuccessful and V1 collides with V3 (Figure 2.9 b). We note that we also modeled the same type of accident on a bi-directional road with two lanes per direction, where a larger number of vehicles were present on the road (i.e. 25). However, for simplicity we offer here the basic version of the scenario.



a. Initial situation b. Accident situation

Figure 2.9 View obstruction followed by tailgate scenario (VOTS)

The modification of the speed and acceleration of vehicles is due to driving maneuvers such as braking, pulling over, or acceleration. In this scenario, average values were considered for acceleration between events that determined significant modifications. The motion equations that define the movement of the vehicles are presented below. In all formulas, the distance is expressed in [m], the speed in [m/s] and the acceleration and deceleration in [m/s^2]. Negative values were used for deceleration.

We considered that the separation distance between two vehicles **x** and **y**, when **x** follows **y**, is safe when it is higher than a threshold **R** calculated based on the characteristics of the two vehicles [KCF+03]. Thus, **R** is calculated as the sum of the delay time range (DTR) and the braking on set range (BOR) as presented below (adapted from [KCF+03]).

[ECS1.0] R= DTR + BOR. DTR and BOR are calculated as:

DTR = (Vx-Vy)*t_delay+0.5*(Ax-Ay)*t_delay^2

$$BOR = \frac{(Vxp\text{-}Vyp)^2}{-2*(Axr\text{-}Ayr)}$$

In the equations above, *Vx* and *Vy* are the speed values, and *Ax* and *Ay* are the acceleration or deceleration values of vehicles **x** and **y**. The time interval *t_delay* is the sum of the reaction time of the driver and the braking systems lag. The reaction time of the driver is the interval between the moment the driver notices an event in traffic and the moment the driver acts accordingly. The braking system lag is the time between the application of the brake (pedal) and the application of the brakes (shoes) on the wheel. *Vxp* and *Vyp* are the predicted velocity values for vehicles **x** and **y** after the delay time *t_delay* has passed. *Ayr* is the deceleration of **y** and *Axr* is an approximation of the expected deceleration of **x**. We note that within the modeling of the scenario we calculated the predicted safe distance when the reaction delay time has passed (i.e. DTR is null), and we used a value of -9 m/s^2 for the emergency braking deceleration of a vehicle (i.e. *Axr*).

The calculations of speed values and separation distance between two vehicles are based on classical kinematic equations (e.g. [Phy03]). Thus, for a vehicle traveling with a constant acceleration *A* between time points t1 and t2, the speed at t2 is calculated as:

[ECS1.1] V2 = V1+ A*(t2-t1),

V1 and V2 are the speed values of the vehicle at times t1 and t2 respectively. If the distance between two vehicles **x** and **y** at time t1 is D1 and **x** is traveling with acceleration Ax and **y** with acceleration Ay between t1 and t2, then at time t2 the distance between **x** and **y** is:

[ECS1.2] D2 = D1 – AuxDx + AuxDy, where AuxDx = (Vx*DT)+0.5*(DT^2*Ax) and AuxDy = (Vy*DT)+0.5*(DT^2*Ay) with DT =t2-t1.

VOTS - ECAM fluents and events (Step 2)

The set of fluents and events used for modeling the VOTS scenario is presented in Figure 2.10. We note that this set was also intended to provide the possibility of modeling other rear-end accidents related to VOTS. In our definitions, we used the constants NBD for Normal Braking Deceleration (i.e. - 4 m/s^2) and EBD for Emergency Braking Deceleration (i.e. -9 m/s^2). We used the variables *ax* and v*x* to identify the values of the acceleration and velocity of a vehicle, and the variable *d* to identify the separation distance between two vehicles.

VOTS Fluents:
Vehicle (v): existence of vehicle **v** in the scenario.
Road (r): existence of road **r** in the scenario.
Stopping (x): vehicle **x** is reducing its speed after a pull over maneuver.
Stopped (x): vehicle **x** is stopped.
Know_About (x, y): the driver in vehicle **x** is aware of vehicle **y**.
Heavy_Braking (x): vehicle **x** executes an emergency braking (i.e. the deceleration is 9 m/s^2).
Following (x, y): vehicle **x** is following vehicle **y**.
Approaching (x, y): vehicle **x** is approaching **y** (i.e. **x** is behind **y** and reduces the distance to **y**).
Collision (x, y): vehicle **x** has collided with **y.**
Safe_Distance (x, y): vehicle **x** is following **y** at a safe distance, i.e. the braking distance of **x** is bigger than the current separation distance between **x** and **y**.
Speed (x, vx): speed **vx** of vehicle **x**.
Acceleration (x, ax): acceleration **ax** of vehicle **x**.
Distance (x, y ,d): separation distance **d** between vehicle **x** and **y**.

VOTS events:
Pull_Over (x): vehicle **x** starts to pull over and brakes moderately, i.e. the deceleration becomes Normal Braking Deceleration (NBD) = - 4m/s^2.
Brake_Heavily(x): vehicle **x** starts to execute an emergency braking, i.e. the deceleration becomes Emergency Braking Deceleration (EBD) = - 9 m/s^2.
Unsafe_Separation (x, y): the separation distance between vehicles **x** and **y** begins to be unsafe.
Get_Safe (x, y): the separation distance between vehicles **x** and **y** becomes safe.
Zero_Separation (x, y): the separation distance between vehicles **x** and **y** becomes zero (meters).
Acknowledge (x, y): the driver in vehicle **x** begins to have information about vehicle **y**.
Out_of_Attention (x, y): the driver in vehicle **x** ceases to have information about vehicle **y**.
Realize_Danger (x): the driver in vehicle **x** recognizes an imminent danger.
Approach (x, y): vehicle **x** is currently following vehicle **y** and starts approaching it.
Move_Away (x, y): vehicle **x** currently follows vehicle **y**, and **y** begins to increase its separation distance to **x**.
Follow (x, y): vehicle **x** starts following vehicle **y**.
Stop(x): vehicle **x** stops.
Sudden_Steer (x): vehicle **x** executes a sudden steering maneuver.
Start_Scenario: the scenario description is started.
Stop_Scenario: the scenario description is ended.

Figure 2.10 Fluents and events for VOTS

VOTS - Initiation and termination maps for fluents (Step 3)

The initiation and termination maps for fluents (i.e. which events initiate and terminate which fluents) are presented in the following. We note that these maps are characteristic to the scenario represented here, and if other analyses need to be performed, further relations between the elements of the model can be easily defined.

Fluent Heavy_Braking.

Initiates (Brake_Heavily (x), Heavy_Braking (x), t).

Fluent Stopped.

Initiates (Stop(x), Stopped(x), t).

Fluent Stopping.

Initiates (Pull_Over (x), Stopping (x), t).

Fluent Approaching.

Initiates (Approach (x, y), Approaching (x, y), t).
Terminates (Move_Away (x, y), Approaching(x,y), t).

Fluent Know_About.

Initiates (Acknowledge (x, y), Know_About (x, y), t).
Terminates (Out_of_Attention (x, y), Know_About (x, y), t).

Fluent Safe_Distance.

Initiates (Get_Safe (x, y), Safe_Distance (x, y), t).
Terminates (Unsafe_Separation (x, y), Safe_Distance (x, y), t).

Fluent Collision.

Initiates (Zero_Separation (x, y), Collision (x, y), t).

Fluent Following.

Initiates (Follow (x, y), Following (x, y), t).
Terminates (Sudden_Steer (x), Following (x, y), t).
Terminates (Sudden_Steer (y), Following (x, y), t).

Several conditional clauses for events to terminate fluents have been also defined:

Terminates (Sudden_Steer (x), Distance (x, y, d), t) <- HoldsAt(Distance(x,y,d), t) ∧ HoldsAt (Following (x, y), t) ∧ Happens(Sudden_Steer(x), t).

Terminates (Sudden_Steer (y), Distance (x, y, d), t) <- HoldsAt(Distance(x,y,d), t) ∧ HoldsAt (Following (x, y), t) ∧ Happens(Sudden_Steer(y), t).

Terminates (Brake_Heavily (x), Acceleration (x, ax), t) <- HoldsAt(Acceleration(x, ax), t) ∧ ax≠EBD ∧ Happens(Brake_Heavily(x), t).

VOTS - Constraints (Step 4)

Derived Happens and HoldsAt directives

For derived events, we needed to determine the moment when they occurred. We performed the identification of such time moments using the fluents that are initiated by the corresponding events. As a fluent does not hold at the time when the event that initiates it happened, but immediately after, we used a time deviation Δt to differentiate between these two moments (i.e. a fluent does not hold at time $t-\Delta t$ but starts to hold at time *t*).

• Event *Approach* and fluent *Approaching*.

Happens (Approach (x, y), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Speed (x, Vx), t) ∧ HoldsAt (Speed (y, Vy), t) ∧ (Vx > Vy) ∧ ¬ HoldsAt (Approaching (x, y), t-Δt).

HoldsAt (Approaching (x, y), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Speed (x, Vx), t) ∧ HoldsAt (Speed (y, Vy), t) ∧ (Vx > Vy).

• Event *Unsafe_Separation* and fluent *Safe_Distance*.

Happens (Unsafe_Separation (x, y), t) <- HoldsAt (Distance (x, y, D), t) ∧ HoldsAt (Speed (x, Vx), t) ∧ HoldsAt (Speed (y, Vy), t) ∧ HoldsAt (Acceleration (y, Ay), t) ∧ $D \leq (Vx\text{-}Vy)^2 / (-2 * (EBD\text{-}Ay))$ ∧ HoldsAt (Safe_Distance (x, y),t-Δt).

HoldsAt (Safe_Distance (x, y), t) <- HoldsAt (Distance (x, y, D), t) ∧ HoldsAt (Speed (x, Vx), t) ∧ HoldsAt (Speed (y, Vy), t) ∧ HoldsAt (Acceleration (y, Ay), t) ∧ $D > (Vx\text{-}Vy)^2 / (-2 * (EBD\text{-}Ay))$. We note that the above comparisons for distance are based on ECS1.0.

• Event *Zero_Separation* and fluent *Collision*.

Happens (Zero_Separation (x, y), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Distance (x, y, 0), t) ∧ ¬ HoldsAt (Collision (x, y), t-Δt).

HoldsAt (Collision (x, y), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Distance (x, y, 0), t).

• Event *Stop(x)* and fluent *Stopped(x)* for stationary vehicle.

Happens(Stop(x),t) <- Happens (Brake_Heavily(x),t1) ∧ t1<t ∧ HoldsAt(Speed(x,vx),t) ∧ vx=0 ∧ ¬HoldsAt(Stopped(x),t-Δt).

HoldsAt (Stopped (x),t) <- HoldsAt (Speed (x, 0), t).

We also defined several additional constraints:

• Event *Brake_Heavily* and event *Realize_Danger*.

Happens(Brake_Heavily), t) <- Happens(Realize_Danger(x), t).

• Derived event *Follow* - initially vehicle **x** follows **y** and **y** follows **z** and **y** starts executing a steering maneuver for changing lanes.

Happens (Follow (x, z), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Following (y, z), t) ∧ Happens (Sudden_Steer (y), t).

• Derived fluent *Distance* - vehicle **x** follows vehicle **y** and **y** follows vehicle **z**.

HoldsAt (Distance (x, z, d), t) <- HoldsAt (Following (x, y), t) ∧ HoldsAt (Following (y, z), t) ∧ HoldsAt (Distance (x, y, d1), t) ∧ HoldsAt (Distance (y, z, d2), t) ∧ d = d 1+ d 2.

• Additional *Acceleration* definitions - stationary vehicle, stopping vehicle and vehicle in heavy braking. The acceleration of a vehicle is considered 0 m/s^2 at all time moments exactly after the moment when the vehicle came to a full stop. We recall that NBD stands for normal braking deceleration and EBD for emergency braking deceleration.

HoldsAt (Acceleration (x, 0), t) <- HoldsAt (Speed (x, 0),t) ∧ HoldsAt (Stopped (x), t).

HoldsAt (Acceleration (x, NBD), t) <- HoldsAt(Stopping (x), t) ∧ ¬ HoldsAt (Stopped (x), t).

HoldsAt (Acceleration (x, EBD), t) <- HoldsAt (Heavy_Braking (x), t).

Trajectory definitions

We present below the *Trajectory* definitions that we introduced in our model and the *HoldsAt* definitions determined by them. These were used for modeling the speed of vehicles and the distance between vehicles.

• Fluent *Distance* assessed in relation with *Following*.

HoldsAt (Distance (x, y, d2), t2) <- Happens (Follow (x, y), t1) ∧ (t1<t2) ∧ (dt = t2 – t1) ∧ Trajectory (Following (x, y), t1, Distance (x, y, d2), dt) ∧ ¬ Clipped (t1,Following (x, y), t2).

Trajectory (Following (x, y), t1, Distance (x, y, d2), dt) <- (t2 = t1 + dt) ∧ ¬ HoldsAt (Changing_Lane (x), t2) ∧ ¬ HoldsAt (Changing_Lane (y), t2) ∧ Calculate_Distance(d2, ax, ay, vx, vy).

In the definition above, *Calculate_Distance* is a function that calculates the current separation distance between vehicle **x** and **y** using formulas ECS1.1 and ECS1.2. Since a constant value for acceleration is used in these formulas, the function takes into consideration all the possible moments when the acceleration of the vehicles can be changed and checks if these moments occurred before making the calculation. For the considered scenario, the vehicle V3 changes its acceleration when it starts to execute the pull over maneuver or when it stops before the end of the scenario. A change in the acceleration for vehicle V2 that affects the calculation of the separation distance can occur only due to a heavy braking maneuver executed before the lane change maneuver. The vehicle V1 can change its acceleration due to a heavy braking maneuver or when it stops before the end of the scenario but no collision with V3 has occurred. Also, this vehicle changes its acceleration to null when a collision occurs and the separation distance is zero. Several sub-functions are used by *Calculate_Distance* to keep track of modifications of the vehicles' acceleration. An example of such sub-functions that is used when a vehicle **x** does not change its acceleration till the evaluation moment but a vehicle **y** in front changes its acceleration due to a pull over maneuver is given below (t1 and t2 are the time points from the *Trajectory* definition).

Calculate_Distance <- ¬Clipped(t1, Acceleration(x, ax),t2) ∧ Happens(Pull_Over(y),tpo) ∧ tpo >t1 ∧ tpo <t2 ∧ ((Happens(Stop(y),tyst) ∧ tyst>t2) ∨ ¬Happens(Stop(y),tyst)) ∧ dAuxT=t2-tpo ∧ HoldsAt(Distance(x, y, d1),tpo) ∧ HoldsAt(Speed(x,vx),tpo) ∧ HoldsAt(Speed(y,vy),tpo) ∧ HoldsAt(Acceleration(y,ay),t2) ∧ HoldsAt(Acceleration(x,ax),t2) ∧ auxDy =((vy*dT)+((dT*dT*ay)/2)) ∧ auxDx =((vx*dT)+((dT*dT*ax)/2)) ∧ auxD =(d1-auxDx+auxDy) ∧ ((auxD≤0 ∧ d2=0) ∨ (auxD>0 ∧ d2 =auxD)).

• Fluent *Speed* determined in relation with *Heavy_Braking*.

Trajectory (Heavy_Braking (x), t1, Speed (x, v2), dt) <- HoldsAt (Speed (x, v1), t1) ∧ (auxV =v1-EBD* dt) ∧ ((auxV>0 ∧ v2 = auxV) ∨ (auxV≤0 ∧ v2=0)).

Here, *auxV* is an auxiliary variable and we used ECS1.1 for calculating the speed of the vehicle when the acceleration has a constant value of EBD.

HoldsAt (Speed (x,vx),t2) <- Happens (Brake_Heavily (x), t1) ∧ (t1<t2) ∧ (dt = t2 – t1) ∧ Trajectory (Heavy_Braking (x), t1, Speed (x,vx), dt) ∧ ¬ Clipped (t1,Heavy_Braking (x), t2).

• Fluent *Speed* determined in relation with *Stopping*.

Trajectory (Stopping (x), t1, Speed (x, v2), dt) <- HoldsAt (Speed (x, v1), t1) ∧ (auxV =v1-NBD* dt) ∧ ((auxV> 0 ∧ v2 = auxV) ∨ (auxV≤0 ∧ v2=0)).

As above, *auxV* is an auxiliary variable and ECS1.1 was used for calculating the speed of the vehicle when the acceleration has a constant value of NBD.

HoldsAt (Speed (x, vx),t2) <- Happens (Pull_Over (x), t1) ∧ (t1<t2) ∧ (dt = t2 – t1) ∧ Trajectory (Stopping (x), t1, Speed (x, vx), dt) ∧ ¬ Clipped (t1, Stopping (x), t2).

Several assumptions have been made when modeling the behavior of the vehicles and are reflected in the specifications of fluents and events. For example, we choose to terminate the fluent that represents the longitudinal distance between vehicles when a vehicle in front or behind executes a steering maneuver. Consequently, the *Safe_Distance* no longer holds if evaluated for two vehicles traveling on different lanes. However, this is only a behavior of this particular representation and does not mean that the vehicles are in immediate danger. Also, when three vehicles follow each other, and the vehicle situated in between executes a steering maneuver, the last vehicle starts following the first vehicle. We also set additional conditions for fluents to hold or events to happen. For example, a vehicle **x** performs a heavy braking when a *Realize_Danger(x)* event happens. However, such a heavy braking maneuver can take place in contexts other than the one in the considered scenario. We explicitly set the value of acceleration for several situations in which a vehicle can exist, such as for a vehicle that came to a full stop. This facilitates the evaluation of other fluents such as the speed of a vehicle. For continuous modeling of separation distance and speed, we used *Trajectory* predicates. If the calculations resulted in negative values we set the result to null since no speed or distance can be negative in our description. Events such as *Approach*, *Brake_Heavily*, *Unsafe_Separation,* or *Zero_Separation* take place at unique moments in time that we identified with accuracy given by a Δt time step. These time points are needed in the *Trajectory* predicates for the starting points of the triggering fluents.

We defined the narrative of the scenario, which is presented in Figure 2.11.

Narrative for VOTS (Step 5):
Initially P (Road (r)).
Initially P (Vehicles (Vi), ∀ i ∈ {1,2,3}.
Initially P (Know_About (V1, V2).
Initially P (Know_About (V2, V3).
Initially P (Safe_Distance (Vi, Vj), ∀ i, j ∈ {1,2,3}, i≠j.
Initially P (Following (V1, V2)).
Initially P (Following (V2, V3)).
Initially P (Speed (Vi, Initial_Speed)), ∀ i ∈ {1,2,3}.
Initially P (Distance (V1, V2, Initial_Separation)).
Initially P (Distance (V2, V3, Initial_Separation)).
Initially P (Acceleration (Vi, Initial_Acceleration)),∀i∈{1,2,3}.
Happens (Start_Scenario, t0).
Happens (Follow (V1, V2),t0).
Happens (Follow (V2, V3),t0).
Happens (Pull_Over (V3), t1).

Figure 2.11 Narrative for VOTS

VOTS - Implementation and Analyses (Step 6)

Implementation details and limitations

The model presented above was implemented in Prolog. The termination and initiation maps for fluents represent the initial conditions of the scenario that are valid at all moments in time and therefore were implemented using only the Prolog predicates *term* and *init*. Beside the common definition for *HoldsAt* predicates, and the explicit definitions for *Happens* predicates, new definitions implementing the constraints defined in Step 4 were needed. Also, auxiliary predicates were needed for implementing the sub-functions used by the *Calculate_Distance* function. New predicates used in diverse calculations (e.g. determination of the safe distance between two vehicles), and for determination of specific time points when some events happen (e.g. when a vehicle came to a full stop) were also added. In this scenario, as for all the other scenarios that were modeled, we explicitly defined the events that marked the starting and ending point of the scenario (i.e. *Start_Scenario* and *Stop_Scenario*.)

Several problems linked to the implementation of ECAM in Prolog apply to the example presented in this section. The occurrence of infinite loops imposed difficulties in implementing certain constraints that were logically correctly defined using Event Calculus. An example is the specification of a heavy braking event defined in relation to a small separation distance between two vehicles. This action leads to a modification of the speed and implicitly to the modification of the distance between vehicles. Since this distance is calculated based on speed, and the derived heavy braking is determined based on distance, the specification of such relations resulted in an endless loop. Introducing additional events that are explicitly given can solve such problems. For example, in our implementation we have used the event *Realize_Danger,* which leads to a heavy braking maneuver. However, this may reduce the flexibility of the program in modeling derived events, i.e. events that occur based on the states or values of other fluents and/or the occurrence of other events. Furthermore, we encountered problems when implementing *Trajectory* definitions. These definitions require the specification of the time moments when certain events start certain fluents. When such events are not explicitly specified in the narrative of the scenario, as in the case of derived events, the time of their occurrence needed to be specified via routines in the program. We implemented the determination of such time moments via search functions that analyze whether an event occurred based on the validity of the fluent initiated by it (i.e. using the clauses defined in step 4). These functions verify whether a fluent is valid using the time given in a query and searching the time space (i.e. the time interval between the time point specified in the query and the moment when the scenario ends) using a time step defined in the implementation. Since a fluent is valid immediately after the moment it was initiated, the event that starts it is considered to happen at the moment that is one time step before the moment when the fluent first holds. If the search reaches the moment when the scenario ends, the event did not occur. In this implementation, the considered time step was 0.01 seconds. Even if this is a fairly low value, some inaccuracy is still introduced within the accident modeling. This method of determining the moments when derived events happened is valid only for the first occurrence of the considered events. Thus, we employed this method for those events that can occur only once within the scenario development (e.g. Z*ero_Separation(V1,V3)*).

We defined derived events to indicate when certain actions occur in traffic as a result of the combinations of specific conditions within a scenario. This helped us model the dynamic behavior of accident scenarios, and model the effects of introducing new actions into the scenario. To our knowledge, the use of derived events within systems based on Event Calculus was not employed in previous works. Such previous systems require all the events to be explicitly specified when the system is built (e.g. [CM00, EFD+02]). This means that all the events that can occur when a situation is developing in time need to be defined beforehand and need to be given in the narrative. However, this does not allow the investigation of how the variations of diverse parameters or actions can dynamically influence the changes in the modeled situation.

For cases where such dynamic dependencies are of importance, as when modeling accidents where the traffic conditions dynamically affect each other (e.g. a braking maneuver is executed due to a danger), it is necessary to build a system that can represent dynamic relationships. This is possible by using derived events within modeling systems based on Event Calculus. We believe that our work represents a step towards developing more advanced systems for modeling and analyzing time-developing situations. However, as illustrated above, a number of problems need to be addressed for such systems to become valuable tools.

Analyses

The analyses that can be performed using ECAM depend on the fluents and events defined within the modeling of the scenario. We provide in the following examples of the traffic analyses that can be performed based on the previously introduced implementation of VOTS. When performing analyses, we used the following initial settings: Initial_Speed = 20m/s, Initial_Separation = 40m and Initial_Acceleration = 0 m/s^2. Also, the time moments when events happened were t0 = 0 s, t1=10 s, t2=13 s, t3=14.5 s, t4=15.5 s and t5 =20 s.

We interrogated the system to determine ***whether*** fluents held at certain time points, and ***if*** and ***when*** certain events took place. For example, we could determine if a collision between V1 and V3 occurred. A collision between two vehicles was represented as a fluent that holds true from the moment it occurs until the end of the scenario. Therefore, we interrogated the system about a collision between V1 and V3 at the ending point of the scenario. However, such interrogation can be performed at any time moment. The query about a collision between V1 and V3 evaluated true, indicating that an accident happened. The query in Prolog syntax with the answer marked in bold is presented below:

| *?- holdsAt(collision(v1,v3),20).* **yes**

We note that the system could also be interrogated to determine when the collision actually occurred using the *Zero_Separation(V1,V3)* event.

We then analyzed the influence of the modification of certain parameters on the development of the scenario. These types of analyses are important for determining when and how to act to avoid accidents. Thus, if the initial settings were modified so that the *Realize_Danger(V1)* event occurred at time t4=14.5 seconds, no collision was noticed. We could also determine the moment when V1 had stopped. The corresponding queries and answers are presented below:

| *?- holdsAt(collision(v1,v3),20).* **no**

| *?- happens(stop(v1), Tstop_V1).* **Tstop_V1 = 16.8 ? yes**

Various other investigations could also be performed using the ECAM model for VOTS. Thus, it was possible to analyze issues of interest such as the velocity of vehicles, the separation distance between two vehicles, and whether two vehicles followed each other:

| *?- holdsAt(speed(v1,Vel_V1),16).* **Vel_V1=15.5? yes**

| *?- holdsAt(distance(v1,v3,D13),14).* **D13=48? yes**

| *?- holdsAt(following(v2,v3),10)***.* yes**

2.3.3 Vehicular communication and ECAM

Even if vehicular communication is generally thought to have a high potential for supporting active safety systems (e.g. [AF96, AVN00]), it may not be effective in all traffic situations. For example, communication may have little impact in helping avoiding lane departure accidents. Therefore, it is necessary to be able to identify in which traffic scenarios communication can be efficiently used. Since traffic situations differ a great deal one from another, it is important to be able to determine specific requirements that traffic scenarios impose on a communication system used as support for the safety system. It is thus important to investigate when certain information needs to be sent in specific scenarios for avoiding accidents. For example, if two or more vehicles may be in danger of colliding at an intersection, it needs to be determined when a warning should to be issued for the vehicles to efficiently make use of it. In order to avoid accidents or at least reduce their consequences, it is also necessary to investigate the relations between the time development of traffic scenarios and different actions that can be taken in traffic (e.g. braking, steering). For instance, during a specific scenario a braking maneuver that takes place at a certain moment may lead to the avoidance of an accident. Using an active safety system that integrates communication, it would be possible to issue a warning that allows such maneuver to happen (i.e. the braking).

In the following, we focus on vehicular communication as the enabling technology for supporting active safety systems. More specifically, we address the following issues:

- Analyze how accidents can be avoided via diverse actions and investigate if communication can be used to enable such actions.
- Investigate the quantitative impact of scenario conditions (e.g. velocities, driver reaction time) on accident avoidance.
- Determine requirements on information transfer that need to be fulfilled by vehicular communication to be effective in accident avoidance.

Communication concepts in ECAM

We assumed that the vehicles are equipped with communication devices and are able to exchange data describing their situation in traffic. This data contains information about the current movement characteristics of a vehicle such as speed, acceleration or heading, and information about certain events related to traffic that are detected by a vehicle, such as a traffic jam or an accident. We further assumed that communication fulfills certain performance requirements with regard to the dissemination of such information between vehicles. Proceeding from these assumptions, we can also assume that important data sent by a vehicle is always received by other vehicles that have an interest in it. However, we introduced a delay in receiving such information and thus model at a high level the consequences of possible flaws in the communication system, such as loss of data (which then needs to be retransmitted), and data delivery latency due to medium access control, multihop communication, or sending and receiving processes.

We further assumed that an active safety system acting as a driving assistant is installed in each vehicle and analyzes data received from other vehicles to present the drivers with warnings about dangers in traffic. We also assumed that the drivers pay attention to the information presented by the assistant system and can employ defensive driving measures according to these warnings. However, the drivers need a certain amount of time to understand the information presented and react to it. For simplicity, we included in this interval the time needed for a system in the vehicle to perform an action based on driver's maneuvers (e.g. braking system lag).

In the following, we use the VOTS example to illustrate how communication concepts can be integrated within ECAM. We define additional events and fluents that describe at a high level the communication between vehicles. We also add constraints describing new relations between fluents and events.

Communication components in the ECAM model for VOTS

For this scenario, a notification is issued when a vehicle breaks down and is forced to execute a pull over maneuver. Thus, the vehicle executing a pull over (i.e. V3) transmits a warning message describing its situation. The message is sent when the maneuver starts to be executed. The additional fluents and events within the modeling of the scenario are presented in figure 2.12.

Communication-related fluents:
Communicate (x, y): bi-directional communication between vehicle **x** and vehicle **y**.

Communication-related events:
Establish _Communication (x, y): vehicles **x** and **y** start to communicate with each other.
Release_Communication (x, y): vehicles **x** and **y** cease to communicate with each other.
Send_Pull_Over_Notification(x): vehicle **x** sends a notification indicating that it executes a pull over maneuver.
Receive_Pull_Over_Notification (x, y): vehicle **x** receives data indicating that a vehicle **y**, positioned somewhere in front of it, executed an emergency pull over maneuver.

Figure 2.12 Communication-related entities for VOTS

The new constraints for the modeling of the scenario were:

• Event *Send_Pull_Over_Notification*.

Happens(Send_Pull_Over_Notification (x),t1) <- Happens (Pull_Over(x), t1).

• Event *Receive_Pull_Over_Notification* determined using the communication.

Happens(Receive_Pull_Over_Notification (x, y),t1) <- Happens(Send_Pull_Over_Notification (y),t2) ∧ HoldsAt(Communicate(x, y), t2) ∧ ¬ Clipped(t2, Communicate(x, y),t1) ∧ t1=t2+Comm_Delay

Comm_Delay is the parameter introduced for representing the latency in receiving by vehicle **x** the data sent by vehicle **y**. This was initially set to 1 second.

• Event *Realize_Danger* determined in relation with communication and due to a received notification.

Happens(Realize_Danger(x), t1) <- Happens (Receive_Pull_Over_Notification (x, y),t2) ∧ t1=t2+Drv_React_Time

Drv_React_Time is a parameter indicating the driver reaction time, which was set to 1.5 seconds based on [KLP+99]. The above definition indicates that the driver considers that a danger may occur in the near future based on the received pull over notification. Further conditions can also be considered for the driver to detect and react to such a danger. For example, an additional condition could be that the separation distance between the sender and the receiver becomes lower than a safe threshold. We recall that when a *Realize_Danger* event happens, the driver employs an emergency braking. This is reflected by the occurrence of the *Brake_Heavily* event.

• Event *Acknowledge* determined in relation with communication.

Happens (Acknowledge (x, y),t1) <- Happens(Establish_Communication (x, y), t2) ∧
t1=t2+Drv_Ack_Time ∧ ¬ Clipped (t1, Communicate, t2).

Drv_Ack_Time is the time needed by a driver to notice, understand, and react, if needed, to some information about another vehicle. We used the same value of 1.5 seconds that was used for the reaction time of the driver. The event defined above is used for indicating the moment when a driver starts to be aware of another vehicle's conditions using the information exchanged via communication.

Communication and accident avoidance – an analysis using ECAM

The goal of this analysis was to investigate whether, and in what conditions, vehicular communication can contribute to the avoidance of accidents. Therefore, we analyzed if different accidents can be avoided by making specific information available to drivers at specific moments in time. We then investigated how diverse scenarios and component elements of them (e.g. velocities, driver reaction time) may impose requirements on the use of communication.

Accident avoidance due to data exchange between vehicles

The time development of traffic scenarios is dependent on the events that occur in traffic such as the maneuvers performed by vehicles. As indicated by collision avoidance research (e.g. [KLP+99, TCE+00, PJL+00]), avoidance of accidents can be achieved by cautious driving and, in the case of immediate dangers, by employing avoidance maneuvers such as heavy braking and sudden steering. Therefore, we investigated if active safety systems based on communication can help the driver to perform actions that can help avoid crashes. We illustrate these investigations by the use of VOTS scenario.

As presented in the previous section, in VOTS the driver in V1 realizes the existence of an immediate danger in traffic and performs a heavy braking when receiving the notification about the pull over maneuver of V3. Thus, the action that can lead to the avoidance of an accident between V1 and V3 is an early heavy braking of vehicle V1. The narrative of VOTS was modified for modeling the use of communication. Thus, we suppressed the explicit occurrence of *Realize_Danger (V1)* and *Acknowledge(V1, V3)* events and eliminated the initial time moments t3 and t4. The time moment t5 became t3 in the new narrative. We added three events indicating when the communication between vehicles is initiated. These modifications are illustrated below (all other statements remained the same):

Happens (Establish_Communication (V1,V2),t0).

Happens (Establish_Communication (V1,V3),t0).

Happens (Establish_Communication (V2,V3),t0).

Happens (Pull_Over (V3), t1).

Happens (Sudden_Steer (V2), t2).

Happens (Stop_Scenario, t3).

t3 > t2 > t1 > t0.

The implementation of the system was completed with the Prolog entities that model the fluents, events, and constrains related to communication modeling. The initial settings remained the same and the time moments were t0 = 0 s, t1=10 s, t2=13 s, and t3 =20 s. We then interrogated this extended system about the occurrence of a collision between V1 and V3. In this case, due to the modifications in driving behavior based on the information received via vehicular communication, no collision happened:

?- holdsAt(collision(v1,v3),20). **no**

This result showed that V1 received the notification about V3's condition early enough to be able to stop safely. We also checked if and when the vehicles came to a full stop:

| *?- happens(stop(v1),T_stop_V1).* **T_stop_V1 = 14.79? yes**

| *?- happens(stop(v3),T_stop_V3).* **T_stop_V3 = 15.09? yes**

We note that similar investigations were performed for various scenarios (e.g. intersection crashes with perpendicular path), where we obtained similar results.

Accident analyses and communication performance

An active safety system such as the above driving assistant system based on communication can be effective only if the data used for analyses is provided in a reliable and timely manner. Therefore, we were interested in assessing the relationship between the communication delay and the possibility of avoiding an accident.

Many variables exist with the use of communication in traffic safety, and different scenarios can impose very different demands on communication. Therefore, we analyzed various scenarios and in each of them we considered that a notification is issued for indicating a dangerous situation. This notification was designed to determine an action in traffic that could leads to accident avoidance.

For the analyzed accident scenarios we performed two types of investigations. First, we kept constant the initial parameters of the scenario (e.g. velocities, accelerations, distances) and evaluated the maximum delay in delivering a warning message to the vehicles in need. Second, we modified different parameters in the scenario (e.g. driver reaction time, initial speed of vehicles, distances, maneuvers) and assessed the communication delay that is required for achieving accident avoidance. We illustrate below these analyses using the VOTS scenario.

Within VOTS, we investigated the maximum delay that can be tolerated by the driving assistant system for receiving and processing the pull over notification.

When keeping constant all the initial settings we determined that for a communication delay higher than 3.59 seconds, the use of the assistant system could not provide accident avoidance. Still, the consequences of the accident can be diminished even if avoidance is not achieved. Thus, for a 3.6 second delay we noticed a reduction of around 60% of V1's speed at the moment of impact compared with the initial case. This should be reflected in a reduction of the risk of injuries.

We also investigated the communication delay when modifying parameters of the VOTS scenario such as the initial speed of the vehicles, the initial separation distance between vehicles, and the driver reaction time. For the sake of brevity, we illustrate in figure 2.13 the dependence between the minimum delay required for accident avoidance and the initial separation distance between vehicles and the initial velocity of the vehicles respectively. All other settings in the scenario were kept constant.

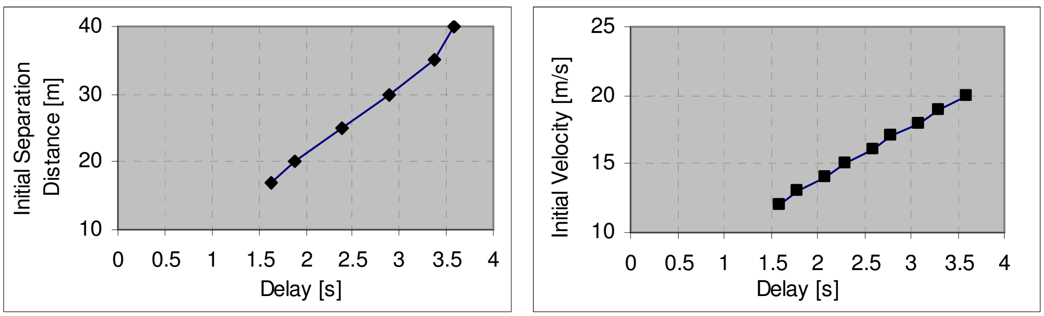


Figure 2.13 Communication delay - initial separation distance and initial velocity

A smaller separation distance required a smaller delay in delivering the information. This was expected since the vehicles were closer to each other and thus in more danger of colliding. A smaller initial speed value also required a smaller delay. This was a result of the shorter distance (and thus the shorter time) needed by V3 to come to a stop after it breaks down when initially had a lower velocity. This required that the following vehicle (i.e. V1) be announced in a shorter time to enable it to stop safely. We also investigated the modification of the initial speed values only for V1 and V2 (i.e. V3's speed was kept constant at 20 m/s). In this case, a speed value of 21.5 m/s determined a minimum delay of 2.65 seconds, which was almost 1 second lower than the value obtained under the initial settings. For speed values higher than 21.5 m/s, a collision between V2 and V3 occurred, which altered the original scenario.

We note that the delay requirements on notifications varied a great deal between different accidents scenarios. In many scenarios, a delay of 1÷2.5 s was sufficient for achieving accident avoidance. However, in some cases, especially for intersection scenarios, we obtained smaller values, such as 0.6 s. The delay could have also even lower values, as we noted when we modified certain settings of the scenarios, e.g. the characteristics of the vehicles. However, in those cases, the settings were not realistic, i.e. there was no real accident with such description and the settings were extreme. One such extreme example would be a case in which ordinary vehicles were situated at 50 meters from an urban crossroad and approached it at a speed of 90 km/h.

The investigations that we have performed also showed that simple operations of safety systems may not result in the desired improvement of traffic safety. For example, in [SCA+04] we investigated intersection accidents involving elderly drivers. An in-vehicle safety system that reacts to notifications received from vehicles that pass through the intersection was considered.

This system could also have an automatic mode, where a braking maneuver was performed based on information included in a specific warning message. For instance, for the scenario presented in figure 2.14, the system could employ an automatic braking when two vehicles may collide at an intersection. The scenario implies that vehicle V2 is stopped and then tries to pass through the intersection. The driver in V2 does not notice the approaching V1. When V2 starts to cross, its acceleration is low, as the elderly driver in V2 tends to drive carefully. V1 is mislead by V2's maneuvers and realizes too late that V2 indeed wants to pass but it will not be able to pass on time. V1 tries to brake to stop, but due to the short separation distance, crashes into V2. A possible solution is to force V2, which comes from a non-priority road, to send a notification when it starts to pass through the intersection. Based on the information included in this message, the system in V1 identifies V2 as a possible danger and notifies the driver or applies a braking maneuver. However, if the safety system reacted automatically by braking, it could induce an accident (under specific settings of the scenario). This is because this simple safety system forced V1 to brake too early, which then arrived into the intersection when V2 was still there. If no braking had been employed, V1 would arrive in the intersection after V2 has passed. Consequently, active safety systems need to be deliberative, and reason about potential consequences of actions.

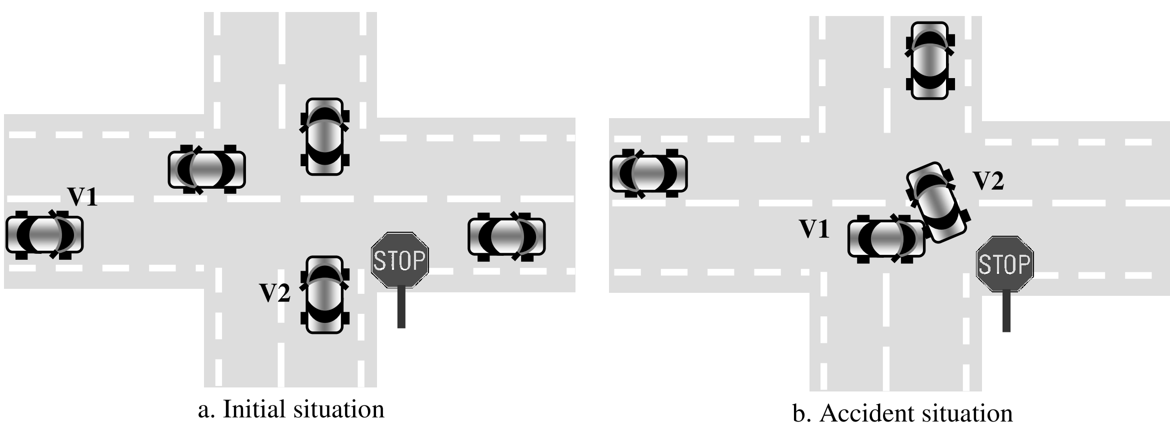


Figure 2.14 Intersection accident example

3. Safety communication system analysis

This chapter provides an analysis on the design of a communication system intended to provide a timely and reliable dissemination of safety data between vehicles. We define requirements, identify the main design issues of the system, and discuss the upsides and downsides of possible alternatives. We thus discuss approaches to vehicular safety communication and design aspects of the system such as operation modes, and networking and transmission techniques.

3.1 Requirements analysis

The vehicular environment, the functionality of active safety systems, and accident dynamics impose requirements on vehicular safety communication.

Requirements imposed by the vehicular environment

The vehicular or traffic environment is the environment where vehicles travel. We refer to the vehicles and roadside servers equipped with communication means as hosts.

A set of properties exhibited by the vehicular environment that can impose requirements on the design of the communication system used for exchanging safety data between vehicles is presented below:

• The communicating hosts move on well-defined paths (i.e. the roads) (e.g. [KLP+99]). A host can be mobile or fixed (e.g. [MKO00]). A mobile host is a vehicle and is located on a road. A fixed host is a communication entity and is located on the side of the road (e.g. a gateway).

• The movements of mobile hosts are (currently) controlled by human entities, i.e. the drivers. The drivers react to relevant changes in the environment and have the ability to estimate the relative distance to other vehicles or obstacles on the road or roadside, and the relative velocities of other vehicles (e.g. [WH98a, GMC+00]).

• The movement of vehicles is usually performed according to well-defined traffic rules (e.g. vehicles stop when traffic lights are red). Vehicles perform maneuvers such as braking, overtaking, and lane changing based on the individual perception of the traffic situation by the driver. The movement of a vehicle is usually performed considering the current traffic situation of other vehicles situated in its vicinity (e.g. [AF96, BV01, ZKV00]). However, the drivers may not always respect traffic rules, nor can they always correctly predict the movements or intentions of other vehicles. Consequently, the maneuvers made by vehicles are not always safe (e.g. [USDT99, ZKV00, Eva04]).

• Each vehicle is characterized by dimension parameters such as width and length (e.g. [WH98a, KLP+99]). The movement of vehicles can be described using motion parameters such as speed, heading (i.e. driving orientation), and acceleration (e.g. [MKO00, BKP+02]).

• Vehicles can travel in geographical areas that may present significant topographical differences (e.g. [KSA02]).

• Vehicles have the freedom of joining and leaving the traffic (e.g. [BV01]).

• A road can be categorized according to its functional type (e.g. as highway, urban road, or country road [FAT99, SBS+02]). Other parameters related to a road such as road conditions (e.g. slipperiness), or construction characteristics (e.g. existence of a divider) can be used to describe a road (e.g. [BSH00, KSA02]).

The influence of the above properties on the design and functionality of the safety communication system is discussed in the following.

- The mobility of the hosts and the possible communication with fixed hosts need to be reflected in the communication and networking techniques.
- The type of data that need to be exchanged is determined by the information that could be of use for the driver. The traffic environment accommodates different types of roads and this can influence the type of data and its processing.
- The characteristics of the vehicles (e.g. length) can influence the communication service area and the design of the communication system.
- The fact that the vehicles travel on dedicated paths (i.e. roads) and exhibit specific behaviors affects the design of the communication protocol and the transmission technique. The random exiting and entering of roads by vehicles needs to be reflected in the network organization and management. This also affects the design of the communication protocol.
- The behavior of a driver in a vehicle depends on actions performed by surrounding vehicles and on actions of other traffic participants (e.g. pedestrians). This influences the development of the communication system in various ways (e.g. network management, service area, or information dissemination technique).

With consideration given to the properties of the vehicular environment and the use of communication as the enabling technology for safety systems, we present below a set of basic requirements on communication:

• The communication needs to take place between hosts that can constantly modify their position, speed, and driving orientation (e.g. [AF96, BH00]). The communication takes place in environments where the transmission patterns change frequently. The communication performance can be affected by elements specific to traffic situations such as terrain, buildings, weather, or vehicle distribution [AF96, KSA02, MN97, SBS+02]. The communication needs to accommodate frequent disconnections and failures, as well as high levels of interference (e.g. [BV01]). This requires a communication system that can reliably deliver data in time and can assure a high availability of the safety information (e.g. [AF96, MN97, FAT99, TAF00]). High frequency of providing traffic information is needed, e.g. at least each 1-2 seconds (e.g. [AF96, HBE+01]). Furthermore, small transmission latency needs to be achieved. Many factors influence the latency, e.g. channel access delay, relaying delay. Different proposals have been made in the literature for data delivering latency in vehicular networks (e.g. [AF96, Coc97, ONS+00, KTT+02, CC05]). Values between 100 ms (e.g. [CC05]) and 1 second (e.g. [Bri01]) were thus proposed. For applications such as collision warning and collision avoidance based on multihop data exchange, delay values lower than 0.6 seconds were shown to induce important improvements to traffic safety (e.g. [WH98a, BSH00]).

• The communication needs to take place between hosts that may join and leave the network at very high rates. The mechanisms employed for network management and addressing need to cope with this dynamic behavior (e.g. [BH00, BV01]).

• The vehicular communication needs to be operational at any time, in any place, and under a wide variety of conditions (e.g. [KLP+99, TAF00]). The communication also needs to be functional in zones with relatively high density of vehicles (e.g. 20 vehicles per kilometer) [BV01].

• The communication may need to take place beyond the local transmission range of the hosts. This implies both line-of-sight (LOS) and multi-hop communication, which implies that the development of forwarding techniques are needed (e.g. [MN97, TAF00]).

• The exchange of safety data can be done regularly, when certain events occur in traffic (e.g. transmission of notifications due to events such as accidents), or in both cases (e.g. [AF96, BH00, KTT+02]).

• The service area for communication needs to be selected with consideration given to aspects related to traffic such as driving patterns and characteristics of vehicles (e.g. dimension, maximum braking distance). Additionally, the relevance of safety data is space bounded. Other aspects that need to be considered are the connection time between hosts and the amount of information that needs to be transferred (e.g. [HBE+01, AMF+02]). Services areas of varying sizes have been proposed for traffic applications. Even for the same application, proposals differed a great deal. For instance, for traffic jam notifications, 200 meters to 5 kilometers were proposed (e.g. [AF96, BSH00, BH00]). For collision warning applications, communication areas between the average visibility of the driver (i.e. 100 meters), and several hundreds meters (e.g. 500 m) were proposed (e.g. [Win96, AF96, WH98b, KBS+01, HBE+01]).

• The content of exchanged data needs to assure fast processing and should be relevant for traffic safety (e.g. [AF96, HBE+01]).

Active safety systems requirements

The operation modes of collaborative active safety systems impose specific requirements on the functionality of a safety communication system. Using crash avoidance research (e.g. [KLP+99, TCE+00, PJL+00, ZKV00, KCF+03]), we have defined a set of high-level requirements for active safety systems. We discuss here how these requirements relate to vehicular communication. The generic requirements for active safety systems are presented in the following.

• Active safety systems must be reliable and must be efficient in determining dangers in traffic and performing actions accordingly.

When communication is used for supporting the safety systems, the data exchange between vehicles needs to be performed in a reliable and timely manner. Delay values as much as few seconds need to be achieved for the data to be transferred from a system installed on a vehicle to the system installed on another vehicle. The type and amount of information that is exchanged is determined by the data needed by the safety systems for performing analyses of traffic situations. The safety information can extend over several hundred bytes at one instance and if it is provided regularly, a channel bandwidth of at least several hundreds of kbps may be required.

- Active safety systems must be accurate and must provide effective support to the driver.

For vehicular communication, this requirement is primary reflected in the need for timely exchange of accurate information between vehicles. To effectively help the driver, the safety system needs to produce accurate and comprehensive notifications (e.g. [Alb99, ZKV00]). Consequently, the type of data exchanged using vehicular communication depends on the information that needs to be presented to the driver.

- Active safety systems should not lead to the mental overload of the driver.

Research in driving behavior indicated that drivers are able to successfully cope with secondary tasks such as the use of safety systems that issue warnings [IIK+02, AHK+02]. However, the presentation of warnings should not distract or overload the driver. The content of notifications and the method of presenting them are certainly important. Thus, a wide variety of interfaces such as audio (e.g. chimes, voice), video (head-up display, car computer display, rear/side mirror display) or tactile (e.g. seat vibration, brake pulse) are currently under investigation (e.g. [ZKV00, TCE+00, KCF+03]). Furthermore, the safety system needs to issue notifications early enough for the driver to be able to employ maneuvers that help in avoiding or mitigating collisions. We note that driver reaction time between 1 and 3 seconds should be taken in consideration [KLP+99]. The safety system also needs to assure a small number of false and nuisance alarms [GMC+00, BKP+02]. If a large number of warnings are presented to the driver or if they are presented too early, the driver's confidence in the system degrades significantly [KLP+99, TCE+00]. These factors require the safety system to have accurate data early enough to be able to perform traffic analyses and employ actions. For safety systems that integrate communication, this translates again into the need of having a reliable and timely data exchange.

- Active safety systems need to operate in a wide variety of traffic situations.

When communication is used as support for the safety system, the above requirement demands the utilization of a communication system that is able to function on different roads, in different areas, and under a wide variety of traffic conditions (e.g. network load, weather conditions, terrain topology).

- Active safety systems need to be economically feasible.

The successful deployment of active safety systems requires the development of systems with reasonable costs. For safety systems that integrate communication, this aspect addresses both the cost of the equipment mounted on vehicles, and the infrastructures related to roads that may need to be developed. We note that solutions designed to improve traffic safety can be technically feasible, but not economically feasible. For instance, a system using sign-to-vehicle communication that implements collision warning functions at intersections was considered less appropriate for current deployment due to high costs [LMFS97].

Requirements derived from accident analyses

The study of accidents makes it possible to identify specific functional requirements on the use of communication systems that support on-board safety systems. In our study we analyzed accidents both theoretically, based on relevant literature (e.g. [USDT99, SITC01, NSD01, NSS+03, NSS01, USC03, Eva04]), and also via simulations using the ECAM system introduced in the previous chapter. The following requirements were identified:

- The data exchanged between vehicles needs to describe in detail the traffic situation in the proximity of a subject vehicle. Information such as position, heading, speed and status of the vehicle is essential. This information can extend over several hundreds bytes. As traffic data needs to be provided frequently, and a large number of vehicles may exchange it, low transfer rates (e.g. tens or few hundreds kbps) may not be appropriate. Furthermore, the use of specific notifications for describing hazards in traffic (e.g. a vehicle stopped in the driveway) can have a significant impact on avoiding collisions.
- All traffic data needs to fulfill strict requirements on latency. Values of several seconds may be enough to avoid simple accidents such as rear-end scenarios involving a small number of vehicles. However, in more complex situations and for the majority of traffic accidents values, values that are minimally lower than 1 s are needed for multihop communication. Moreover, values that can lead to high efficiency of safety systems would preferably be under 0.6 s.
- The required communication area can vary from tens to hundreds of meters, e.g. 80 meters to 700 meters. In most cases, several hundreds meters are needed for assuring the possibility of avoiding accidents. Additionally, values over 800 meters are usually not needed, and values less than 50-60 meters are usually too small to provide a real opportunity for avoiding a crash.

3.2 Approaches to vehicular communication

We provide in the following an analysis of proposals for developing vehicular communication systems, with consideration given to the safety functionality of the communication system that is integrated in collaborative safety system.

Based on the specific operations performed for disseminating traffic information, the proposals for vehicular communication can be categorized into four main approaches:

- Vehicular communication using satellite systems.
- Vehicular communication based on infotainment infrastructures (e.g. gateways mounted on the roadside).
- Vehicular communication based on cellular systems.
- Direct vehicular communication.

We studied these approaches to identify the level of support they could provide for implementing safety communication. Aspects of particular interest were the possible performance of the communication system (e.g. data rate, latency, link availability), the availability and the cost of the system, and the possibility for the system to integrate special features (e.g. specific service area, use of geographical data). We do not include in the analysis below the use of satellite networks since it is generally considered that the large delays, high costs, and possible low performance did not recommend them for implementing collaborative safety applications [NTF96]. The considerations regarding the other three approaches are presented in the following. The conclusions are then summarized using a qualitative comparison table.

Vehicular communication based on infotainment infrastructures

This approach to vehicular communication employs the development of dedicated communication infrastructures associated with roads (e.g. [NTF96]). These infrastructures are usually developed for implementing services such as delivery of traveler information. An example is presented in figure 3.1, where several communication servers provide communication for vehicles on a road. These servers are connected with each other and with an Access Network using a Vehicular Support Network that can be a wired or a wireless network. The Access Network is also connected to a Traffic Service Center that provides information about traffic, or to other networks that provide various services (e.g. Internet).

The vehicular communication based on such infrastructures has been subject to intensive efforts in the last years, leading to remarkable results such as the development of the Vehicle Information and Communication System (VICS) in Japan [Yam96, MKI+99]. This system is used to collect and analyze traffic data received from different sources and then to deliver the results of these analyses to vehicles using FM broadcast, radio beacons (i.e. on 2.49 GHz), and infrared communication. The solutions for vehicular communication based on infotainment infrastructures can include not only the installation of communication stations along the roads, but also the integration of other elements with roads or roadsides. An example is a sensorial system that integrates magnetic sensors and video cameras to detect the presence of pedestrians and vehicles, and alerts upcoming vehicles to them. Another example would be systems formed by devices installed on traffic signs and traffic lights that send various notifications to vehicles (e.g. adaptive speed limits) (e.g. [AHR00, Bis00, AHR01]).

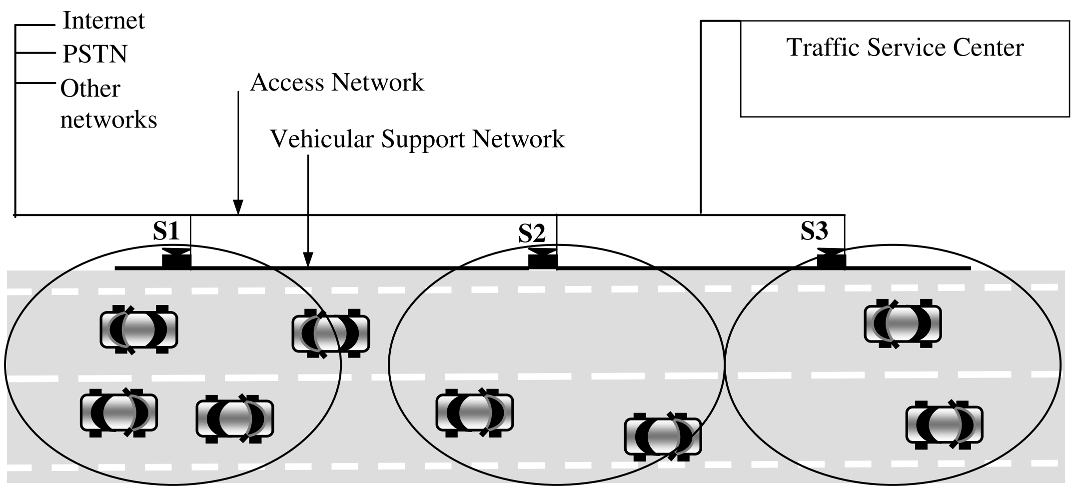


Figure 3.1 Vehicular communication based on an infotainment infrastructure
(S1, S2 and S3 are dedicated communication servers)

Several limitations apply to the use of vehicular communication based on infotainment infrastructures, like the ones mentioned above, when exchanging safety information. This approach employs a client–server technique and even when data has to be exchanged only between vehicles, a server located on the roadside needs to be involved. This induces latency and therefore the exchange of data that requires a very small latency is not supported well. Furthermore, many systems provide only unidirectional services (e.g. broadcast, toll collection) and they will need to be modified for safety vehicular communication. The management of a large number of vehicles can also pose problems, and require a large number of roadside devices and/or a high bandwidth system, which are both expensive to achieve. In addition, the development and deployment of communication systems using dedicated infrastructures is usually a long-term objective that requires extensive funding. The applicability of these communication systems is usually limited to specific geographic locations [Win96, MIK01]. This hinders the ubiquitous utilization of such systems. For instance, current proposals for developing systems based on infotainment infrastructures address mainly services for highways and freeways (e.g. [MKI+99]). Since accidents happen on all types of roads it is desirable for a safety system based on communication to be able to perform well under a wide variety of topographical conditions and on all types of roads.

Vehicular communication based on cellular systems

This approach implies the development of communication systems that make use of cellular networks such as GSM (e.g. [AVN00, MIK01, Bre01, KBS+01]). An example is presented in figure 3.2, where each vehicle is equipped with a mobile station (MS). Similar to a regular cellular network, a number of base stations (BS) provide services to mobile stations. This type of cellular network can offer traffic services that can be located within a base station or within other entities in the network (e.g. the operation and maintenance center). This network can be also connected to a traffic service center or with other networks that provides traffic services.

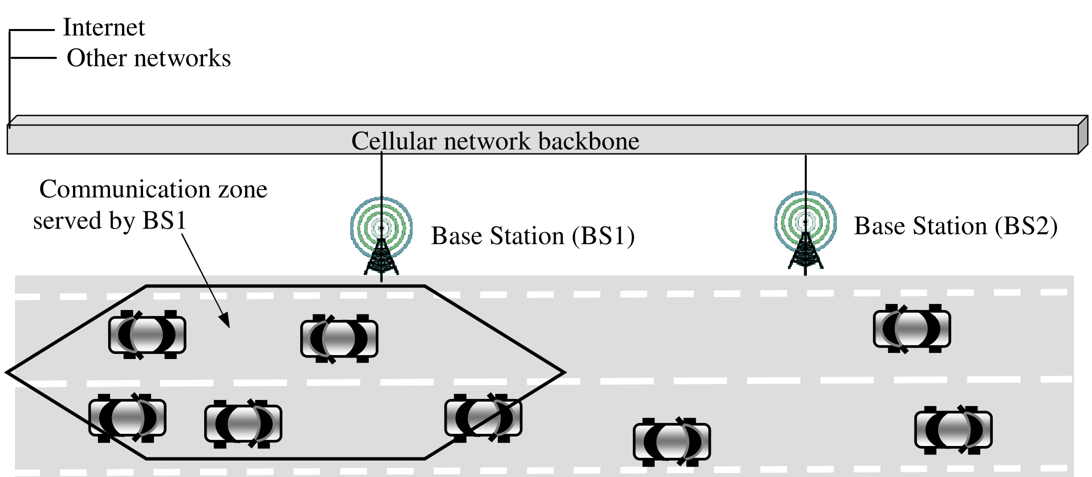


Figure 3.2 Vehicular communication based on a cellular network

Car manufacturers and telecomm operators have expressed a significant interest in the development of vehicular networks based on a cellular approach. The possibility of using well-established communication networks that give extensive coverage, are based on international standards, and have a wide market penetration is enticing [AVN00]. Different types of applications that make use of cellular systems have been proposed, the most common being telematic applications that relate to roadside assistance and infotainment [Bre01]. These applications follow a client-server approach where a mobile station (MS) mounted on a vehicle connects to a base station (BS) when certain information is required by the driver or by some system in the vehicle (i.e. POP-oriented service provision). The BS then contacts the service that provides the requested information. This service can be located in the BS or at some distant monitoring unit that processes data related to traffic. For example, mobile office applications (e.g. e-mail or financial transactions) were developed and adapted for integration into vehicles [Bre01]. PUSH-oriented services, where BS delivers information to vehicles without being previously solicited, can also be provided. An example is the delivery of emergency notifications indicating nearby accidents or traffic jams. Safety applications such as emergency calls in case of vehicle failure or automatic accident notifications have also been proposed [LHC+00, FBD+01]. An example is the Volvo on Call system that makes use of a GSM phone and a Global Positioning System (GPS) receiver [Vol04]. If a vehicle is involved in a crash, this system sends the vehicle position and the status of the airbag to a service center.

Even if the success of several traffic applications using cellular networks indicates the potential of this technology, several technical limitations can hinder the utilization of these networks for implementing safety communication. Real-time applications such as collision avoidance for large numbers of vehicles moving at relatively high speeds and in various environments are not well supported by cellular networks [Win96, MN97]. These networks were not designed with the intention of implementing vehicular communication or any similar application. They don't employ flexible connectivity and fast access to the radio channel, nor can they manage a large number of users located in a small area. Also, cellular networks cannot usually assure very low latency for data transmission, and high availability of the radio links [AVN00, HBE+01]. Additionally, the data rates provided by cellular networks can be too low to accommodate a large number of communicating vehicles that send data frequently. The possible lack of coverage, especially in rural areas, can also hinder the utilization of cellular networks for supporting systems that implement safety applications (e.g. [Win96]). Other important issues that currently hinder the utilization of cellular networks are the high cost of communication and the lack of well-defined provision of services [Per99, Bre01, HBE+01, Haa02]. While the former is a typical problem related to cellular networks, the later addresses the undecided distribution of market roles between car manufacturers and telecom operators with regard to content and service providers.

Direct vehicular communication

The last approach to vehicular communication that we have analyzed proposes the use of direct communication among vehicles. This approach implies the direct exchange of information without the involvement of a communication infrastructure. An example is presented in figure 3.3, where vehicles are equipped with full-duplex transceivers and can communicate directly one with another. The dotted arrows in the figure indicate such communication links.

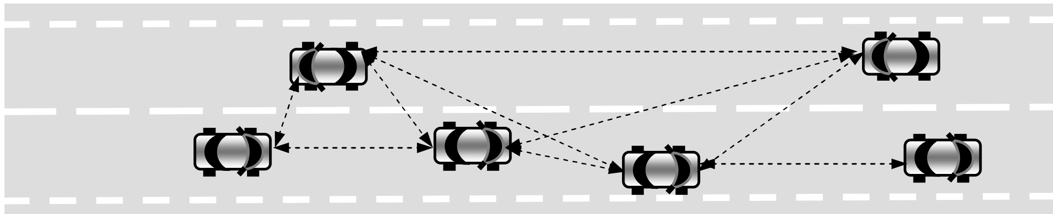


Figure 3.3 Direct vehicular communication between vehicles

To implement such systems, several frequency spectrums were proposed. An example of this is the 5.9 GHz band proposed within the Dedicated Short Range Communication (DSRC) specifications [KTT+02, FCC04]. Investigations of the usability of communication systems developed for the 2.4 GHz ISM band have been also conducted [SBS+02, MWF02]. Examples of such systems are wireless local area systems such as IEEE 802.11 [Sta04] and wireless personal area systems such as Bluetooth [Blu01].

In comparison with the previous approaches, the use of direct communication does not require the development and deployment of infrastructures, and thus allows a flexible and ubiquitous utilization of the communication. When such communication systems are integrated within vehicles, they can be used not only on highways and expressways, but also on any ordinary road and in any geographical area. Moreover, an appropriate design of the communication protocol and the transmission media can give the possibility of having high data rate communication with low interference. The direct exchange of data also facilitates the development of a vehicular network that can provide fast connectivity, low delays, and high availability [Win96, KBS+01]. A network having such characteristics is able to efficiently support the exchange of time-bounded safety data used by onboard safety systems. Additionally, such a network is able to exploit the geographic relevance of the traffic data. This is an advantage since information from neighboring vehicles is usually highly relevant for the assessment of a traffic situation [HBE+01].

The direct communication approach also opens up the possibility of developing cost efficient vehicular communication systems. This is mainly because there is no need to build expensive communication infrastructures as needed by the approach based on infotainment infrastructures, and the cost of communication can be very low, e.g. compared to the cost of using a cellular network [Win96, HBE+01]. Still, the initial cost of developing and deploying the system needs to be taken in consideration because this type of communication can efficiently function only when a sufficient number of vehicles are equipped with communication devices [AVN00, BH00].

The main problem associated with this approach is the difficulty of developing a reliable, scalable, and stable system. Another drawback is that it may be difficult to implement certain applications without using a fixed infrastructure due to the lack of coverage. This can lead to a fragmented vehicular network, which hinders the dissemination of information in larger areas.

Approaches to vehicular communication – final remarks

Table 3.1 summarizes in a qualitative manner the analysis of approaches to vehicular communication. The term System Availability has a *Global* component that identifies the possibility of deploying and using the communication system on a wide variety of roads. The term *Link Availability* indicates the probability that a host will acquire the communication channel and establish a communication link in a timely manner.

Table 3.1 Comparison table for approaches to vehicular communication

	Approach to vehicular communication		
Parameter	Based on infotainment infrastructures	Based on cellular networks	Direct
Communication latency	Medium	High	Low
Link availability	Medium	Low to Medium	Medium to High
Data rate	Medium to High	Low to Medium	High
System availability • Local • Global	 High Low	 High Medium	 High High
Flexibility (of connection)	Low	Low	High
Cost competitiveness • Initial cost • Operational costs	 High Medium	 High Medium to High	 Low to Medium Null to Low
Communication service area	Medium	Large	Small to Medium
Exploit geographic relevance of data	No	No	Yes
Support for large area notifications	Medium	High	Low to Medium
Support for safety communication	***Low to Medium***	***Low***	***High***

We note that some of the parameters in Table 3.1 (e.g. latency, data rate) may depend on specific features of the communication system (e.g. a specific medium access control scheme or a specific routing protocol).

By looking at the properties of the approaches analyzed and at the requirements for safety vehicular communication, we have concluded that the direct communication approach is the most appropriate technique for exchanging safety data among vehicles.

3.3 Design components analysis

We provide in the following an analysis of the components of a safety communication system and the technologies that can be used for implementing them. We start by discussing the operation mode of the system and then focus on functional aspects such as networking techniques and transmission procedures. We then present the features we have selected to be part of a communication system that we propose.

3.3.1 Operation mode of the system

Reactive and proactive functionality

The vehicular communication system designed to support collaborative active safety systems can operate using a reactive or/and a proactive approach.

The reactive approach implies the sending of notifications to warn approaching vehicles about hazards in traffic. This happens when certain events take place in traffic, and the safety system in the (sender) vehicle decides that other vehicles need to be informed about these events.

The proactive approach implies the regular sending of information, which is used by the safety systems for detecting hazards in traffic and reacting to them.

In operational terms, the proactive approach can be more effective than the reactive approach because it is directed toward trying to avoid the occurrence of dangerous situations and, in case this is not possible, limiting their consequences. Using a proactive exchange of data, in-vehicle safety systems can predict well in advance the possibility of accident occurrence and can efficiently act towards eliminating it. In comparison, the reactive approach is directed only towards limiting the consequences of dangerous situations that have already occurred. Still, the reactive approach is valuable as there are cases when issuing notifications is useful for improving traffic safety. For example, when a vehicle breaks down it would be difficult for nearby vehicles to detect this event, whereas they can be timely and conveniently announced via a notification.

In terms of realization of the communication system, the proactive approach poses more difficult problems than the reactive approach. Thus, the proactive approach requires special care in designing the transmission procedures since it should assure the provision of vehicles with accurate safety data in a regular manner and at short intervals. This may imply a constant high occupation of the communication channel, which can induce problems such as difficulty of accessing the transmission medium and information loss. In comparison, the reactive approach needs only to accommodate bursty traffic and requires care in assuring the delivery of notifications in an area of interest. In normal operations, such notifications should not be too frequently issued.

Inter-vehicle communication and vehicle-to-road communication

The vehicular communication can basically take place only among vehicles (inter-vehicle communication or IVC) or between vehicles and servers located on the roadside (vehicle-to-road communication or VRC).

As previously mentioned, the development of a communication system between vehicles and roadside has a series of disadvantages for implementing safety applications since vehicles need to exchange data about each other. However, such systems can be used to provide vehicles with additional safety services such as the road conditions in a certain area [OMT+99, MKA+00, AHR01]. They can also provide delivery of information over wider areas, such as in the case of distant notifications. For example, a traffic jam notification at long distance (e.g. 2- 5 km) can be useful for drivers that may want to select another route to their destination. The use of an infrastructure can also solve the problem of fragmented networks.

The development of communication systems where vehicles directly exchange safety data represents the best alternative for implementing safety services. However, the realization of these systems is more difficult than using a road infrastructure, which can act towards managing the communication.

Short-range and long range communication

The communication system operation can cover a large or a small area. We call short-range communication the case when the system covers an area up to several hundreds meters (e.g. up to 800 m); anything greater we refer to as long-range communication.

The development of a system using long-range communication for supporting collaborative safety systems seems less appealing. This is because most of the proposed safety systems such as collision warning and collision avoidance are based on information about nearby vehicles (e.g. [KLP+99, ZKV00, TCE+00, PJL+00, MH02, BKP+02, KCF+03]). In addition, sending data in larger area can have several disadvantages. More powerful transceivers are needed and this can generate more interference. Even if a small transmission range is used, covering a larger area requires extensive use of routing, which can lead to channel saturation. A number of related works have shown in different contexts that long-range communication is less valuable for exchanging data used by onboard safety systems (e.g. [AF96, KBS+01]).

The short-range technology specifies a small transmission range and is appropriate for the transmission of safety data since neighboring vehicles usually have important information. With an appropriate choice of the physical media, this technology can allow for high data rate and lower interference levels [FAT99].

3.3.2 Networking technique

The vehicular network can be mainly organized using a client-server [Tan04], or a peer-to-peer [Gon01] approach.

The client-server approach implies that there is a central entity (i.e. a server) that regulates the communication. When some service is needed, the clients contact the server, which provides the requested service. This approach implies that a server is located on the roadside or one of the vehicles assumes the role of the server. If a server is used, the vehicles need to communicate via this server, which induces latency. As mentioned in the previous section, an extensive infrastructure containing and linking the servers then needs to be built on all roads where the service is provided. If the vehicles act as servers, they have to announce their existence to the clients and then provide the services requested by them. The procedure of selecting and replacing the server can be complex, and may involve extensive use of communication. This can hinder or delay the exchange of traffic data. Furthermore, a server as the service provider represents a bottleneck that can easily become saturated if many vehicles need the same service at the same time. This is the case when all vehicles traveling on the same road sector solicit the use of a safety service. In addition, the willingness of the car owner to let his/her vehicle act as a server may be an issue.

The P2P networking approach does not require any centralized control to manage the network behavior. Traditional P2P technology specifies that the communicating parties interact as equals and there are no central units for managing the exchange of information [Gon01]. Mobile peer-to-peer technology defines the application of the P2P networking approach in mobile environments [KSP+01], such as in the vehicular environment. Several features recommend the use of this technology for vehicular networking:

- *Equal communicating hosts:* assures that the communicating hosts have the same opportunity to send and receive safety-related data.
- *Flexible interconnectivity:* facilitates the direct establishment of the communication links between hosts, and thus the fast exchange of data within the network.
- *Community-based communication:* defines the virtual grouping of hosts that have similar interests.

A network formed by vehicles can be based on previous information or can be ad-hoc.

In a network based on previous information, the vehicles have communicated sometime before, e.g. using a negotiation phase where vehicles select the communication partners. This method usually implies that the communicating vehicles met each other in the past and kept data about each other. However, keeping information about all the possible vehicles would not be feasible. Also, vehicles may need data from vehicles they have not met before. Furthermore, additional delays may occur when selecting the communication partners.

Ad-hoc connectivity implies a dynamic establishment of communication links between hosts that do not need to have any previous information about each other. This type of connectivity assures high flexibility of the link management, and allows the spontaneous establishment and ending of the communication. Furthermore, it provides self-organization and supports the development of a fault-tolerant network.

3.3.3 Transmission procedure

Several transmission procedures may be applicable to vehicular communication. Unicast, muticast, broadcast, and scoped broadcast [Sta04, WC02] are possible candidates.

Unicast specifies the transmission of data from a source to a specific receiver. Within the vehicular network, this implies that the sender not only know the identity of the destination, but also decide that this destination should receive its data. This can be difficult and time consuming, as the sender needs to have previous data about the receiver in this case. Additionally, it is uncertain if the receiver will actually need the data provided by the sender, as the traffic analysis is performed from the point of view of the sender vehicle. A system of this type would also require a data forwarding mechanism

Multicast specifies that a source sends data to a group of receivers defined using some common properties. This implies that the sender knows the identity of the group and decides that this group would make use of its data. Similarly to unicast, forwarding of information needs to be implemented.

Broadcast specifies the sending of data to all receivers in the transmission range, which can further relay the received information. This type of communication eventually provides the receivers with the data needed but potentially at the cost of a very high channel occupation. It can thus provoke a broadcast storm, which leads to problems related to contention, collisions, and bandwidth congestion [TNC+02]. Also, this method can induce information overload, as not all the receivers will actually be interested in the received data.

A special form of broadcast is the scoped or directed broadcast, where senders broadcast their data and the receivers use special techniques for filtering the information received and eventually forwarding it. In this case, the senders need not know the identities of the receivers, the information management can be improved, and the hosts can be provided only with the data they can make use of. However, defining the methods for identifying the appropriate senders makes this approach difficult to realize.

Finally, we comment on two concepts for exchanging data among vehicles: communication based exclusively on physical data transfer and communication using contextual information.

The first concept is a method of communication that uses only techniques at the physical layer to fulfill the requirements (e.g. encoding, modulation).

The second concept makes use of the above techniques, but tries to improve the information management at higher layers by considering elements from the environment. Thus, techniques such as information filtering and forwarding are designed to operate using contextual information such as the position or velocity of vehicles.

3.4 Selected design features

We selected the direct communication approach for developing a safety communication system. We made this choice taking into consideration the scope of the system, the requirements on safety communication, and the advantages of this approach in comparison with the other approaches.

With regard to the operation mode of the communication system, both the reactive and the proactive approach are important and can successfully support the reduction of the number and the consequences of accidents. However, due to its advantages, the realization of a system using the proactive approach is desirable. Therefore, we have primarily opted to build a communication system that provides proactive operations. We further enhanced this system with a reactive operation mode, as particular situations require that specific notifications be sent. We also decided to encapsulate the safety data in short messages so as to optimize the use of the communication channel. This type of messages is also appropriate since data required for traffic analysis by active safety systems tends to be compact [MKO00, KTT+02, MH02]. The use of short messages also facilitates the fast update of safety information, which is essential for an accurate assessment of dangers in traffic [KBS+01]. To implement the proactive and the reactive operation modes of the system, we allow the communication system to use both regular updates of data concerning traffic safety and event-based communication. Thus, hosts issue messages containing safety information on a regular basis. Additionally, they can issue dedicated messages when significant events occur in traffic.

Due to the benefits of direct communication, this method was chosen as the primarily means for data exchange. However, by acknowledging the advantages of using a road infrastructure when one exists, we have considered a unified view of the vehicular communication by merging inter-vehicle communication with vehicle-to-road communication. We still call this direct communication, as in this case the vehicles communicate directly one to another, but can also have a direct communication with some devices installed on the roadside. Thus, vehicles traveling on roads and fixed communication entities that can be located on the roadsides are considered part of the same vehicular network and can communicate using the same protocol. We emphasize that the vehicles can communicate with an infrastructure but the communication is not based on such infrastructure.

We have selected short-range radio communication due to its advantages for exchanging safety data among vehicles. We have not opted for a specific wireless media because we aimed at developing a system that is able to use different technologies if this is needed. Nevertheless, certain requirements regarding transmission properties such as medium access, propagation, and interference need to be fulfilled by the media employed. Current systems working in microwave and millimeter-wave bands (e.g. around 2.4 GHz, 5.9 GHz, 60 GHz or 76 GHz) are the most suitable for implementing vehicular communication. Examples of advantages provided by such systems are narrow radio beams, reduced interference, and the possibility of having a wide band data transmission [FAT99]. Differences exist between these systems in terms of their Quality of Service (QoS). However, they are generally considered well adapted for supporting communication in the vehicular environment [ONS+00].

As a networking technique, we have opted for the mobile P2P. However, since we also allow VRC, we see the network more as a hybrid P2P network, where the hosts have the possibility of soliciting specific services from dedicated hosts (i.e. servers that can be located on the roadside). This network is formed in an ad-hoc manner.

The selected transmission procedure was scoped broadcast due to its advantages over the other procedures, and the possibility of realizing a communication system that takes advantage of the specific environment where the exchange of data takes place. Thus, we propose techniques for network management and information dissemination that take into consideration the current traffic situation of the communicating hosts.

As the concept for communication, we have opted for communication using contextual information. This is because one of the most dominant characteristics of the vehicular environment is that vehicles react and coordinate their driving maneuvers according to their traffic situation, and according to actions performed by nearby vehicles. This creates a unique need for situation awareness that we intended to provide support for in our vehicular communication system.

4. Vehicular communication specifications

We present in this chapter the communication and networking techniques that we propose for organizing the vehicular network and for exchanging safety data in the vehicular environment. We also introduce a vehicular communication platform intended to provide an implementation framework for these techniques, and to integrate the resulting communicating system within a vehicle.

4.1 Overview of networking and communication

The communication needs to provide timely and reliable exchange of safety data among vehicles. Random establishment of communication and frequent link failures need to be considered. Frequent transmission of data by a significant number of vehicles located in a small area needs to be accommodated. Forwarding of data may also be necessary. Additionally, the vehicles should be able to select the important information from the received data. The vehicles should also be able to send both regular data describing their current view of the traffic, and emergency notifications about hazards in traffic.

Considering the above factors, we apply two methods for controlling the dissemination of safety information in the vehicular environment. First, we define an organization of vehicles in virtual clusters, which help in managing the vehicular network. These clusters are created and maintained according to the current interest in traffic safety of the vehicles. Second, we design a special communication protocol, an anonymous context-based broadcast protocol. This is a scoped broadcast where vehicles send safety data and the receivers need to determine if they are the intended destination of the received data. For this, the receivers use a context-based filtering of information. The filtering is based on a set of rules defined using research results in crash analyses and guidelines for developing active safety systems. In this thesis, we illustrate the protocol operation with a basic set of rules as a proof-of-concept. We present below an overview of the network organization and the communication protocol. The following sections give details on the specific techniques that we have developed.

Vehicular network organization is essential for obtaining scalable and reliable communication. However, due to the very large number of vehicles, a system for tracking them all would be unfeasible. Additionally, only vehicles that are in close proximity one to another usually provide useful information [ZKV00]. Furthermore, a vehicle would not benefit by having data about a very large number of vehicles [AG96]. A solution that matches traffic dynamics is the organization of vehicles in manageable clusters. Therefore, we propose that the hosts (e.g. vehicles) organize themselves into Local Networks (LN) in which they exchange safety information. We define a local network as a community of hosts that share a common interest in the current traffic situation. A host belonging to a local network maintains information about other hosts from the same local network. However, for determining changes in the local network, a host also needs to analyze data sent by hosts not currently belonging to the same local network. A formal definition of local networks is provided below. We define a set V of vehicles equipped with communication devices and a set F of fixed hosts such as servers that can communicate with vehicles. A local network is defined as the set of hosts H that share a common interest in traffic safety. This interest is defined as a set of conditions that model a traffic situation in which the hosts exist at a given moment. Examples of such conditions are the separation distance between vehicles, the driving orientation and the velocity of vehicles, and the characteristics of the road on which the vehicles travel (e.g. slipperiness). The formal definition of a local network LNi is:

$LNi \subseteq F \cup V,\ i \in N$ (N is the set of natural numbers)

$\forall\ Hj, Hk \in LNi \mid Interest(Hj) \cap Interest(Hk) \neq \emptyset$

An example of the vehicular network organization is given in figure 4.1, where two local networks, one formed by three vehicles and a server (i.e. LN2), and another formed by two vehicles (i.e. LN1), are illustrated.

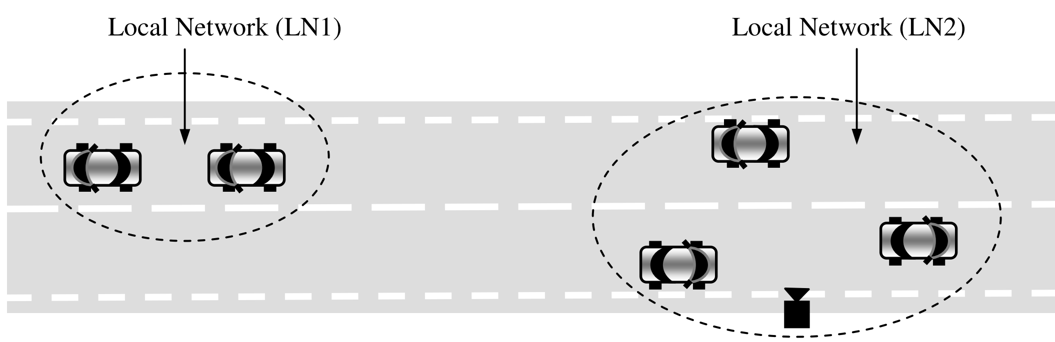


Figure 4.1 Local networks example

The specific methods for organizing and managing local networks are presented later in the chapter. Below, we give an overview of the criteria used for determining if vehicles are of interest one for another. Thus, the criteria were:

- C1. Vehicle's locations.
- C2. Service area extent.
- C3. Local network composition.
- C4. Parameters of the driving situation, e.g. relative distance between vehicles, relative heading, road status, vehicle status, road type.

Criterion C1 is due to the fact that positioning data are needed by in-vehicle safety systems to identify dangerous situations. For the vehicles to have location information, we considered them equipped with accurate positioning devices. This assumption is feasible since the market penetration of positioning devices is growing rapidly [Jon01], and their accuracy can be less than one meter [MDF+00, MH02, KTT+02]. For example, Global Positioning System (GPS) [GWA01] receivers can be used if they can give a precise indication of the position. However, the basic GPS system may not be accurate enough and improvements to it were developed, thus differential GPS systems and assisted GPS systems were proposed [MDF+00, DR01]. Also, since the GPS system is based on satellite communication, the positioning system should be enhanced with techniques such as Dead Reckoning [WM00], which supplements the possible temporary loss of satellite visibility. We note that alternative position systems can also be used, and the research area of positioning in vehicular networks is rapidly growing. For instance, the applicability of positioning techniques using radio ranging technologies (e.g. [MDF+00]) or of localization algorithms for wireless nodes (e.g. [CMH01, MLR+04]) in vehicular network are currently under investigation.

Criterion C2 is defined because research in traffic safety has indicated that vehicles in proximity usually have important data (e.g. [ZKV00]). In our work we have primarily considered a 300 m service area, which we encoded as Service Area Threshold (SAT). For defining the service area size we investigated proposals for safety systems such as in [KLP+99, ZKV00, TCE+00, PJL+00, MH02, BKP02, KCF+03]. The systems proposed in these works use sensors for detecting dangers around a vehicle. The development of these systems included extensive studies of the drivers' requirements and vehicles kinematics for defining the detection zone of the safety system. For instance, the range of forward collision warning (FCW) systems was defined as a function of the relative velocity of the vehicle on which the system is installed, and an identified collision object. Such systems specify a detection range of at least 100 meters [ZKV00]. However, most of the systems studied were autonomous, since as far as we know, very few proposals for collaborative systems exist. Using wireless data exchange, the detection of dangers in larger areas should be employed, since this is one of the main advantages of collaborative systems. Therefore, the service area of the communication system needs to be larger than the area defined for autonomous systems. Our selected value was thus three times larger than the value proposed for FCW systems. We also investigated via simulations the appropriateness of this value, and alternatives to it, from the communication performance point of view.

Criterion C3 is defined based on traffic analyses that indicated that the number of vehicles having important traffic data is usually limited (e.g. [AG96]). Thus, the local network composition sets an upper bound for the number of hosts that can coexist in a local network at a given moment. To be able to assess dangers in traffic, a vehicle needs to keep data about a number of vehicles in front of, behind, and lateral to [ZKV00] itself. Considering the accident dynamics, keeping data about several vehicles in front, both in the same lane and on adjacent lanes is of major importance. Also, the information about vehicles situated immediately behind or two vehicles behind a subject vehicle, which travel in the same lane and on adjacent lanes, is important [MCG+02]. In addition, data about vehicles situated in front and behind a subject vehicle that travel on lanes that are not adjacent may be of use. However, research in traffic safety has indicated that having information about more than 3-4 vehicles traveling in front of a subject vehicle does not contribute to the improvement of traffic safety [AG96]. Considering the above points, the number of vehicles a subject vehicle has interest in can be limited. For example, on a bi-directional road with one lane per direction a vehicle may need to keep data about 3 vehicles in front of or in parallel to it in both directions, 2 vehicles in behind it in the same lane, and 2 vehicles behind it in the adjacent lane (i.e. since these vehicles may be involved in an accident that propagates and can affect the subject vehicle). This sums up to 10 vehicles. In our proposal we encoded the number of hosts that can coexist in a local network as the Maximum Number of Hosts (MNH). With consideration given to a wide variety of traffic scenarios (e.g.

[KLP+99, BKP+02, TCE+00]), the most common size of vehicles (e.g. 4-7 meters), the average number of lanes of a road (e.g. less or equal with 6), and the size of the communication area, an appropriate range for MNH would be from 10 to around 40 vehicles. Therefore, we empirically set MNH to 20 and investigate the appropriateness of this value in different scenarios. We note that MNH can also be adapted depending on the type of road on which the vehicles travel.

Criterion C4 addresses parameters indicated in accident reports as important for the development of traffic situations into accidents (e.g. [USDT99, NSD01, SSN03, USC03, Eva04]). These parameters are used by in-vehicle safety systems (e.g. collision warning and collision avoidance) for identifying hazards in traffic (e.g. [TCE+00, PJL+00, KCF+03]).

The communication protocol that we propose employs anonymous broadcast for disseminating short messages between vehicular hosts. Each host broadcasts short messages that can be received by other hosts in its transmission range. We did not consider the addresses of the communicating hosts to be a priori known. Therefore, our protocol requires the receivers to analyze the content of the received messages to determine if they are the intended destination. When the information embedded in a received message is considered important for traffic safety, the receiving host *accepts* this data. Otherwise, it discharges the message. A receiver can also decide to forward a message based on the embedded data. Consequently, the communication protocol is context-based. We refer to the process of analyzing, considering, dropping, or forwarding a message by a host as information filtering and forwarding. To implement the filtering and forwarding of data, a host considers various elements related to its current traffic situation. The communication is illustrated in figure 4.2, where the white boxes represent data describing other hosts that was accepted by the respective vehicle. This data is further used for organizing and maintaining local networks. As previously mentioned, the protocol functionality is dual, i.e. proactive and reactive. For the constant update of data describing the traffic, we defined Basic Safety Messages (BSM). We also allowed vehicles to communicate with servers located on the road side if these exist. Consequently, the content of basic messages is different for vehicles and for fixed hosts because the latter are not characterized by motion parameters. For simplicity, throughout this chapter we use the terms basic safety message and basic message interchangeably. For sending notifications about hazards in traffic we defined Warning Messages (WAM). We note that other types of messages can be defined to extend the protocol functionality.

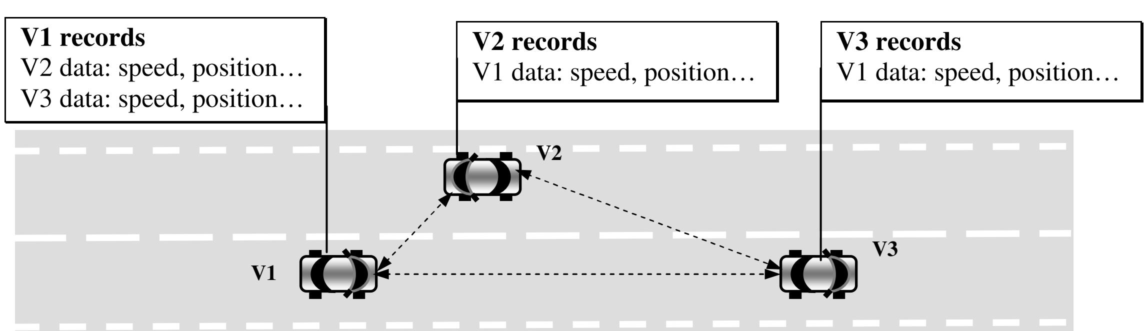


Figure 4.2 Communication example

4.2 Protocol operations

The protocol functionality relies on the following rules for information management:

Rule I. *Acceptance of a message by a host*. Received basic safety messages and warning messages can be accepted if the information filtering indicates that they contain data of interest. The information contained by accepted messages is written in a database associated with the communication protocol. Messages that were already accepted or are older than the currently accepted messages received from the same senders are dropped. All messages that are not accepted are dropped.

Rule II. *Local maintenance of data describing senders*. A host H maintains data about a sender host S as long as within a time interval T_record another BSM from S is received by H. If this event does not happen and the time interval T_record has passed, the host H removes all information about host S. When a new BSM is received by H and the information contained by it is recorded, the time interval T_record related to this record is reinitialized.

Rule III. *Generation and transmission of Basic Safety Messages.* A host H generates for transmission basic safety messages at short regular intervals. A timer Tint_BSM is associated with the generation of these messages and is initialized each time a BSM is transmitted. When this timer triggers, a new BSM is generated for transmission. If, due to medium access, a BSM cannot be transmitted until a new BSM is generated, the old BSM is erased and the new BSM is considered for transmission.

Rule IV. *Transmission of messages other than Basic Safety Messages*. Messages other than BSMs are transmitted as the result of events that occurred in traffic.

Rule V. *Forwarding of messages*. Basic safety messages can be forwarded based on specific methods that depend on the organization of the vehicular network. Warning messages are also subject to retransmission.

Rule VI. *Priority of messages*. Warning messages and basic safety messages sent by a subject host have the highest priority. Routed BSMs and retransmitted WAMs have lower priority and are sent after high priority messages.

Rule I is employed because the basic safety messages contain the information necessary for a receiver to determine if a sending host is of interest. Additionally, a host is allowed by default to accept any received warning message. However, the protocol can be configured to specify the conditions that need to be fulfilled for a host to accept warning messages. These settings are introduced when we present the safety information content and digest. Rule II is used to avoid the maintenance of stale data about hosts that are not of interest anymore. Rule III assures that a host regularly provides the other hosts with up-to-date data describing its view of traffic conditions. Rule IV is used to generate notifications about dangerous events or other events of interest that may occur in traffic. Rule V is employed because there are situations when information forwarding is needed to provide the hosts with more complete traffic data. Rule VI is employed because any subject host is primarily interested in successfully sending its own messages (i.e. BSMs and WAMs) so the other traffic participants can acquire timely knowledge of its characteristics and situation in traffic. If a WAM and a BSM compete for transmission, we choose to let the WAM be transmitted first. This is because the WAM describes a danger that already exists.

The conceptual representation of the protocol functionality for reception of messages and for transmission of BSMs and WAMs is presented in figure 4.3 and 4.4 respectively.

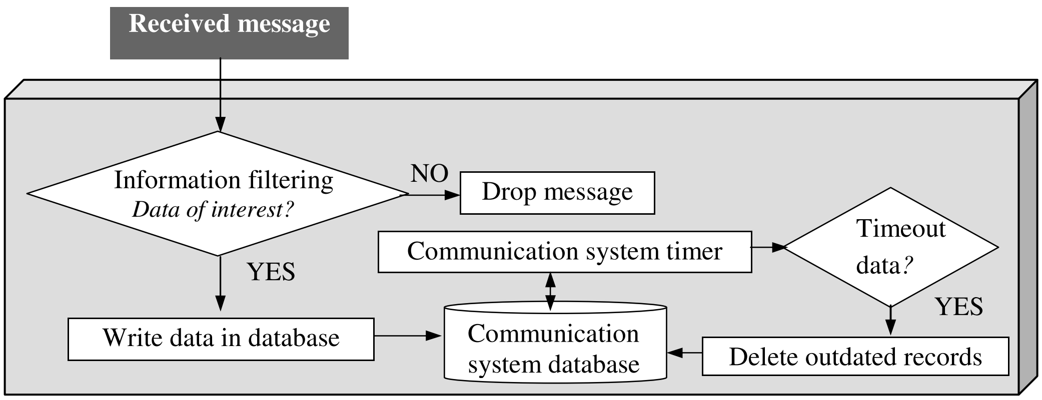


Figure 4.3 Communication protocol functionality - message reception

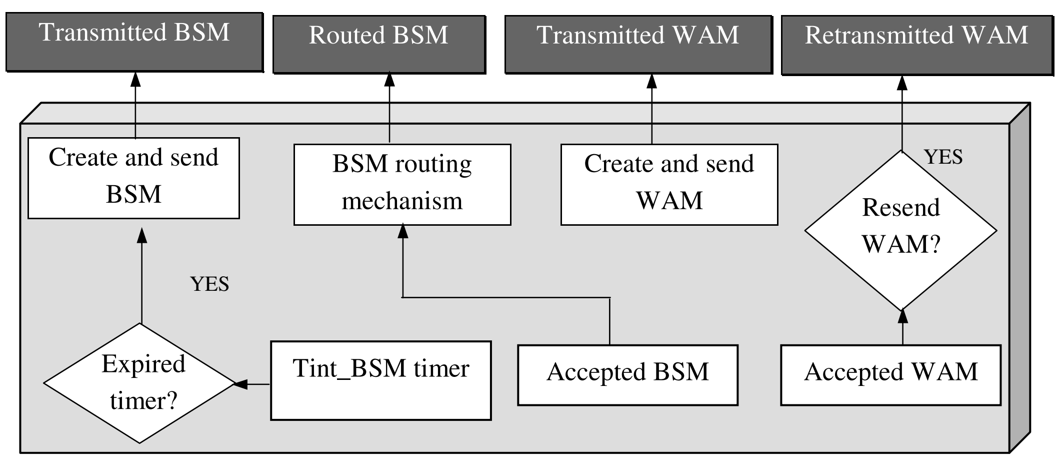


Figure 4.4 Communication protocol functionality – message transmission

The procedures used by a host for accepting, sending, and forwarding messages make use of the information recorded in the database associated with the communication protocol. Therefore, the database is updated at very short intervals (i.e. 5 ms) with data describing the subject host. In addition, the database is updated when a message is accepted, and when a message is issued by the subject host.

All messages that need to be sent, with the exception of basic safety messages generated by the subject host, are recorded in a dedicated queue of the communication protocol. This is because they may not be transmitted immediately due to transmission problems such as medium access, or they need to wait until higher priority messages are transmitted. The queue is divided into four sections: one for WAMs sent by the subject host, one for retransmitted WAMs, one for routed BMSs, and one for other messages if they are defined. Each section operates following the FIFO (first-in-first-out) model, and the transmission of messages from the queue is controlled by their priority. As previously mentioned, WAMs and BSMs issued by the subject host, which have the highest priority, are sent before any other messages. Then, retransmitted WAMs and routed BSMs are transmitted. Each section of the queue has an associated timer that controls its operations. Thus, when a section is not empty, it tries to empty itself after a short interval (i.e. 0.01 s), which is measured by the associated timer. However, the messages are transmitted only if their priority allows this, and certainly, if the transmission medium can be used. Each section of the queue continues to try to empty itself until no messages are left. Old messages are usually erased after a time interval, which is dependant on the protocol implementation. We note that other control elements (e.g. specific timers) can be associated with the queue when specific methods are used for sending messages. For instance, we defined specific time randomizers associated with the sections where routed BSMs and retransmitted WAMs are recorded. These timers are used by the information forwarding techniques. For practical reasons, the sections of the queue are limited in size. If they overflow, the oldest message from the section is removed and the current message is inserted.

BSMs generated by the subject host are intended to be sent immediately after they have been issued. However, this may not be possible due to problems in accessing the transmission medium. Therefore, a generated BSM is kept in a one-dimensional transmission buffer. If a new BSM is generated and the buffer is not empty, i.e. an older BSM was not yet transmitted, the content of the buffer is erased and the new message is written into it.

4.3 Network operations and organization

Network operations overview

The management of local networks is done via specific network operations that consider data provided by the filtering mechanism, data registered in the communication system database, and timeout information provided by the system timer. These operations are:

- Initiate a local network
- Add a host to a local network
- Remove a host from a local network

An overview of the network management is given in figure 4.5.

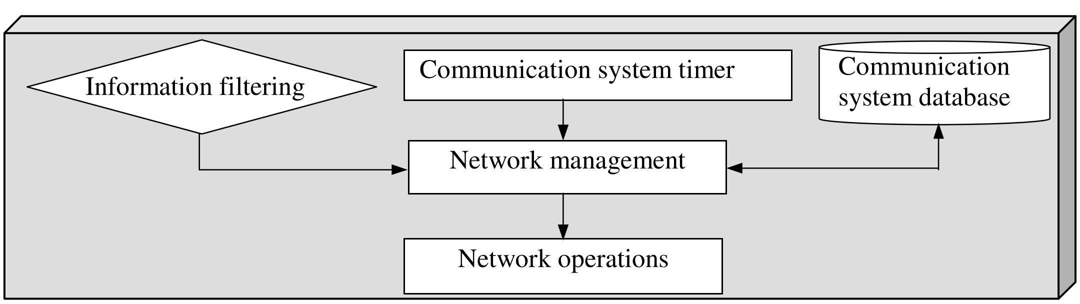


Figure 4.5 Network management overview

Vehicular network organization

We define and discuss here two conceptual methods for organizing the vehicular network. These methods are focused on the individual and the associative nature of the traffic; we call them *host-oriented* organization and *cluster-based* organization.

Host-oriented organization is based on the individual nature of a host focused on avoiding accidents. Within this method, each host defines, constructs, and maintains its own local network. In case of a vehicle, this network is initiated as soon as it enters the traffic. For a fixed host, the network is initiated when this host becomes operational. Within this approach, each host takes the role of an organizer host by analyzing the information received from other hosts and deciding which of them should belong to its own local network. This group of hosts is continuously updated. The removal of hosts from a local network is time-based, i.e. if the information describing a host is not updated in a time interval, this host is removed. When employing the host-oriented approach, the local networks corresponding to different hosts can overlap. In addition, the hosts are responsible for sustaining the global traffic awareness by forwarding some of the information received. An example is presented in figure 4.6. In this case, each vehicle creates its local network according to its current interest in traffic safety. For example, V1 and V3 are part of V2's local network, but only V3 is part of V4's local network.

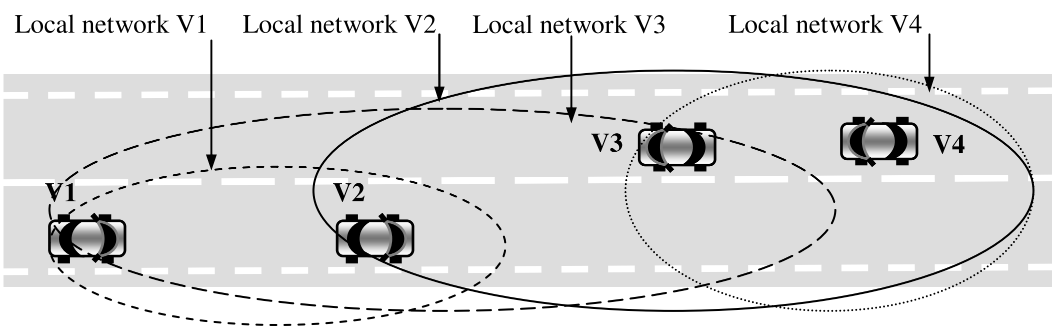


Figure.4.6 Host-oriented organization example

Cluster-based organization is based on the associative nature of the traffic for forming distinct groups of hosts with a similar interest in traffic safety. Thus, the hosts deciding that their traffic safety can benefit from such an association form local networks. An example of four vehicles traveling on a road with a divider is presented in figure 4.7. Here, V1, V2 and V3 decide to form a local network. V4, which travels on the other side of the road, is not part of this local network since its traffic data is of no immediate interest for the other three vehicles.

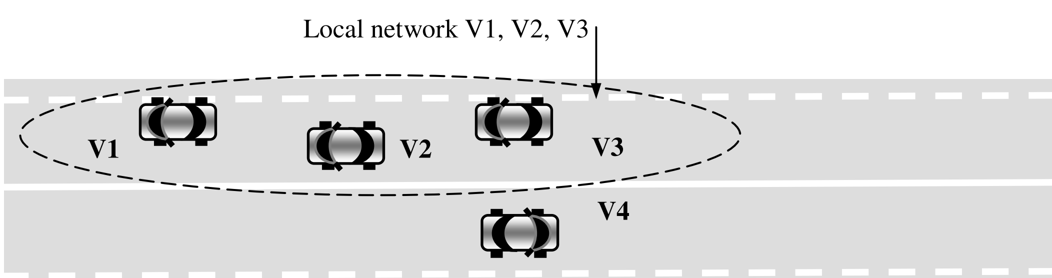


Figure.4.7 Cluster-based organization example

Within the cluster-based organization, each host belonging to a local network has to maintain information about all the other hosts from the local network. Therefore, each host needs to be provided with management functions for joining, leaving, or initiating a local network. A basic method for joining and establishing local networks is using time constrains. Thus, if a host enters the traffic and does not receive within a time interval information of interest about a currently formed local network, it initiates a new one. Otherwise, the host joins an existing local network. As mentioned before, host membership to a local network is interest-dependent. Thus, a host can choose to join another local network if the data sent by hosts belonging to it is considered more valuable than data sent by the members of the local network in which the vehicle is currently registered. When a member leaves a local network, the other hosts need to remove the data associated with the departing host. This can be done using a time-based method, or issuing a leaving announcement. The sending of a leaving announcement has several drawbacks. Due to the frequent fragmentation of the network, such notifications may need to be sent very often. This may lead to an overload on communication and can hinder the reception of more important data. Also, the leaving notification may not reach some hosts if the network is fragmented. Therefore, we consider more appropriate the basic time-based method that requires a host to remove the records associated with other hosts if the data describing them is not updated within a time interval. An extension of the cluster-based organization is to allow the hosts to be members of more than one cluster. This approach can allow better analyses of complex traffic situations but impose difficulties in managing local networks, as a host needs to have data about hosts from different local networks. Since a host aims to keep data about all members of a local network but the composition of the network is limited (and implicitly the number of hosts a subject host can keep data about is also limited), additional network management functions are needed.

The host-oriented organization considers each host to be responsible for organizing its own local network according to its singular interest. The cluster-based organization assumes a group of hosts is collaborating to organize a local network. These hosts aim at maintaining consistent group membership throughout the local network. The establishment and maintenance of local networks is more flexible within the host-oriented organization, since every host decides whether or not to register sender hosts. Thus, operations such as joining or exiting a local network are not necessary. We note that these procedures can be quite complex in the cluster-based approach, as the hosts need to collaborate to establish and maintain the local network. Additionally, a strict cluster-based organization may not always accurately represent the safety needs of vehicles in traffic. For example, hosts situated at the borders of local networks may not benefit from data sent by hosts that are part of adjacent local networks. This is because the hosts maintain only data sent by members of the same local network. This situation can be improved by using multiple memberships and forwarding of information between local networks.

In both approaches, situations can exist in which a host is not able to directly receive information of importance for its traffic safety due to communication problems (e.g. packet collision, shadowing). Therefore, we provided the hosts with the capability to retransmit, when necessary, received safety data. We note that in both cases this can pose difficulties, as the hosts may need to identify other hosts that do not have data about one another. Within the cluster-based approach this may be simpler to implement as a member of a cluster should have information about all the other members. Still, when the cluster is formed the vehicles that should be part of it may be not included if their communication partners do not try to resend their data. To keep the hosts informed about dangerous situations in traffic, we allowed them, by default, to accept warning messages sent even by hosts that are not part of their local network. Warning messages can, however, also be set to be delivered only within a local network.

Considering the issues mentioned above, we decided to focus on the development of a safety communication system using the host-oriented approach. We note that work has also been done on the cluster-based approach, but more investigations are needed to assure proper operations. Consequently, we see this approach as subject for future work.

In the rest of this chapter, we present details on the techniques proposed for implementing data communication and network management with consideration given to the host-oriented network organization.

4.4 Safety information

As previously mentioned, our protocol uses basic safety messages (BSMs) for proactive operations and warning messages (WAMs) for reactive operations. The size of each type of messages and the format of the message fields are implementation-dependant. BSMs include information used by safety systems (e.g. collision warning and avoidance) to determine if a dangerous situation has occurred or could occur in traffic in the near future. Thus, the content of these messages was defined considering the information needed by safety systems and data relevant to assessing the possibility that accident could happen [MH02, KCF+03, KLP+99, TCE+00, ZKV00, Eva04]. However, since it is possible for future systems to need or use additional data, we provided a reserved field in the message structure where such information can be encoded.

We note that the large majority of events in traffic should be determined using the data included in BSMs. Therefore WAMs should mainly address those situations where an explicit notification can significantly help increase traffic safety or traffic convenience. An example of such a situation is a major vehicle failure that makes this particular vehicle dangerous to other traffic participants. As presented below, we included in BSMs information about vehicle status. We also provided the possibility of including additional data about the vehicles' components (e.g. brake and steering wheel status). Still, in case of sudden failure of a vehicle, it is appropriate to rapidly warn the nearby vehicles, as this helps in obtaining a more efficient response to the situation. Another example in which WAMs are useful is an indication about a traffic jam that can be used to reduce the impact wave on the traffic, avoid sudden braking of a vehicle, and allow a driver to choose an alternate route to a destination. We note that the generation and transmission of emergency notifications is closely related to the functionality of the onboard safety system. Such a system is responsible for determining when danger occurs and when notifications need to be sent. The safety system should also specify how a warning message should be send, e.g. its frequency and time validity, in order for the data provided via this notification to be valuable for other vehicles. Therefore, in our protocol we have mostly focused on supporting the efficient distribution of warning messages rather than providing specific techniques for disseminating WAMs in particular situations. This is because covering the whole range of such situations would be infeasible. We also believe that the specific processing of warnings should be part of the functionality of the safety systems rather than part of the communication system. Thus, we provide a general mechanism for issuing warnings, which can be further specified for different safety applications.

4.4.1 Basic safety messages

Each received BSM that has not been previously received is analyzed by the receiving host to determine if the data contained by it is of importance. If this is the case, the receiver accepts the message and records the data. Otherwise, the message is dropped. An accepted message is forwarded if the mechanism used for information forwarding indicates this. The BSMs are different for vehicles and for fixed hosts since the fixed hosts are not characterized by motion data. The basic safety messages contain two identifiers indicating the identity and the type of the sender host. Each host has a unique identity (e.g. the serial number of the installed communication equipment). The host type is encoded via two values: *fixed* and *vehicle*. Each BSM also contains a sequence number. Each time a message is sent, the sequence number is increased and included in the message. When the counter for the sequence number reaches its highest possible value, it returns to null and then starts counting again. The maximum value of the counter is implementation-dependant but needs to be large enough to accommodate the transmission of a large number of messages. A host that maintains data about a sender does not accept a BSM from this sender if the message has a sequence number smaller than a previously accepted message received from the sender. (We note that an exception is made for messages with very small sequence numbers such as 0, 1, or 2 that are received after messages with sequence numbers close to the maximum possible value of the sequence counter).

BSM messages for vehicle hosts

The structure of BSMs for vehicles is presented in table 4.1.

Table 4.1 Basic Safety Message – vehicle host

TID	SID	MSqn	PS1	PS2	VSp	VSt	VHd	HIDs	RID	RT	RSl	NH	RSp	OI

TID - Type identifier
SID = Sender identity
MSqn = Message sequence number
PS1 = First (latest) positioning indication
PS2 = Second (earlier) positioning indication
VSp = Vehicle speed
VSt = Vehicle status
VHd = Vehicle heading (if available)
HIDs = Identities of hosts in sender local network
RID = Road identity (if available)
RT = Road type (if available)
RSl = Road slipperiness indication (if available)
NH = Number of hosts in the sender local network
RSp = Road speed limit (if available)
OI = Other information e.g. brakes status, blinkers status (Note: field currently reserved)

These BSMs contain motion data indicating the speed, the heading, and the position of a vehicle host. Two consecutive positioning records are included in BSMs and indicate the most recent location and the second most recent location of the sender. We included two positioning records so the onboard safety system could perform more advanced analyses and predict with more accuracy the movement of a vehicle. We also use these data within the information filtering process employed by the communication system. Data about vehicle status and road characteristics are included if available. Here, available means that there is a technology integrated in the vehicle that can provide this data or this data has been previously received via vehicular communication. The road characteristics include the road type that indicates if the road contains a divider (i.e. the road can be *divided* or *undivided*), and if it is an *urban* or a *rural* road. Another piece of information included in messages is an indication about the condition of the road surface with regard to slipperiness. This was encoded using two generic values: *dry*, meaning that the road surface is optimal for driving, and *slippery*, meaning that some phenomena such as ice or heavy rain may influence the movement of the vehicle on the road. The messages also include the speed limit associated with the road the vehicle is traveling on, and the status of the vehicle. The vehicle status is encoded with two generic values: *good*, meaning functional vehicle, and *poor*, meaning that the functional parameters of the vehicle are below nominal values. The BSMs also contain the number of hosts that belong to the same local network as the sender host, and their identities. This information is used by the communication protocol for filtering messages. The *Other Information* field is reserved for future use. It can contain data such as brake status or blinker status if this is needed by the safety system installed in vehicles.

BSM messages for fixed hosts

The structure of BSMs for fixed host is presented in table 2.

Table 4.2 Basic Safety Message – fixed host

TID	SID	MSqn	PS	HIDs	NH	HServ

TID - Type identifier
SID = Sender host identity
MSqn = Message sequence number
PS = Positioning indication
HIDs = Identities of hosts in sender local network
NH = Number of hosts in sender local network
HServ = Services provided by the fixed host with specific information

The messages include the position of the fixed host and the number and identities of other hosts from the same local network. The messages also contain the services provided by the fixed host, with their specific information. Two basic services are defined for all fixed hosts. These are:

- Road identification (RI): road ID and type.
- Speed limit on road (SLR): speed limit value.

This data can be used by vehicles when filtering the received information. Additionally, we have defined several services that can be provided by a fixed host:

- Road slipperiness (RS): data about road slipperiness in a road perimeter associated with the fixed host.

- Road hazards (RH): indications about hazards associated with the road such as the existence of current working places and dangerous spots.
- Warning messages store&relay (WSR): indication of the fact that the fixed host is configured to store and retransmit certain warnings.
- Other services, e.g. infotainment: the identities of other services.

We note that to provide some of the services above, the fixed hosts need to be equipped with devices that allow collection and analysis of traffic data, e.g. for determining the road slipperiness or the road congestion. The RS service provides data used by vehicles for assessing the possibility of dangers in traffic. This data is also used when filtering received messages. The RH service provides information that can be used by collision warning systems for notifying the driver. The WSR service specifies that a fixed host can keep for a certain interval an accepted warning message, and then retransmit it. This depends on the type of emergency indicated in the warning message. This service is provided to notify upcoming vehicles about a dangerous event that exists on the road, because those vehicles may not have received data about the event due to network fragmentation. Previous works (e.g. [BH00]) have indicated the advantages of using such technique when disseminating data about dangerous events in traffic (e.g. data about traffic jams).

Transmission rate for Basic Safety Messages

BSMs are designed to provide a vehicle with accurate and timely information describing the current traffic situation. These messages need to be delivered in a timely manner, and need to be sent frequently enough that vehicles are able to perform a correct assessment of hazards in traffic. However, the channel bandwidth is limited, and delivering BSM with very high frequency can lead to channel congestion, and consequently to higher delays and information loss. When many vehicles travel on the road, the problem is more acute as the contention for the medium is higher. Therefore, to define an appropriate value for the transmission rate of BSMs, both the requirements of safety applications and the load on the communication channel need to be considered.

Two approaches can be taken to disseminate BSMs: a fixed rate approach, where BSMs are transmitted at fixed time intervals, and an adaptive approach, where BSMs are transmitted at varying time intervals. In this work we have limited the fixed hosts to the use of the first approach, as they only provide services for vehicles when they exist on the road. For BSMs generated by vehicles, we have investigated the use of both approaches. For the fixed rate approach, we investigated appropriate values for the transmission intervals from a communication point of view, and compared the results against the demands of safety applications. For the adaptive rate approach, we considered diverse aspects of the traffic dynamics, and offer in the following an example based on the velocity of vehicles.

The goal of the adaptive approach is basically to control the transmission rate so as not to overload communication, while keeping the hosts informed. One solution may be to apply empirical algorithms that use an additive or multiplicative method for reducing the transmission rate once some vehicles are aware of each other. In this case, the transmission rate is decreased with a fixed value every time when a number of messages (e.g. 100) is generated. The process is repeated until a minimum value of the transmission rate is reached. However, this may leave hosts uninformed as new vehicles may join the traffic. Therefore, we considered the use of contextual information to adapt the transmission rate. We note that the applied algorithms need to be general enough to accommodate a variety of traffic situations. For very specific situations such as traffic jams or singular accidents on highways it is also possible to apply more specific algorithms, such as the algorithms proposed in [BH00] and [YLZ+04].

An interesting aspect in the dynamics of traffic is the relationship between the velocities of the vehicles and the traffic density. When a low number of vehicles are on the road, their velocities can be high as traffic flows freely [RML02]. At high velocities the vehicle distribution is lower as the separation spaces between vehicles are relatively high. For dense traffic the velocities of the vehicles are reduced, and have fairly low values for very dense segments of traffic [Eva04]. Consequently, when vehicles travel with low velocity, the transmission rate of BSMs can be lower since the movement characteristics of the vehicles do not change rapidly, and in-vehicle safety systems can still correctly identify hazards in traffic. When the velocity is higher, the frequency of sending BSMs also needs to be higher as major changes in position are frequent. We note that the disseminating rate of BSMs needs to have both a minimum boundary that supports an efficient operation of the safety system, and a maximum boundary that prevents channel overload.

In the following, we introduce a proposal for an algorithm that considers the velocities of the vehicle when adapting the transmission rate of BSMs. This algorithm specifies the calculation of the transmission interval between two consecutive BSMs. We differentiate between velocities that are characteristics to urban roads and velocities characteristics to highways and country roads. We note that regular speed limits in many EU countries are 30 to 50 km/h in residential areas, 70 to 90 or 100 km/h for country roads, and 100 to 150 km/h for highways. We define the maximum time interval for delivering BSM as Tmax_BSM and the minimum interval as Tmin_BSM. Based on previous studies (e.g. [WH98, KTT+02]) and analyses of traffic accidents, we set Tmax_BSM to 0.5 seconds and Tmin_BSM to 0.1 seconds. We define Vmin as a minimum of the regular velocity for a vehicle, and set it to 20 km/h. We then define a high velocity threshold *Vhst* as a minimum of the velocity regularly used by vehicles on higher-speed roads: We set this parameter to 90 km/h based on the speed limits on rural roads in many EU countries. Considering the above parameters, the transmission interval *Tint_BSM* for BSMs is defined below. *Vveh* is the current velocity of a vehicle.

$$T\text{int}\_BSM = \begin{cases} T\max\_BSM, Vveh \le V\min \\ T\max\_BSM * \dfrac{V\min}{Vveh}, V\min < Vveh \le Vhst \\ T\min\_BSM, Vveh > Vhst \end{cases}$$

We note that the third member of the above formula can be modified to be similar to the second member, in which case a smaller transmission interval can be obtained for relatively high speeds. However, this can also lead to a more extensive use of communication. Therefore, we choose to impose a fixed transmission interval for high speeds that is appropriate for diverse traffic safety applications and may not introduce channel congestion. We also note that the above method is general, so as to cope with all traffic situations, and further specifications of rate adaptation algorithms are possible, and are subject to future work.

4.4.2 Warning messages

Warning messages (WAM) can be generated when emergency situations occur in traffic. The sending and forwarding of warning messages are regulated by the functionality of the safety systems located in a vehicle. These systems are also responsible for settings the parameters in the warning messages and indicating if the warnings should be delivered locally, i.e. within the local network of the sender, or should be delivered in an area beyond the local network. It is of great importance to achieve a strong correlation between the detection of hazards and the generation of warnings. Thus, there are situations when vehicles may not need to issue notifications on their own, but only relay WAMs received from other vehicles. This helps to avoid communication channel overload. For example, when a vehicle is stopped in a driveway, the vehicles approaching it significantly reduce their velocities. As a consequence, they can generate notifications to warn upcoming vehicles. These notifications are further relayed by the receiving vehicles. Vehicles that are at some distance from the event can experience the same speed reduction and can issue their own WAMs. Obvious, this increases the load on the channel as the new and the older messages (i.e. the forwarded messages) coexist in the network. However, if the vehicles corroborate the reduction of their speed with the reception of the notification about the stopped vehicle, they can refrain from transmitting their (own) notifications. New transmission is unnecessary because new notifications would refer to the same event and other vehicles should be informed about it via the initial WAM and its retransmissions. However, special attention needs to be given to such processing and the identification of situations when explicit notifications should not be sent so as to avoid leaving vehicles uninformed.

To generate warnings, we have identified two main approaches: singular generation and continuous generation. The first approach specifies that a WAM is issued when the safety system identifies an existing dangerous situation in traffic. This message is then repeated a small number of times, (e.g. 3-5) to increase the probability of being received by other hosts. The second approach specifies that when the safety system in the vehicle identifies a dangerous situation, an initial WAM is issued. Copies of this message are generated until the situation is not considered dangerous anymore, or until it is assumed that the vehicles that needed to receive the notification were informed. In this case, the overload of the channel can be higher than in the previous approach. If a large number of vehicles detect the dangerous situation and start to issue WAMs continuously, the overload of the channel will be significant. Therefore, in this case we have considered the application of rate reduction algorithms that adapt the transmission rate of WAMs using an empirical additive or multiplicative rate adaptation. This implies that the transmission rate is modified with an implementation-dependant factor that is added or multiplied to a fixed rate value. A similar approach has been taken in [YLZ+04] with positive results. We note that we did not apply the same approach as for BSMs due to the differences in generation and transmission of WAMs and BSMs. Thus, warning messages can be delivered in an area larger than the extent of a local network, and they are usually accepted and forwarded by a host. The dynamic of propagating these messages and their rate of multiplication needs to provide the hosts in an extended area with information in a very short time. Vehicles facing emergency situations tend to travel with similar velocities, e.g. high and then low velocities in the case of an accident on a highway. Even when the vehicle travels at a low speed, a warning message still needs to be delivered as fast as possible as it indicates a situation that can constitute an immediate danger. Therefore, a rate adaptation algorithm using the velocities of the vehicles cannot be considered appropriate.

We note that the second approach can be considered a special case of the first approach in certain situations. For instance, even if a vehicle needs to issue warnings about the same static event as the above-mentioned vehicle stopped in the driveway, these WAMs can be considered different as they have a different moment of transmission. In this work we have mainly focused on the transmission of WAMs using the singular approach, especially when analyzing the communication system efficiency in specific accident scenarios. For the continuous approach, we have investigated the dissemination of WAMs at a constant rate when particular vehicles detect hazards in traffic.

As previously mentioned, a host usually accepts a received warning message. However, the protocol can be configured so that the receivers perform filtering of WAMs. To allow this, two options are included within warning messages. The first option addresses the acceptance of notifications issued by hosts from the same local network. It is possible to issue warnings that should be received only if the sender is part of the receiver's local network. To implement this, we provided a field *default acceptance* in WAMs, which is by default set to true but can be invalidated. True means that the WAM can be accepted by any host. False means that the WAM can be accepted only by hosts from the same local network. The second option to allow filtering rates the degree of urgency represented by the dangerous situation that required the WAM to be sent. Thus, warning messages contain an indication of the *criticality* of the event. We used this term to indicate how dangerous a certain traffic situation is at a moment in time. Two parameters are used to describe criticality of a dangerous situation: the *criticality type* and the *criticality level*. The criticality type provides a high-level description of the situation. We defined two types of criticality: *imminent*, meaning that a dangerous situation will immediately occur, and *existing*, meaning that a dangerous situation already happened. The criticality level is a parameter that provides the possibility of setting a numeric value (e.g. 1–5) to indicate the level of emergency associated with a dangerous situation. The criticality level and type can then be used when deciding if a warning message should be accepted by a host.

The WAM structure is presented in table 4.3. These messages contain the sender identity and the moment when the message was sent. These two fields uniquely identify the transmitted message. The messages also contain the position of the dangerous situation or event, and a short description of it. We note that the position of the dangerous situation or event is considered similar to the position of the host that issued the warning if this host is a vehicle. If the sender is a fixed host, the position of the dangerous event can differ from the position of the sender. For instance, if a broken vehicle exists on the road and the fixed host sends notifications about this vehicle, the position of the vehicle is included in the message. We defined several descriptors for dangerous situations: *existing accident*, *obstacle on the road, traffic jam, high possibility of collision*, *highly slippery road*, *vehicle breakdown*, and *undefined danger.* Other information included in the WAM messages is the criticality type and level, the retransmission counter, and the default acceptance indication. As with BSM, a reserved field, i.e. *OED,* is allocated for future use.

Table 4.3 Warning Message

TID	SID	SitPS	SndTime	RtrCnt	DSD	CrT	CrL	DA	OED

TID - Type identifier
SID = Sender host identity
SitPS = Dangerous situation position
SndTime= Sending moment of the warning message
RtrCnt = Retransmission counter

DSD= Dangerous situation description
CrT = Criticality type
CrL = Criticality level
DA = Default acceptance
OED – other emergency data (field reserved)

4.4.3 Other messages

Other types of messages can be defined and used within the vehicular network. To illustrate, we offer a proposal for infotainment messages. These messages can contain data about services and resources offered by hosts, and other information of general interest. We defined two categories of infotainment messages, the *resources/services-oriented messages* and the *general interest messages.* These messages have lower priority that BSMs and WAMs.

The *resources/services-oriented messages* also contain two types of messages, the *resources/services discovery messages* and the *resources/services advertising messages.* The *discovery messages* are request messages sent by hosts that would like to use certain services and resources offered by other hosts. These messages contain the sender identity and the list of requested services and resources. They also contain additional identification and authentication data about the requester host. The *advertising messages* are inviting messages that indicate resources and services available on different hosts. These messages contain the sender identity and a list of offered services and resources with a short description.

The *general interest messages* contain data describing points of interest related to traffic (e.g. nearest medical center). These messages contain the sender identity, the information identity, and the information content.

We note that this is only an example of possible extensions of the protocol, and the work presented in this thesis focuses exclusively on the safety operation of communication.

4.5 Information forwarding

We provide below details on the techniques defined for forwarding information within the vehicular network. We alternately refer to these techniques as routing or retransmission.

4.5.1 Forwarding of basic safety messages

The vehicular network is organized in local networks where hosts exchange data. The hosts employ anonymous broadcast to disseminate short messages, and only the messages containing relevant data are accepted. Due to the broadcast characteristic of the communication protocol and the dynamic self-management of the network, the need for routing is reduced to those cases in which the hosts cannot directly receive data of interest from each other. Still, such situations can occur if the hosts are too far one from another or due to transmission problems that affect the radio wave propagation (e.g. shadowing, multi-path propagation, interference and collisions). In figure 4.8 an example is offered, in which the communication between V1 and V3 is hindered by truck T. We call the routing between hosts belonging to the same local network *intra-network* routing.

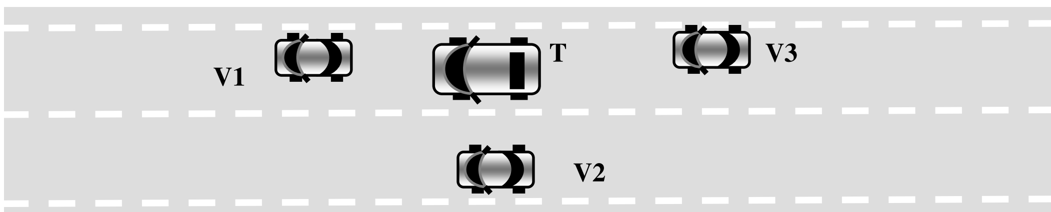


Figure 4.8 Example of situation when routing is needed

Besides routing within a local network, there are situations when forwarding of information can be performed between local networks. We call this type of routing *inter-networks* routing. This routing should not be usually required due to the proposed network organization. Still, the inter-networks routing may be needed to implement services that require the delivery of information beyond the boundaries of a local network. For example, long-distance accident notifications may require inter-networks routing. However, the communication characteristics and possible complexity of implementation limit the applicability of such routing. Since we employ short-range communication, the lack of coverage between local networks may also be a considerable problem. One solution would be to deploy a sufficient number of fixed hosts on the roadside and use them to deliver messages over larger areas by relaying information between neighboring local networks created by these fixed hosts. In our proposal we have also considered a special form of inter-networks routing by allowing hosts from a local network to accept warning messages sent by hosts from other local networks when these messages indicate major dangers in traffic.

In the following, we focus on intra-network routing and present our proposals with consideration given to the development of the communication network using the host-oriented approach.

Intra-network routing

In our proposed protocol, we used a scoped broadcast for delivering messages. This is still a broadcast protocol; therefore a simple solution for routing can be classical flooding (e.g. [WC02]). This specifies that each host re-broadcasts each message received from other hosts if the message has not been previously received. However, this solution is highly inefficient due to problems such as redundancy, contention, collisions, and bandwidth congestion (e.g. [TNC+02]).

Since we propose a context-oriented broadcast where the receivers must determine if they are the intended destination of messages, no identities of destinations are present in messages. Therefore, for forwarding information we employ the same strategy, namely to require the receivers to determine if a message should be retransmitted. Thus, a host accepts only messages that are of interest and these messages can also be routed, if necessary.

Given the specifics of the vehicular environment, we propose a routing technique using a mediation mechanism based on the characteristics of the hosts that can directly communicate with each other. Each host indicates within its BSMs the identities of the other hosts it knows about, and which are part of the same local network. These indications are recorded in the database associated with the communication system, and are used by the mediation mechanism to decide whether a message should be retransmitted. When a BSM is accepted by a subject host, the mediation mechanism will also detect if the message needs to be routed. This decision is made by determining if the sender of the message could be of interest to some members of the subject host's local network that are not aware of the original sender at the moment the message was accepted by the subject host. We call these members *non-informed* hosts. The subject host identifies the non-informed hosts by analyzing its local network database. An example of intra-network routing is presented in figure 4.9 where vehicles V1, V2, and V3 are equipped with vehicular communication devices, whereas the truck T is not. The truck also hinders the direct communication between V1 and V3. In this example, V2 detects that V1 and V3 can be interested in each other's data and retransmits this information.

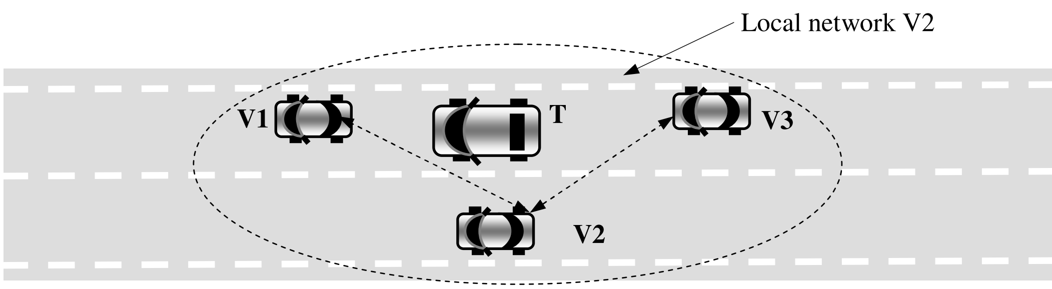


Figure 4.9 Inter-network routing example for host-oriented organization

To determine if the sender may be of interest for the non-informed hosts, different strategies can be applied. A basic approach would be to analyze the relative distance between the sender and the hosts recorded in the subject host database. Analyses of traffic situations revealed that there may be a high probability that two vehicles (i.e. the sender and a host in the database) that are of interest for the subject host and are located close enough to each other will have interest in each others' data. When a BSM is accepted, the mediation mechanism then needs to check if there are hosts that do not have data about the sender and are located within a certain distance from the sender. We used as the basis for the distance threshold the size of local networks (i.e. the Service Area Threshold) since a host will not consider data from hosts situated outside the communication service area. The rule used for implementing the mediation mechanism in this case is presented below. Let us consider that the subject host maintains data about senders from the set S, and receive a basic safety message from A. If the subject host accepts this message, it will resend it if the following rule holds:

Routing rule: $\exists B \in S$, $B \neq A$, and $Dist(A,B) \leq SAT$, where $Dist(A,B)$ is the Euclidean distance between A and B.

However, there may be situations when the above technique leads to extensive forwarding of information. Therefore, we also propose a more restrictive routing technique, then compare the performance of both techniques within the evaluation. An extended routing scheme is to apply an algorithm similar to the one used to determine if a sender is of interest for a subject host. Such an algorithm uses the distance comparison as above, but extends the analysis by investigating other parameters such as the relative heading or the possibility that two vehicles will meet in an intersection. The complete algorithm for determining that a sender is of interest is presented in the section *Information filtering and network management*. The algorithm for routing is a slightly simplified version of the filtering technique as it checks whether two hosts may have an interest in each other, but did not register or deregister hosts from the local network database. The algorithm runs until a host that has interest in this sender is found, or until all the hosts in the database are analyzed. Let us again assume that a subject host maintains data about a number of senders from the set S and receives a basic safety message from a sender A. If the subject host accepts this message, it will retransmit it if the following rule holds:

Routing rule: $\exists B \in S$, $B \neq A$, and B has interest in A data.

A problem related to routing of BSMs is that the same message can be forwarded at the same moment by a number of hosts close to each other. This will lead to a peak-load on the channel and can consequently reduce the communication quality. It can thus lead to information loss, especially when the medium access scheme does not provide a method to efficiently reduce the effects of transmission problems such as the hidden terminal. To alleviate the consequences of such problems, we randomize the moment of forwarding BSMs. Thus, before forwarding a message, a host waits a random amount of time. This interval is selected between 0 and the current transmission rate of BSMs.

Forwarding of information increases the load on the communication channel. For reducing such a load, previous work proposed algorithms for delivering messages between vehicles that require a vehicle to wait an interval to determine if its transmission area has been mainly covered by transmissions from other hosts [SFL+00]. If this is the case, the respective host refrains from transmission. However, data provided by BSMs needs to be available at hosts as soon as possible, and waiting only adds to the delay in providing this information. In addition, due to the highly dynamic traffic environment, refraining from transmission based on analysis of received messages cannot be applied in all traffic situations. As also indicated in [Brie00], there are situations where the hosts that need certain data will not be able to receive it because the hosts responsible for retransmitting it did not provided the respective data, assuming that other hosts had already provided it. For example, when shadowing hinders the exchange of data, a host may not be able to correctly estimate that the transmissions from other hosts were successful by investigating whether its transmission area has been covered. Therefore, for forwarding information we have opted for a combination between a heuristic flooding protocol and a topology-based flooding protocol (as defined in [YGK03]). This may introduce some overload but can assure the delivering of data of interest to the hosts in need.

4.5.2 Forwarding of warning messages

WAMs contain important indications about dangerous situations in traffic and therefore are subject to retransmission. Delivering a warning message to as many hosts as possible is the desideratum and we take advantage of the redundancy provided by a flooding-like technique. Thus, the retransmission of WAMs is controlled by counters. Each WAM includes a retransmission counter that indicates how many times it was retransmitted. When a host retransmits a warning message, the retransmission counter is decreased and the new value is included in the transmitted message. A host that received and considered a warning message, retransmits the message if this was not previously retransmitted and if the retransmission counter is higher than zero. The retransmission counter is set to a higher value if the original issuer of the WAM decides that it is important to disseminate the message in a larger geographical area, i.e. the default acceptance field is validated. We defined the retransmission counter based on the value of the maximum number of hosts (i.e. MNH) that can coexist in a local network at a moment in time. Thus, the retransmission counter is β*MNH, and we have empirically used β=1 for large area warnings and β=0.5 for warnings within a local network.

Similarly to the routing of BSMs, the same warning message can be received and then resent simultaneously by a number of hosts. This can create a peak-load on the channel and can lead to delays and information loss. Therefore, each host delays the transmission of a retransmitted WAM. One possibility for delaying the retransmission of warning messages is to apply the same strategy used when forwarding BSMs, i.e. using a retransmission delay randomly chosen between 0 and a maximum value, e.g. 0.1 s. Another possibility is to adapt the retransmission delay with regard to the distance to sender. The reason behind this technique is to allow the distant hosts to relay messages faster, which can lead to a more rapid propagation of the information in an extended area. In this case, the retransmission delay is inversely proportional to the distance to the sender. For this technique, we defined the retransmission delay as:

$$Tretrans\_WAM = \begin{cases} \begin{cases} Tdefer * K * \dfrac{SAT}{D}, Tretrans\_WAM < T\max\_WAM \\ T\max\_WAM, otherwise \end{cases}, D < K * SAT \\ Tdefer, otherwise \end{cases}$$

In the equation above *D* is the distance to the sender, *SAT* is the communication service area, *Tmax_WAM* is the maximum value for the defer time, and *Tdefer* is a regular value for deferring the transmission of a WAM.

4.6 Information filtering and network management

Information filtering addresses the consideration and rejection of messages. Network management addresses the initiation of a local network and the addition and removal of hosts from a local network. In this section we elaborate on the techniques used by a host for deciding whether to accept a BSM. When such a message is accepted, certain network operations can be performed. Additionally, accepted BSM can be forwarded.

4.6.1 Parameters

The techniques used for filtering and network management are implemented using IF-THEN rules and are based on a number of parameters. The rules were defined based on analyses of traffic situations that may develop into accidents, and based on guidelines provided for the development of safety systems such as collision warning and avoidance (e.g. as in [KLP+99, TCE+00, PJL+00, ZKV00, MH02, KCF+03]).

We previously established that the service area of the vehicular communication is limited to the Service Area Threshold (SAT) and the number of hosts from a local network is limited to the Maximum Number of Hosts (MNH). We also assumed that the vehicles are able to communicate with fixed hosts if these are installed on the roadside. However, roadside hosts are not necessary for performing the exchange of data between vehicles but can be used for provision of services to vehicles. If the fixed hosts are installed close enough to each other, they can communicate via the vehicular communication. We also note the possibility of developing a dedicated communication network for the fixed hosts, apart from the vehicular network. This can enhance the provision of different data to vehicles but it was outside the scope of our work.

We define *primary parameters* that describe a subject host and the other hosts the subject host had received messages from. The parameters describing these senders are extracted from the information included in accepted basic safety messages. The parameters describing the subject host are provided by onboard sensors. In addition, we define *derived parameters* that are obtained using primary parameters and possibly using onboard information systems located in vehicles (e.g. Geographical Information Systems (GIS) [ESRI95]). In [CS02c] we present considerations about the design of safety-oriented GIS systems.

The primary parameters are:

- Identity and type of communicating hosts.
- Two consecutive positions of sending and receiving hosts.
- Heading of vehicle hosts.
- Velocity of vehicle hosts.
- The slipperiness coefficient of the road.
- Status of vehicle hosts.
- Road types (if available).
- The number of hosts in a local network.
- The speed limit on the road (RSL) (if available).

The derived parameters and the techniques used for determining them are:

- Relative distance between two hosts: the difference between the current locations of two hosts.

- Similar heading: compare whether two vehicles are traveling in the same direction or not. If the difference between the headings of two vehicles is smaller that a predefined threshold value, the vehicles are considered to travel in approximately the same direction. Otherwise, the vehicles travel in opposite directions. We evaluated the heading having the Y coordinate (i.e. direction North) as reference, and set the threshold value to 90 degree.
- Membership of two hosts to the same road. We propose two methods for evaluating this parameter:
  - a) The use of information systems (e.g. GIS) for indicating the identities of the roads on which the hosts are located. The road identity is then included in BSMs and is compared at the receiving host with the identity of the road the receiver is traveling on.
  - b) The use of an algorithm that estimates, using multiple positioning records, if two hosts are situated on the same road. We employed an algorithm that analyzes the movement vectors of two vehicles between two successive positioning records. The angle between these vectors is evaluated, and if it is close to 0 or 180 degree (e.g. within 10^0), the vehicles are considered to be on the same road. If this is not the case, they are regarded as being on different roads. Details are presented in Appendix A, section A1.
- Relative positioning of two vehicle hosts. This parameter indicates if a vehicle is situated behind, or ahead of, another vehicle. As with the parameter above, two methods can be used:
  - a) Information systems for indicating the locations of the hosts on a digital map. These locations are then compared and the parameter is evaluated.
  - b) The use of an algorithm that evaluates, using multiple positioning records of the hosts, whether a host is situated behind, or ahead of, another host. We employed an algorithm that analyzes the angle between the vector given by two consecutive positions of a vehicle, and the vector between the latest positions of the two vehicles. This angle is compared with 90 degree and indicates if a vehicle is behind or ahead of the other. Details are presented in Appendix A, section A2.
- Possibility of route contention. This parameter indicates the possibility for two vehicles to meet at an intersection. We proposed a method using estimations of the movement of two vehicles. Using two consecutive positioning data points of the vehicles, we determine if an intersection point exists, and then calculate its coordinates. We then evaluate, using the latest values of the velocities of the vehicles, if the vehicles could arrive at this intersection point at the same moment. We then relaxed the requirement on the strict equality of the time moments when vehicles arrive at the intersection point, and introduced a contention interval. This is the interval when the vehicles are supposed to be in danger of colliding at the intersection. We considered in this way the physical dimensions of the vehicles and possible small variations of their velocity when approaching the intersection. Details are presented in Appendix A, section A3. We note that an information system can also be used to evaluate the route contention. However, the calculations for determining if the vehicles might meet in the intersection still need to be performed.

When evaluating the derived parameters, we used a two-dimensional representation (i.e. X and Y coordinates) of the location of a host. In the work presented in this thesis we did not consider the existence of a GIS or another system that would help evaluate the derived parameters, we used only the evaluation algorithms. The primary parameters marked with "if available" did not affect the decisions if they could not be provided. In these cases, the statements that use them were not evaluated.

4.6.2 Decision techniques

We provide below a basic set of rules used for implementing information filtering and the operations for network management. We note that these rules are a proof of concept, being an example that we used in our work. This set can be further extended or modified based on recommendations provided by domain experts (i.e. traffic safety experts). We also note that these rules are specific to the host-oriented organization, which was considered in this work for the development of the communication system. The rules use the parameters introduced in the previous section and evaluate conditions related to the sending and receiving host. When these conditions are determined to be true, the sender is considered of interest and the currently received BSM is accepted. The main factors that we considered for defining the rules were:

A. The vehicles in close proximity usually have important data. Their number is limited.

B. Vehicles in front of, or behind, traveling on the same road and in the same direction have data of interest.

C. Vehicles coming from an opposite direction can constitute a danger on undivided roads.

D. Vehicles can collide if they arrive at an intersection at the same time.

E. Fixed hosts located on the roadside provide services to vehicles.

Aspect **A** is derived from works in traffic safety, e.g. [KLP+99, ZKV00, MH02]. **B** is stipulated within proposals for collision warning systems, e.g. [ZKV00, KCF+03]. **C** is derived from the development of head-on collisions, e.g. [NSS+03, USC05] and **D** from the development of intersection collisions, e.g. [PJL+00, MH02]. **E** is derived from our design of the vehicular network.

Rules for information filtering

We present below the rules used by a receiver to determine if a sender is of interest and thus accept a received basic safety message. The rules below are presented using natural language and the logical connectives *AND* and *OR*. We use parentheses to delimit multiple clauses.

Case 1. The receiver and the sender are vehicle hosts

Inclusion rule:

(I1) The Euclidean distance between sender and receiver is less than SAT.

Regular rules:

(R11) The sender and the receiver are traveling on the same road *AND* have similar heading *AND* [the receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered].

(R12) The sender and the receiver are on the same undivided road *AND* have different headings *AND* the sender is ahead of the receiver *AND* [the road status or/and the sender status indicate the possibility for a danger to occur] *AND* [the receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered].

(R13) The sender and the receiver are traveling on different roads *AND* a route contention is detected *AND* [the receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered].

Case 2. The receiver is a vehicle host and the sender is a fixed host

*Inclusion rule***:**

(I2) The Euclidean distance between sender and receiver is less than SAT.

Regular rule:

(R21) The sender offers a service that is of interest for the receiver *AND* [the receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered].

Case 3. The receiver is a fixed host and the sender is a vehicle host

Inclusion rule:

(I3) The Euclidean distance between sender and receiver is less than SAT.

Regular rule:

(R31) The receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered.

Case 4. The receiver is a fixed host and the sender is a fixed host

Inclusion rule:

(I4) The Euclidean distance between sender and receiver is less than SAT.

Regular rule:

(R41) The receiver maintains data about less than MNH vehicle hosts *AND* both the sender and the receiver provide specific additional services.

Rules I1, I2, I3 and I4 are due to aspect A and the space limitation of the communication service area. We note that vehicles situated at the border of this area may frequently enter and leave the area. This can create an undesired instability and extensive processing of the information received by repeated removal and addition of senders to receiver's local network. Therefore, when evaluating the relative distance between vehicles we have introduced a hystrerezis around the area threshold. Rule R11 is due to aspects A and B, and the limitation of the composition of a local network. Rule R12 is due to aspects A and C and the limitation of the composition of a local network. Rule R13 is due to aspects A and D and the limitation of the composition of a local network. Rule R21 and R31 are due to aspects A and E and the fact that the local network is limited in composition. Rule 41 is due to aspect E, the limitation in composition of the local network, and the specific functionality of fixed hosts defined within the communication protocol.

The rules presented above have a high degree of generality and can be further specified. For instance, rule R11 can be completed with clauses that check if the sender is no more than several vehicles (e.g. 2) behind, or no more than several vehicles (e.g. 4) ahead of, the receiver. The set of rules used for filtering information can be also extended by adding new rules. For example, rule R13 can be completed by a condition that checks the value of a time-to-collision parameter for the possible intersection collision. Only when this parameter is below a certain threshold, the rule will evaluate true. In our work, we have also used such specializations of the rules. For instance, rules R12 and R41 were replaced by:

(R12s) The sender and the receiver are on the same undivided road *AND* have different headings *AND* the sender is ahead of the receiver *AND* [the road is slippery *OR* the sender status is poor *OR* the sender speed is excessive] *AND* [the receiver maintains data about less than MNH hosts *OR* the sender is closer to the receiver in comparison with the farthest host previously considered].

(R41s) The receiver maintains data about less than MNH vehicle hosts *AND* the sender and the receiver provide the WSR service.

Processing of rules

When ***both*** the *inclusion rule* and ***one*** of the *regular rules* hold at the ***same time,*** the sending host is considered of interest and the receiving host accepts the newly received basic safety message. As previously presented, the same rules can be applied for forwarding of basic safety messages.

Rules for network operations

The network management is provided by network operations that are performed in two cases as follows:

- When a basic safety message was accepted by a subject host, which indicates that the sender is of interest.
- When the timer associated with the communication protocol (i.e. T_record) indicates that old records exist in the database, which indicates that the information about these hosts is obsolete.

We also define a least important host, which is used in the rules. Various definitions can be given but in this work we consider this host to be the most distant host from the receiver. However, if a less important host was identified as an existing danger via received WAMs, it would not be considered less important anymore. The second less important host then becomes the least important in this case, and so on. For the rules presented below, we use the same syntax as for the information filtering rules. The generic rules implementing network operations are:

Initiation of a local network: IF a time interval T_Init has passed since a host is active (i.e. since a vehicle host entered the traffic or since a fixed host was made operational) *THEN* the host initiates its own local network.

Addition of a host to a local network: IF a sender is considered of interest *AND* it is not registered within the receiving host database *THEN* register the sender into the receiver's local network.

Removal of a host from a local network: [*IF* a sender is considered of interest *AND* the receiver database contains MNH hosts *AND* the sender is closer to the receiver than the farthest host previously considered *THEN* remove the least important host from the receiver local network] *OR* [*IF* the update time T_record of a record describing a sending host has passed *THEN* remove the host from the receiver local network].

4.7 An integrated vehicular communication platform

A platform for implementing the proposed networking and communication techniques and for integrating the resulting communication system within a vehicle is proposed in this section.

4.7.1 Design principles

We have designed a vehicular communication platform (VCP) that complies with the specifications of our proposed vehicular communication. The design principles that we considered when realizing the platform are presented below:

- Modularity. The modular architecture is due to the diversity of information that needs to be processed and the specific data organization. The modularity also facilitates future extensions.
- Different service levels. A basic service level needs to be provided, but it should be possible to develop platforms that offer various services. Moreover, it should be possible to provide a simplified version of the platform for less specialized vehicles (e.g. vehicles that lack some of the onboard sensors).
- Extendable. It should be possible to add functionality to the platform by adding new modules or extending the existing one.
- Medium-independent. The communication platform should not be restricted to a specific media for transmitting information over the air interface. The platform should then be able to operate with diverse media that fulfill certain requirements regarding the performance of the data transfer and the local processing of data.
- Interoperable. The platform should be able to interoperate with other systems located in a vehicle. Data provided by onboard systems (e.g. GIS) are useful for managing the communication. Also, data that reside on the platform may be of use for other in-vehicle systems (e.g. positioning information for traveler information services).
- Customizable. The VCP should be able to be adapted to the user preferences.

4.7.2 Vehicular communication platform (VCP)

The architecture of the vehicular communication platform is presented in figure 4.10 and contains eight modules:

- Physical Media Manager (PMM)
- Transmission Manager (TM)

- Message Manager (MM)
- Organization Manager (OM)
- Service Space (SS)
- Host Processing Manager (HPM)
- Local Network Processing Manager (LNPM)
- Local Network Members Database (LNMD).

The other entities represented in the figure (i.e. as white boxes) are external to the platform but should exist on a host for the vehicular platform to function properly. Details on the proposed functionality of the platform components are given in the following sections. We note that the platform is intended to be an implementation test-bed for the communication and networking techniques that we proposed, and for future extensions. To evaluate the communication performance (i.e. Chapter 5) we implemented some of the functionality of these components within a prototype.

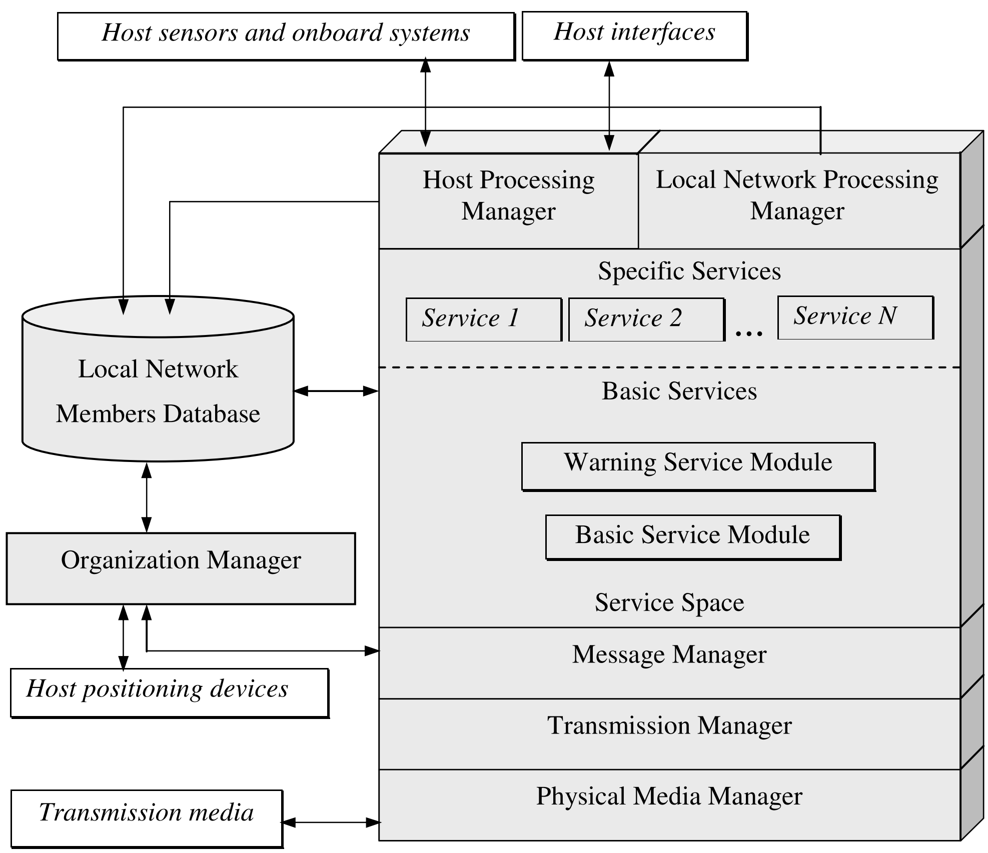


Figure 4.10 Vehicular Communication Platform (VCP) architecture

Physical Media Manager (PMM)

This component is intended to communicate with the physical equipment used for communication and contains the specifications of the wireless media that can be employed for inter-vehicle or vehicle-to-road communication. The Physical Media Manager (PMM) should have the possibility of controlling the functionality of the transceivers installed on a host (e.g. power control). The PMM communicates with the Transmission Manager (TM), which is located above it in the VCP architecture. The VCP may integrate different standards for communication (e.g. IEEE 802.11 [IEE99], DSRC [AST03]). In our evaluation, we used as media a configurable radio layer provided by the GloMoSim network simulator [BTA+99]. A study of an early prototype of VCP connected with Bluetooth devices [ERB01] had been done in [Win03].

Transmission Manager (TM)

This component should manage the sending and the receiving of data from the Physical Media Manager (PMM). The unit may perform fragmentation and reassembling of data if needed. The TM should also have the possibility of determining the correctness of the information received. The unit also needs to maintain information about the communication equipment installed on the host and the standards used for communication. The operations performed by the TM are dependent on the capabilities of the media used for physical exchange of data. The TM receives data in the form of messages from the Message Manager (MM), converts it into a format compatible with the physical communication medium, and sends it to the PMM. The reverse processing is performed when the unit transfers data from PMM to the MM. The TM should also be able to perform data flow control (e.g. queue management).

The TM can be used for managing security aspects of the communication such as data encryption and decryption, and key management. When performing such operations, the TM must consider the performance of the media used and the possible overload of communication. For example, IEEE 802.11b provides a security mechanism that offers modest protection [Sta04]. If more than one transmission media is installed on a host, the TM should be able to select the most appropriate one, and take care of the handover between different media. However, in the work presented in this thesis we did not address handover operations, nor did we focus on additional mechanisms for security; we considered only the security provided by the employed medium.

Message Manager (MM)

The VCP platform was designed to support the message communication by processing and managing messages that contain relevant safety data. The Message Manager is intended to assure primary processing of incoming messages from the Transmission Manager (TM) by analyzing the message type and determining whether the embedded data should be sent to the Organization Manager (OM) or to a service installed on the host. The services are contained by the Service Space (SS) and provide further data processing. The MM controls the data provided by these services that is sent to other hosts. Thus, the unit creates messages from this data and passes them to the TM.

The MM processes messages used by the proposed communication protocol, such as BSMs and WAMs. Other types of messages can be defined and used by specific services if these are installed on a host's VCP. This depends on the service level provided by the specific VCP. As long as a service is installed on the VCP and uses diverse messages for transferring data, the MM is responsible for assuring the initial processing of the messages. Therefore, the MM maintains a catalogue of services that contains the types of messages used by each service. A service can make use of several types of messages but two services cannot use the same type of message for transferring information. When a message is received but its type is not known by the MM, this indicates that the corresponding service is not installed on the host. Therefore, such a message is discharged.

The BSMs received by the MM contain the information needed to determine the sending host's membership in a local network. This data is extracted by the MM and sent to the OM. The OM decides if the sender belongs to the local network in which the receiving host currently resides. If a sender does not belong to this local network, the MM is instructed to drop the received message unless this is a regular warning message (i.e. the default acceptance is valid), or some special message used by a service installed on VCP. For warning messages, further processing based on criticality parameters can be performed. Such processing operations and the processing of special messages need to be indicated within the catalogue of existing services. If such specifications do not exist, the warning or special message is discharged.

The Message Manager can also employ authentication and authorization mechanisms that are used when the sender hosts would like to access some specific services existing on the subject host. This can be done based on host identity and other credentials. However, such operations were not the focus of our work.

Organization Manager (OM)

This component processes the information describing the driving situation and the status of hosts that are part of a local network. The unit manages the organization of hosts in local networks and the routing within such networks according to the specification of the communication protocol. The data needed for performing the network management is extracted from the Local Network Members Database (LNMD) and from the received messages. The OM maintains a log of hosts that are currently registered in the LNMD (i.e. the hosts belonging to the same local network as the subject host). This log contains the identities of these hosts and indications about the last update of the data describing the hosts. The OM uses this log to make decisions and to control the time validity of the data recorded in the LNMD. If the information describing a host is not updated within a time interval, the OM instructs the LNMD to remove the outdated record.

Another task that should be performed by the OM is the communication with positioning systems installed on the subject host. Thus, this unit needs to register and update the positioning data describing the subject host into the LNMD.

Service Space (SS)

We proposed a basic service level for VCP that provides the reception, transmission, and processing of safety data. Two basic safety services that assure these operations were defined: Basic Service Module (BSM) and Warning Service Module (WSM). However, the platform is extendible and other services can be installed within the Service Space. Also, more functionality can be added to the existing services. If a new service is installed on the VCP, the modules that need to interact with it (e.g. Host Processing Manager) should be notified about its identity and should be informed about the messages used by it. New services can be installed using the interfaces embedded in a host that communicate with the Host Processing Manager. However, the possibility also exists to receive services via communication. The modules implementing the services are responsible for processing and managing data received and sent by a host. If a received message is accepted by a host, the message type is used to identify the corresponding service. The data contained by the message is then sent to this service for further processing. When the subject host wants to send some data, this is extracted from the Local Network Members Database or is provided by the Local Network Processing Manager or by the Host Processing Manager. This data is then processed by a service from SS and is sent to the MM for further delivery. In this work we focused on the above-mentioned basic services, which we briefly described in the following.

Basic Service Module (BSM)

This module manages data contained by basic safety messages. This information describes the sender host and the driving situation associated with it, and is recorded by the service module into the Local Network Members Database (LNMD). When a new message received from the same host is accepted, the module updates the corresponding record in the database. We recall that the Organization Manager uses timeout counters to control the validity of these records. The basic service module constructs at regular time intervals, using data extracted from the LNMD and data received from the Host Processing Manager (HPM), basic safety messages describing the subject host. These are then sent to the Message Manager for further delivery.

Warning Service Module (WSM)

This module manages data contained by warning messages. The module maintains a log of warnings and should provide methods for analyzing their degree of emergency. The log contains the identity of the sender that issued a warning message and some additional data (e.g. its position). This log can also be used by the Local Network Processing Manager when performing analyses of traffic situations. The WSM should be able to filter the warning messages received and notify the Host Processing Manager (HPM) only when the criticality level contained in these messages exceeds a pre-defined threshold. A default criticality level is provided in the basic version of the VCP and can be modified, e.g. based on the user preferences. The WSM is also responsible for constructing warning messages when requested by the HPM or by the Local Network Processing Manager (LNPM). These messages are send to the MM for further delivery.

Host Processing Manager (HPM)

This unit should assure the processing of information related to the subject host. The HPM is also responsible for managing the interaction between the VCP and other systems installed on the hosts. Thus, the unit should manage the reception of data from sensors embedded within a host. This data can be analyzed and then registered into the LNMD. With regard to a vehicle host, a wide variety of sensors can be use for monitoring its functionality. These can be basic sensors indicating the engine temperature or the tire pressure, and more advanced devices such as engine analyzers or road-friction sensors. The deployment of such in-vehicle devices has recently witnessed a rapid evolution, and the complexity of in-vehicle networks requires specialized processors and controllers for managing the large amount of data [ZKV00, Bre00]. Therefore, the

HPM should usually not communicate with sensors, but with the specialized units that control them and provide the filtering of data acquired by sensors. The HPM is intended to use the information collected from the host's sensors for performing analyses that help in detecting and predicting dangerous traffic situations. Alarms received from sensors and traffic data analyses can also trigger the transmission of warning messages. In these cases, the HPM should construct a message describing the danger and send it to the WSM for further delivery. Also, the HPM may alert the driver about such events. Therefore, the HPM should be able to manage the communication with the interfaces located on the subject host and should represent diverse notifications on these interfaces. Such notifications are created based on information extracted from accepted messages and data describing the subject host. With regard to a vehicle host, various types of driver-vehicle interfaces have been recently proposed (e.g. video, audio, tactile) [ZKV00]. The HPM needs to be implemented so as to assure the proper representation of the information using such devices. In certain cases, there is the possibility of producing successive notifications for indicating the development of a dangerous traffic situation. Using different levels of emergency constitutes a convenient method for avoiding the mental overload of the driver [TCE+00]. The presentation method needs to be adapted considering driver preferences. Since drivers react differently when facing the same type of traffic situation, the provision of a customizable system is an advantage [MH02].

The HPM should also be able to collect data provided by a user via an in-host interface, and send it to the corresponding unit from the VCP. Examples of data provided by drivers are the request for certain information (e.g. vehicle status) and settings of the VCP such as the safety threshold.

The HPM keeps a list of services installed on the subject host. As mentioned before, the services are mainly installed using the interfaces that exist on a host. However, if a service is received for installation using some vehicular communication, the HPM needs to determine whether it can be installed on the VCP, and if this is the case, should perform its installation.

We note that only some of the functions that can be provided by the HPM were implemented in a prototype that we used for evaluating the vehicular communication system. These functions were also simulated since no in-vehicle sensors were used. Also, as interfaces, we used a standard PC keyboard for inputting data and a PC screen for outputting data.

Local Network Processing Manager (LNPM)

This component is proposed for providing additional analyses and processing of data resident on the vehicular communication platform. The LNPM should analyze data characterizing the subject host and data received from other hosts that belong to the same local network to determine the probability that a dangerous situation will happen. When such situation is detected, the LNPM should create a warning that is sent to the Host Processing Manager (HPM), which can perform the necessary processing to present it on an interface installed on the subject host. The HPM can also send the warning to the WSM to be transmitted to other hosts. In our evaluation, we investigated the success of sending warning messages. However, the LNMP functionality was emulated by defining beforehand when warnings need to be issued.

Local Network Members Database (LNMD)

This component of the VCP is the database that contains the information that characterizes the subject host and the other hosts belonging to the same local network. The information describing the subject host always exists in the database and is provided by the Host Processing Manager. The information describing other hosts is recorded and updated by services installed in the Service Space. As previously mentioned, the Organization Manager controls the removal of these records from the database.

5. Communication evaluation

This chapter presents the details of the evaluation environment and the tests performed to assess the performance of the proposed communication system. We first introduce the evaluation goals, the testing environment, the metrics, the evaluation settings, and the test cases. We then present and discuss the results for each test case.

5.1 Evaluation goals and method

We have developed an experimental prototype of the proposed safety communication system as a version of a vehicular communication platform. Both operation modes of the communication, i.e. proactive and reactive, were implemented. The prototype was then evaluated with regard to the following goals:

- Evaluate communication performance under various conditions using realistic simulations of the vehicular traffic. Since the safety data is used by active safety systems, it is crucial to determine whether its timely and reliable dissemination can be provided by the proposed communication system. To be relevant to vehicular communication, it is necessary to perform the evaluation using communicating hosts that exhibit behaviors close to those of real vehicles. Since vehicular communication needs also to be available in a multitude of traffic scenarios, it is important to evaluate the communication performance under various conditions (e.g. diverse density and mobility of vehicles, various movement patterns).
- Investigate appropriate settings for the parameters of the proposed communication protocol. The functionality of the protocol is influenced by several parameters such as the transmission interval for BSMs and the communication service area. It is important to identify those settings that can provide high-performance communication. It is also important to investigate if the obtained values are realistic.
- Perform a comparative investigation of the techniques proposed for data dissemination, i.e. the techniques for controlling the message dissemination rate, and the techniques for forwarding information.
- Evaluate the efficiency of the proposed information filtering technique. The information filtering is intended to help identify the relevant information and thus minimize the amount of data considered by vehicles. Consequently, improvements of the information management that can be obtained using this technique are of interest.
- Investigate the system usefulness for supporting safety applications, e.g. intersection collision warning system, rear-end collision avoidance system.
- Investigate the functionality of the communication system under diverse settings for transmission (e.g. coverage area).

As an evaluation method we have constructed a dedicated evaluation environment and used it for performing a large number of simulations. A prototype of the system using real devices can also be developed as a proof of concept, and is subject of future work.

In developing the evaluation environment we have taken in consideration the following requirements:

- *Realistic and relevant simulations of traffic patterns.*

The scenarios used need to be relevant to traffic safety. The traffic simulations need to include a sufficient number of vehicles that travel on common types of roads. The vehicles movements, density, distribution, velocities, and dimensions need to be close to real situations. In addition, a basic scenario needs to be defined for evaluating the communication performance and for comparing the different techniques proposed for data dissemination.

- *Realistic settings of the radio communication.*

This includes the definition of the propagation model, the radio type and parameters of the transmission and reception (e.g. transmission power, reception sensitivity).

- *Investigation of both modes of operation for the communication protocol.*

Evaluations of both proactive and reactive mode of operation for the communication protocol need to be performed. Experiments need to be performed for dissemination of basic safety messages alone, and for dissemination of basic safety messages and warning messages.

5.2 Evaluation environment

The evaluation environment contains two components as presented in figure 5.1:

- *Mobile Network Simulator:* an advanced network simulator modified to include the implementation of the vehicular communication system.
- *Traffic Simulator:* a set of traffic simulators that generates movement patterns of vehicles.

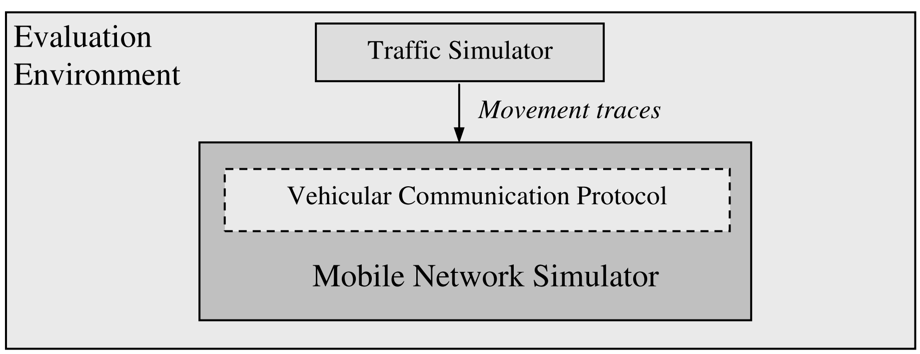


Figure 5.1 Evaluation environment

The network simulator and the proposed safety communication system

The network simulator that we have used was GloMoSim, a realistic simulation tool for mobile networks based on a discrete event engine [BTA+99]. The communication hosts are called *nodes* in GloMoSim and the simulator uses a layered approach with well-defined interfaces between layers. GloMoSim provides support for nodes' mobility by implementing several mobility schemes such as random waypoint [JM96] and mobility trace file (i.e. the movement of the nodes is specified in dedicated files). The simulator also provides configuration files that allow the user to set various parameters of simulations.

Our communication system was implemented in a language similar to C that is used in the network simulator and runs at the application layer of GloMoSim. We implemented the functionality of the communication protocol for disseminating basic safety messages and warning messages. These messages were defined as C structures with lengths of 27 bytes for WAM messages and 112 bytes for BSM messages. However, further encoding of the transmitted traffic data can lead to smaller message size. Our prototype implemented the information filtering, the data management for the local database of a host, and the routing of messages. The local database contained the information about the subject host and the other hosts from the same local network, and was defined as a C structure. The queues used for managing message priority were implemented as linked lists with C structures as elements. The interaction with diverse sensors from a vehicle (e.g. sensors that provide various data such as vehicle position) was simulated via functions that communicate with the routines of the simulator (e.g. the mobility routine gives the position of a node). We employed the trace file mobility option of GloMoSim and inputted the movement patterns of nodes via trace files generated by a traffic simulator that we have previously developed. Several configuration options had been added to the original configuration files of GloMoSim for setting parameters of the communication protocol (e.g. transmission interval for basic safety messages, time interval for deleting stale data). Several other configuration files were also added for diverse settings (e.g. characteristics of hosts, indication of message type).

Traffic simulator

The traffic simulator generates mobility trace files that contain the movements of the nodes. These files contain the identity and the positions of the nodes at different time moments, and are used as inputs for nodes mobility in GloMoSim.

Two types of traffic generators were developed:

- A general-case traffic simulator using a model given in the literature that implements a common scenario, which was employed in the evaluation of communication performance and the comparisons between different communication techniques.
- A specific-case traffic simulator that implements accident scenarios and is used for assessing the system applicability to support the development of safety systems such as collision warning and collision avoidance.

5.3 Metrics and free parameters

As we evaluate wireless communication between moving nodes, the settings of the experiments can influence the evaluation results. For instance, it is possible that some of the vehicles find themselves during the simulation in situations that pose extreme conditions upon communication. The hidden terminal situation is one such example, in which a node cannot successfully access the transmission medium due to concurrent transmissions of nearby nodes. Our proposed protocol is a best effort protocol and we aimed at investigating both absolute and relative performance. Considering the above aspects, we investigated in many cases average values for metrics.

We were interested in investigating if safety information can be exchanged between vehicles in a timely manner. Therefore, we defined the metric *message delay* for measuring the time interval needed for a message to reach its destination. Due to the safety utilization of the exchanged information, this metric needs to fulfill strict requirements. The metric is defined below.

- *Message delay*. This metric is defined as the time between the (initial) sending of a message and the moment when it is accepted by a host. For messages that are routed, the moment when the message was issued first is considered. For a simulation run, the maximum value of the delay for all nodes is determined. As an indication of the median system capabilities, an average value of the delay at each host and over the hosts in a simulation run is also measured.

Investigations regarding communication reliability need to be performed. The transmission capabilities of the nodes are thus evaluated using two metrics, *packet collisions* and *send errors*. Large values for collisions and send errors indicate low communication performance due to information loss. This is because packet collisions lead to deterioration of received packets and consequently to their loss. Send errors address situations when hosts drop messages because these cannot be sent within a time interval. The metrics definitions are:

- *Packet collisions.* The evaluation of *packet collisions* is based on the collision statistics provided by the radio layer of GloMoSim. These statistics calculate the number of collisions detected by each node during a simulation run. The detection of a collision is dependent on the type of radio employed. In our tests we used a standard radio with noise accumulation, where the signal reception is controlled by the signal-to-noise ratio (i.e. SNR-bounded radio). A collision can occur when a node currently receiving a message detects another signal that cannot be captured, and which therefore contributes to the noise. If the power (or energy) of the message currently received become, due to the arriving of the above-mentioned signal, lower than the noise power multiplied with the SNR threshold, it is considered that the message cannot be received correctly. Therefore, its processing is stopped and a collision is counted. For each simulation, the values of the metric were averaged over the total number of nodes. Furthermore, the packet collisions are normalized with the number of messages correctly received and forwarded to the MAC layer plus the number of collisions. The normalized metric represents the fraction of the messages that could have been correctly received, but were discarded due to interference with other signals.
- *Send errors*. This metric represents the number of BSMs that cannot be transmitted due to transmission problems, i.e. busy medium. BSMs are supposed to be sent by each host at regular intervals. As previously mentioned, a BSM that cannot be transmitted immediately is kept in a local buffer. If a new BSM is generated and the previous BSM is still in the buffer, the old BSM is erased and the new BSM is inserted into the buffer. This means that the older message was lost, and we call this a *send error* and count the number of such events at each node. The send errors are averaged over the total number of nodes in the simulation. The obtained values are then normalized with the average number of BSMs that are transmitted by a node. The resulted normalized metric represents the fraction of BSMs that were lost due to send errors.

In the discussion of results we use packet collisions and normalized packet collisions to identify the normalized packet collisions metric. Likewise, send errors and normalized send errors refer to the metric normalized send errors.

The next aspect to be investigated is the efficiency of the filtering technique embedded within the proposed communication protocol. Due to the broadcast feature of the protocol, the hosts will usually receive a large number of messages. However, only a fraction of these messages may contain data of interest. Therefore, the filtering technique is considered successful if the hosts drop a significant number of messages in comparison to the number of received messages. This is because the filtered (i.e. dropped) messages are clearly of no interest for the hosts and therefore should not be considered. As mentioned in [SFL+00] such a metric can also be seen as a measure of the bandwidth utilization. We note that the metric is most relevant when a larger number of vehicles that exchange data exist in the simulation. In addition, the metric relevance is strongly dependent on the simulated scenario. For example, there can be scenarios where the metric is less relevant because all the vehicles in the simulation need to have data about each other. The metric definition is given below.

- *Information filtering rate*. This metric represents the ratio between the number of BSMs accepted by a host and the number of BSMs received by this host. For each simulation run, the results are averaged over the total number of nodes in the simulation.

When disseminating warning messages, it is important to investigate whether they eventually arrive at their destinations, i.e. the hosts that need to receive them. This can be seen as a measure of communication reliability and it is quantified using the metric *Information dissemination success*. We note that the metric is most relevant for specific scenarios, where one can precisely define beforehand the nodes that should receive a certain notification. The metric is defined below.

- *Information dissemination success.* This metric evaluates the ratio between the number of hosts that should receive and accept a warning message, and the number of hosts that accepted the message.

Free parameters

The free parameters are the variables modified for evaluating the behavior of the communication under various conditions. The determination of appropriate values for certain parameters of the communication protocol was one of the evaluation goals. Such parameters were then used as free parameters in the simulations. Additionally, free parameters that characterized the dynamics of the traffic were used. Thus, the free parameters were:

- *Transmission interval* or rate of basic safety messages.
- *Communication system bandwidth*.
- *Communication service area.*
- *Network load* in terms of number of vehicles on the road.
- *Mobility of the nodes*, by modifying the maximum achievable speed for the vehicles (i.e. in the traffic model).

5.4 Scenarios

A general scenario for performance evaluation and specific scenarios for system usability have been used in the evaluation. We describe below the general scenario and offer examples of the specific scenarios with four relevant cases (i.e. two basic cases and two extensions of these). These scenarios are also used for illustrating the obtained results.

Description

a. General scenario for performance evaluation

The basic traffic scenario used for evaluating communication performance and comparing the proposed techniques for information dissemination is an undivided bi-directional road with one lane in each direction (figure 5.2). This is a considered a common topology for rural and urban roads [Eva04].

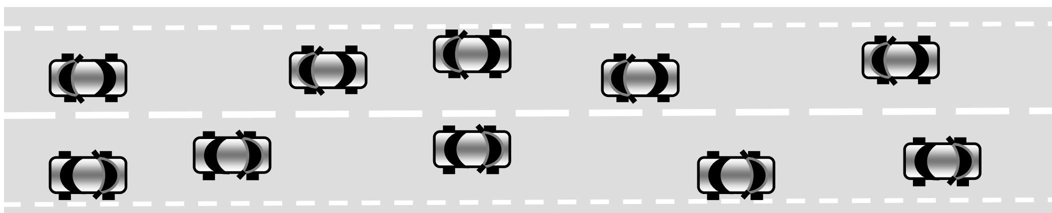
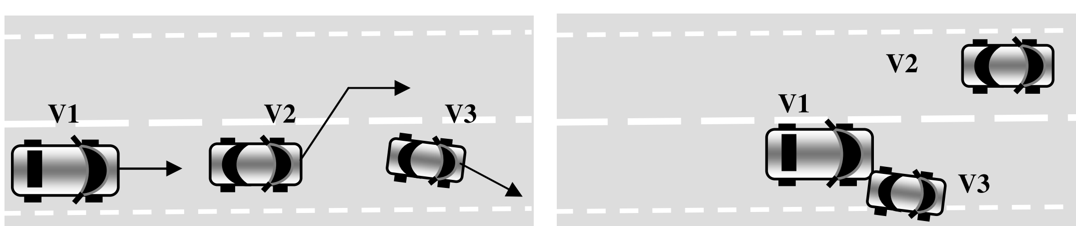


Figure 5.2 General scenario

b. Rear-end accident scenarios for system usability investigation

A classic rear-end accident scenarios was used. Thus, the VOTS scenario (vehicle obstruction with tailgate scenario) introduced in Chapter 2 was initially considered. This scenario is shown in figure 5.3 and was described in detail in section 2.4.2. The scenario involves three vehicles that initially follow each other at a safe distance. Later on, V3 suffers a breakdown and starts to pull over. V2 manage to avoid V3 by steering. When V1 notices V3, it tries to brake but it cannot avoid the collision with V3.



a. Initial situation b. Accident situation

Figure 5.3 Basic rear-end scenario

In addition, an extension of this scenario was used. In this case the accident development is similar to the first scenario, but a larger number of vehicles are present on the road. For this, we have positioned the scenario on one of the driving directions of a highway with two lanes per direction as presented in figure 5.4.

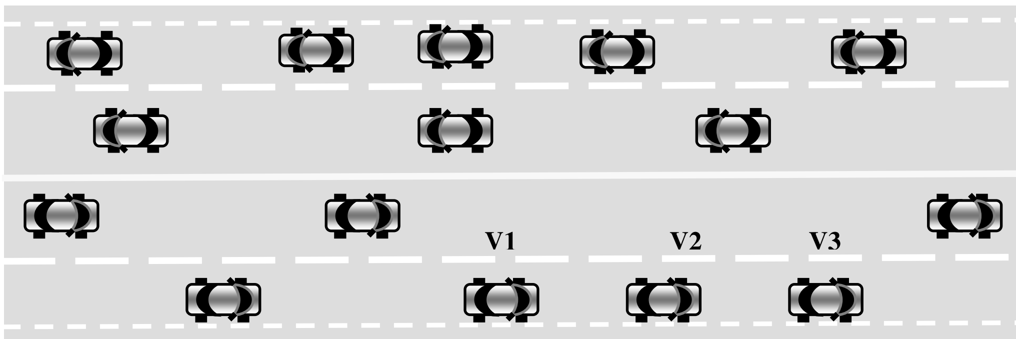


Figure 5.4 Extended rear-end scenario

c. Intersection accident scenarios for system usability investigation

Classic intersection accident scenarios with perpendicular crash were used. The initial scenario that was considered involves two vehicles and is briefly presented in the following. Initially, V2 stops at the STOP sign and then tries to pass the intersection, without notifying the oncoming vehicle V1 or misleading its position and velocity. V1 is confused by V2's maneuver mainly because V2 was initially stopped, and brakes too late and collides with V2.

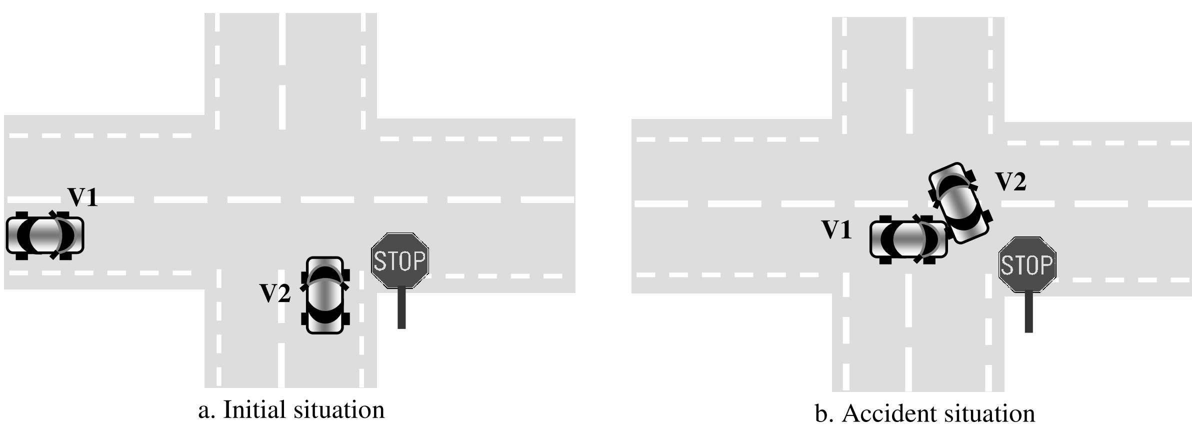


Figure 5.5 Basic intersection scenario

A more complex intersection scenario that employed the same accident in the presence of more vehicles on the intersecting roads was also considered. This is presented in figure 5.6.

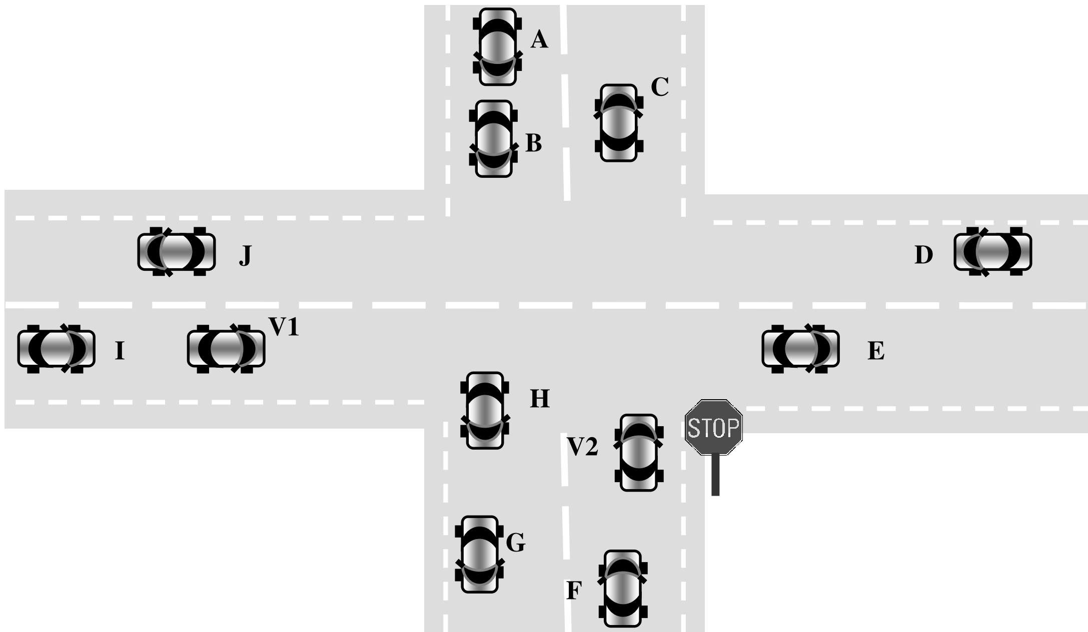


Figure 5.6 Extended intersection scenario

Implementation

a. General scenario for performance evaluation

For generating the movements of vehicles, an accident-free traffic model was used [Kra98]. This traffic model is microscopic and simulates the traffic flow by specifying the movement of a vehicle with regard to the characteristics (i.e. position and speed) of neighboring vehicles. The *car-following operation mode* of the traffic model was employed and describes how a vehicle follows another vehicle at a safe distance when they do not change their lanes during the simulation. The time in the model is discrete and ticks at *dt* intervals. The model specifies the movement of a vehicle so that it is safe with regard to the vehicle in front. The parameters used within the traffic model are the safe velocity v_{safe} representing the velocity of a vehicle that always travels safely, the maximum acceleration *a* and the maximum deceleration *b* of a vehicle, and the maximum velocity that can be achieved by a vehicle v_{max}. The equations of the model that specify the movement of a vehicle between time points *t* and time *t*+*dt* using displacement and velocity are presented below (i.e. adapted from [Kra98]):

$$v_{safe} = v_l(t) + \left(\frac{gap_{(v_f, v_l)}(t) - v_l * t_r}{(t_b + t_r)} \right) \text{ with } t_b = \frac{v_l + v_f}{2b} \quad \text{[E1]}$$

$$v_{des}(t) = \min[v_{\max}, v_f(t) + a * dt, v_{safe}(t)] \quad \text{[E2]}$$

$$v(t+dt) = \max[0, rand(v_{des}(t), v_{des}(t) - \varepsilon * a * dt)] \quad \text{[E3]}$$

$$x(t+dt) = x(t) + v(t+dt) * dt \quad \text{[E4]}$$

The parameters used in the equations are the speed of the leader vehicle v_l, the speed of the follower vehicle v_f, the maximum acceleration a and maximum deceleration b of a vehicle, the separation distance between the follower and the leader vehicle $gap_{(vf,vl)}$, the reaction time of the driver and the braking system lag t_r, and a noise parameter ε. The term *rand(x, y)* represents a random number between x and y. The time interval *dt* used for updating the traffic model (i.e. for generating new positions and velocities of the vehicles) needs to be equal to or smaller than the reaction time of the driver and the braking system lag (i.e. t_r) for the traffic to be safe [Kra98]. Therefore, $dt \le t_r$ was imposed. The random term used in equation [E3] is an uncertainty factor that models deviations from optimal driving. Thus, in this traffic model the drivers are not considered to have a completely accurate perception of the traffic situation in terms of speed of, and distance from, neighboring vehicles. Therefore, they may execute unexpected maneuvers such as a sudden deceleration without an existing reason. Introducing such a random variable makes the model non-deterministic and more realistic with regard to traffic situations.

The simulations were performed by generating a number of vehicles on the road according to a predefined traffic density ρ (measured in vehicles/km/lane). The average separation distance between vehicles was calculated as *avg_separation* =1000/ρ [m]. The initial speed of the vehicles was randomly set at the starting moment of the simulation to a value in the interval [v_{max}, v_{max}-$a*\varepsilon*dt$]. The movements of the vehicles were determined by equations [E1] to [E4].

All the vehicles generated at the beginning of the simulation remained on the road for the entire duration of a simulation run. We implemented this behavior for reasons of consistency and because the employed network simulator requires the specification of the number and identities of the nodes at the beginning of the simulation. The road length was adapted (e.g. 7.5 km, 12.5 km), with regard to the simulation duration and the velocity of the vehicles. The vehicles were positioned at the beginning of the simulation on two sectors of the road starting at its left or right end depending on the driving direction. They were uniformly positioned on these sectors with a separation distance equal with avg_separation plus the length of a vehicle and a guard space. The length of a vehicle plus the guard spaces (i.e. in front of and in behind) was set to 8 meters. The width of a vehicle plus lateral guard spaces was set to 3 meters. The other settings of the simulations are given in the table 5.1.

Table 5.1 Simulation settings

Parameter	**Value**
Maximum speed	25 [m/s] (except when modified)
Acceleration and deceleration	1 [m/s^2] and 4.5 [m/s^2]
Vehicle density	6 [vehicles/lane/km] (except when modified)
Reaction time	1.5 [s]
Noise factor	1.5

The general scenario was implemented as a C program that takes as input a configuration file where the traffic model parameters and other settings (e.g. time granularity *dt,* vehicles dimensions) are specified. This program produces trace files containing the movement characteristics of the vehicles (i.e. time and vehicle identity and position), which are then used as inputs for GloMoSim.

b. Rear-end accident scenarios for system usability investigation

Classical kinematical equations (e.g. displacement calculus [Phy03]), and equations derived from research in crash avoidance areas such as braking on-set range [KLP+99] were used for simulating the movements of vehicles. The movement patterns followed well-defined scenarios and the simulations were deterministic, as the movement characteristics of the vehicles were specified beforehand at all time points in the simulation.

For the initial rear-end scenario we used the following settings. The vehicles have an initial speed of 20 m/s, an initial acceleration of 0 m/s^2, and an initial separation distance of 40 meters. The simulation started at time 0 s. At time 10 s, the vehicle V3 breaks down and executes a pull over maneuver with a deceleration of 4 m/s^2. At time 13 seconds vehicle V2 executes a sudden steer and vehicle V1 executes a heavy braking at time tb=(13 + DRT + RandT), where DRT is the driver reaction time, which was set to 1.5 second, and RandT is a random variable in the interval 0 to 1 second. The maximum deceleration during the heavy braking was considered to be 9 m/s^2, a value that can be achieved by braking systems of current vehicles (e.g. 2005 SAAB 9.5). We note that since this did not affect the development of the scenario, a simplified model was used to represent the passing maneuver of V2 on the other lane. To simulate the scenario, a simulation run of 20 seconds was enough. The length of the road segment on which the accident occurs was 500 meters.

For the extended rear-end scenario, we considered a two-lane bi-directional road on which a rear-end accident similar to the one above takes place. A density of 10 veh/km/lane was used in this case. On the direction opposite to the direction in which the accident happens, the vehicles were uniformly distributed on a road sector starting with the right end of the road. These vehicles travel with constant speed. The road length was selected so the vehicles could remain on the road for the entire duration of the simulation, e.g. a 2.2 km road was needed for simulating a 40 seconds simulation run. The vehicles traveling in the same direction with the direction in which the accident is produced were also uniformly distributed. They also travel with constant speed and their characteristics, i.e. initial position and speed, were selected so that they do not interfere with the development of the rear-end accident. Thus, the time development of the accident remained the same, but it was delayed in time in order to obtain a longer simulation run where vehicles could exchange more messages. The initial velocity of the vehicles not involved in the accident was set to 20 m/s. Vehicle V1 was initially positioned at 500 meters from the beginning of the road (i.e. its left end). The characteristics of the vehicles involved in the accident were similar to the basic scenario.

The above simulations were realized via C programs that take as input a configuration file where different parameters such as time granularity, deceleration, or initial speed of vehicles can be specified. The programs produced trace files containing the description of the movements of vehicles, which were then used in GloMoSim.

c. Intersection accident scenarios for system usability investigation

The simplified scenario contains two vehicles and employs the following settings. At the beginning of the scenario, vehicle V1 has a speed of 10 m/s, an acceleration of 0 m/s, and it is situated at 21 meters from the entry point into the intersection. Vehicle V2 is considered stopped at the beginning of the scenario, i.e. speed is 0 m/s, and it is situated at 4 meters from the entry point into the intersection. Each road lane has a width of 4 meters. The length of a car is also 4 meters. At time 1 s, vehicle V2 starts to pass the intersection with a constant acceleration of 1.5 m/s^2. The simulation is realized via a C program that generates the movements of the vehicles. A simulation run of 10 seconds was enough to simulate the scenario. In this case, each section of the intersection was around 30 meters long.

For the extended scenario, we considered a more complex situation that involves the same crossroad but in the presence of more vehicles. Thus, 10 more vehicles have been added. The initial situation was introduced in figure 5.6. The vehicles move as follows. Vehicles A and B are stopped during the simulation. These vehicles are waiting to pass through the intersection and are positioned at 1 respectively 7 meters from the entry point into the intersection. Vehicle C has passed through the intersection, it is situated at 4 meters after the entry point into the intersection and continues with a constant speed of 8 m/s during the simulation. Vehicle D is situated at 54 meters from the entry point into the intersection, has an initial speed of 20 m/s, intends to stop and therefore starts decelerating from the beginning of the scenario with 4 m/s^2. Vehicle E is situated at 4 meters after the entry point into the intersection and travels with a constant speed of 15 m/s. Vehicle F is situated at 10 meters from the entry point into the intersection, it is stopped and remains stopped for the entire simulation. Vehicle H and G have passed through the intersection and continue with a constant speed of 10 m/s and 15 m/s respectively. At the beginning of the simulation they are positioned at 2, respectively 14 meters after the entry point into the intersection. Vehicle I is situated at 30 meters from the entry point into the intersection and is approaching the intersection with a velocity of 10 m/s. Vehicle J is traveling with a constant speed of 8 m/s and is situated at the beginning of the scenario at 4 meters after the entry point into the intersection. In this case, the right and the upper legs of the intersection were 30 meters long and the left and the lower legs were 60 meters long.

The above scenarios were also simulated using C programs where parameters are specified via input files. These programs outputted trace files containing the movements of vehicles as coordinates and time points.

5.5 Baseline settings

Free parameters values

The ranges of values used for free parameters are presented in the table 5.2.

Table 5.2 Common settings for evaluations

Parameter	Range of values
BSM transmission interval	[0.001 – 2] [s]
Communication system bandwidth	[10 – 2000] [kbps]
Communication service area	[50 – 600] [m]
Network load density	[6 – 20] [vehicles/km/lane]
Mobility of nodes (i.e. via modification of velocity)	[10 – 40] [m/s]

The transmission interval for BSMs was varied from very low values to a value considered a threshold for traffic safety applications (i.e. 2 seconds) [AF96]. The bandwidth variation was within the capabilities of current communication systems (e.g. 9.6 kbps for cellular, 2 Mbps for IEEE 802.11 WLAN [Sta04]). The communication service area was modified according to short-range communication. The load density was varied from regular traffic to high volumes of traffic (e.g. as indicated in [Eva04]). The mobility of the nodes used common speed values for vehicles traveling on different kinds of roads.

Radio model parameters range

Table 5.3 presents the specific settings for the radio model used in the simulations. Classical models for radio wave propagation and radio type (i.e. SNR) were used. We employed the two-ray propagation model, which is extensively used for representation of signal propagation in MANETs deployed in urban or rural areas [TMB01]. In previous work we have used the free space propagation model for testing purposes (i.e. with transmission power of 9 dBm and 15 dBm) [Chi04, CS04a]. However, the free space model is an idealized model, and even if it can be used for simulating an environment with stronger interference due to lower power loss of the traveling signal, it is not as realistic as the two-ray model [TMB01]. Therefore, we have decided to perform further testing using only the two-ray model. In most of the tests, an Additive White Gaussian Noise (AWGN) channel was employed. However, different fading models, e.g. using Rayleigh or Ricean distributions [God02], can be also employed for testing. The Rayleigh model implies that no LOS exists between the communicating hosts. The Ricean model addresses situations when LOS communication between hosts is possible. In this case the interference between LOS and no LOS signals can be modeled via the Ricean K factor (e.g. a K factor of 5 is common [TMB01]). With consideration given to the test scenarios used in the evaluation, the vehicles can exhibit LOS communication, so the Ricean model seemed more appropriate. Thus, we have also performed several experiments using the Ricean propagation model with a K factor of 5. In this test, the general traffic scenario was used for generating the movement patterns of vehicles.

Table 5.3 Radio model parameters

Parameter	Value/Type
Propagation model	Two-ray
Frequency	2.4 GHz, alternative 5.9 GHz
Transmission power	12 dBm (≅ 317 m range) and 23.5 dBm (≅ 614.5 m range)
Bandwidth	2 Mbps (except when modified)
Medium Access Control (MAC)	non-persistent CSMA (Carrier Sense Multiple Access)
Radio type	Based on IEEE 802.11 Signal-to-noise ratio (i.e. SNR) bounded Standard radio with noise accumulation
SNR Threshold	10 dB
RX Sensitivity/RX Threshold	-91 dBm / -81 dBm

The specific settings of the radio model used for testing are detailed in the following. The default SNR threshold, reception sensitivity and reception threshold given in the GloMoSim source were used since these values were similar to those employed for real devices such as WLAN cards (e.g. [Gei02][Swi05]).

The values of the transmission power correspond to a transmission range slightly higher than 300 and 600 meters (i.e. when using the two-ray propagation model). A value of 300 meters was selected as an appropriate service area for traffic safety, and is also proposed within the DSRC specifications [YUA97, FCC04]. The value of 600 meters was employed mostly for testing purposes and was considered an upper boundary for the short-range communication.

The frequency that we used in most of the tests is within the ISM band, which is freely available and is employed by many current communication systems (e.g. WLANs, PANs). We note that in real operation this may imply a higher interference if different systems (e.g. WLAN, inter-vehicle safety communication, road toll collection communication) using this frequency spectrum are active in the same area. Therefore, we also performed tests with 5.9 GHz as frequency. This value was proposed within DSRC as a dedicated frequency for vehicular applications and was adopted in several countries, e.g. the United States [FCC04]. However, the results did not differ extensively and therefore we present in this thesis results obtained when testing at 2.4 GHz.

The bandwidth value used in most of the tests is a realistic value that can be provided by current communication systems (e.g. IEEE 802.11WLANs).

The MAC scheme that we employed was indicated as one of the potential schemes for traffic applications [KTT+02, FH02b].

We mention that the GloMoSim's radio model is implemented based on the IEEE 802.11 standard [IEE99]. The simulator specifies a synchronization time of 192 μsec and assumes a 5 μsec delay for the physical layer if specific delay values are not given in the MAC scheme.

Other settings

Several other specific settings that were used in the tests are presented below.

Routed BSMs were delayed with a value randomly selected from the interval [0, Tint_BSM].

The random delay for avoiding synchronization of retransmitted WAMs was in the interval [0, 0.1] seconds. For delaying WAMs based on the distance to the sender we have primarily used Tdefer = 0.05 s, Tmax_WAM=0.2 s, and K=3. For the continuous transmission of WAMs, the messages were issued at an interval equal to 1 s.

The maximum time a record could exist in the database without being updated was 2 s. The local network database update granularity (i.e. how often it is updated) was 0.005 s.

When BSMs are sent, their dissemination starts at the beginning of the simulation. To avoid the initial synchronization of the transmission, the starting moment for disseminating the BSMs was randomly chosen from the interval [0, 0.1] s.

The interval after which a section of the communication system queue that is not empty tries to empty itself was set to 0.01 s. This happens until no messages are left in the queue section or the simulation run ends. The size of each queue section was set to 100 messages.

When WAMs are sent, they are by default set for large area notifications (i.e. the *default acceptance field* is validated*)*. Only for particular tests did we invalidate this option.

The number of hosts in local networks was set to 20 and all vehicles were considered equipped with communication devices (i.e. 100% penetration rate).

The road was considered slippery. Randomly selected vehicles had a poor status.

5.6 Test cases

Test case 1: Communication performance for dissemination of basic safety messages with constant rate

The communication performance is evaluated for dissemination of BSMs generated at a constant rate. The forwarding of BSMs is performed using the basic approach that considers only the relative distance between hosts that may have an interest one in another. The scenario considered is the general scenario. The following aspects are investigated:

- Influence of transmission interval, bandwidth, network load, hosts' mobility and communication area size on BSMs dissemination delay, packet collisions, send errors and efficiency of information filtering.
- Influence of the transmission power on communication performance.
- Appropriate values for the transmission interval for BSMs.
- The necessary communication system bandwidth for obtaining high performance.
- Appropriate values for the communication service area.
- Appropriate number of hosts in local networks.

The experiments were performed by modifying one of the free parameters when the others are kept constant. When not modified, the values of the free parameters were: transmission interval

0.1 s, communication service area 300 m, network load 6 veh/km/lane, maximum speed in the traffic model 25 km/h, and system bandwidth 2 Mbps. The tests were done using a 12 dBm and alternatively 23.5 dBm as transmission power.

Test case 2: Communication performance for dissemination of basic safety messages with adaptive rate

The communication performance is evaluated when employing the adaptive approach for disseminating BSMs. The forwarding of BSMs is performed using the simplified algorithm as in the previous test case. The scenario considered is the general scenario. The following aspects are investigated:

- Influence of bandwidth, network load, hosts' mobility and communication area size on BSMs dissemination delay, packet collisions, send errors and efficiency of information filtering.
- The necessary communication system bandwidth.
- Appropriate value for the communication service area.
- Appropriate number of hosts in local networks.
- The communication performance in comparison to the constant rate approach.

These investigations were performed using settings similar to those of the previous test case.

Test case 3: Influence of BSMs forwarding technique on the communication performance

This test investigates the differences in communication performance when using the two proposed techniques for forwarding BSMs, i.e. the basic approach based only on distance, and the extended approach where the same decision used for filtering is also used for routing. The following aspects are investigated when using the extended technique for forwarding BSMs:

a. For settings similar to test case 1:

- Influence of transmission interval, bandwidth, network load, and communication area size on BSMs dissemination delay, packet collisions, send errors and efficiency of information filtering. The results are investigated in comparison to the results obtained in test case 1.
- Investigation of the communication performance when using a different fading model, i.e. the Rician model with k=5.

b. For settings similar to test case 2:

- Influence of bandwidth, network load, and communication area size on BSMs dissemination delay, packet collisions, send errors, and efficiency of information filtering. The results are compared to the results obtained at test case 2 and the results obtained in test case 3.a.

Test case 4: Communication performance when disseminating warning messages with singular transmission

The communication performance is evaluated for transmission of WAMs in the presence of (disseminating) BSMs. In these experiments, a warning message is issued when a host identifies some hazard in traffic. To increase the chances of correctly alerting other vehicles about the dangerous situation, each WAM is issued a number of times, which was empirically set to 3. The retransmission of WAMs is performed using the random delay approach. The scenario considered is the general traffic scenario, and the tests are performed using settings similar to test case 1, and the extended routing scheme for BSMs. As mentioned in the baseline settings, the WAMs had the *default acceptance* field validated.

The simulations are performed by randomly selecting several moments in time during a simulation run when a randomly selected node issues a warning message. During each simulation run, a number of 10 moments for the generation of warnings was used. The following aspects are investigated:

- Influence of transmission interval, bandwidth, network load, and communication area size on BSMs dissemination delay, packet collisions, send errors and information filtering efficiency. The results are compared to the case when no WAMs are generated.
- Influence of transmission interval, bandwidth, communication service area, network load and mobility of the hosts on WAMs dissemination delay.
- The above aspects when disseminating WAMs only within the local network, i.e. with the default acceptance field invalidated.

Another aspect that is investigated is the information dissemination success for transmission of WAMs. This is a measure of how many hosts that need to receive a warning message actually got it. The problem here is the definition of a *zone of interest*, i.e. the specification of the vehicles that should receive a specific warning. For a specific scenario where a high probability of collision is detected, this zone contains the vehicles that need to be aware of the danger. However, in the general traffic model used in this test, the definition of such a zone depends of the type and importance of the detected emergency situation and the current topology of the traffic. For instance, a WAM can be of interest only for the hosts from the local network of the sender if the *default acceptance* field is invalidated. However, when the warning message is delivered in an area larger than the size of a local network (i.e. *default acceptance* is validated), a specific definition of the zone of interest needs to be made. In the results presented in this thesis we have considered the issued WAMs to be of interest for vehicles in behind, but on the same lane as, and vehicles in front of the issuer on the opposite lane, which are situated less than 500 meters from the vehicle that issued the warning message.

Test case 5: Communication performance when disseminating Warning Messages with multiple transmissions

Similarly to the previous test case, the communication performance is evaluated for transmission of WAMs in the presence of BSMs. The multiple transmission case implies that a vehicle detecting a danger issues warning messages until the danger does not exist any longer, or is no longer detected by the issuing vehicle. The retransmission of WAMs is performed using the random delay approach. The scenario considered is the general traffic scenario and the tests are performed using the settings from test case 1. The routing scheme for BSMs is the extended scheme. As with the previous test, the WAMs had the *default acceptance* field validated. Also here, the tests are performed by randomly selecting several moments in time during a simulation run when a randomly selected node starts to issue warning messages. The moment when the danger occurs and the interval for which the danger exists are randomly selected. During a simulation run, a number of 10 moments for the occurrence of dangers that determined the sending of warnings was used. The following aspects are investigated:

- Influence of transmission interval, bandwidth, network load, and communication area size on BSMs dissemination delay, packet collisions, send errors and information filtering efficiency. The results are compared to the case when no WAMs are generated.
- Influence of transmission interval, bandwidth, communication service area, network load and mobility of the hosts on WAMs dissemination delay. The results are compared to the case when WAMs are generated with singular transmission.

The information dissemination success for transmission of WAMs is also investigated using settings and assumptions similar to those from test case 4.

Test case 6: Influence of deferred retransmission techniques for WAMs on communication performance

This test investigates the influence of modifying the modality of deferring the retransmission of warning messages by using the proposed technique based on the distance to the sender. Investigations similar to those from test case 4 are performed. The results are compared with those obtained in test case 4.

Test case 7: Investigations of system usability for avoiding accidents

This test case investigates the communication performance in realistic accident scenarios for assessing whether the proposed communication system can provide the necessary level of support to on-board active safety system.

The first type of scenario is the rear-end accident scenario. First, the basic scenario involving three vehicles is considered. All vehicles generate basic safety messages from the beginning of the simulation, and vehicle V3 issues a warning message when it breaks down. The generation of BSMs is performed like the settings presented in test case 1, and the forwarding of BSMs is performed following the extended routing scheme. The WAM transmission is performed according to the singular WAM transmission (i.e. as in test case 4). The WAM retransmission is performed using the random delay approach. The following aspects are investigated:

- WAM delay.
- Information dissemination success for WAM.

The extended rear-end scenario is then considered, and the same aspects are investigated.

The second type of scenario is the intersection scenario. First, the basic scenario with a perpendicular crash involving two vehicles is considered. In this case, vehicle V2 issues a warning message when it starts to pass through the intersection. The distribution of messages (e. BSMs and WAM) and the aspects investigated are similar to the case of rear-end accidents. Similar instigations are then performed for the extended intersection accident.

As previously stated, information dissemination success measures which vehicles that needed to receive a warning actually got one. In the experiments performed in this test case, it was assumed that all the vehicles in the simulation are interested in receiving the issued WAMs. The information dissemination success and the WAMs' delay are metrics that indicate whether the proposed system can be used successfully for timely and reliable provision of notifications to an on-board collaborative active safety system.

5.7 Results presentation and analysis

The results obtained are presented and discussed for each test case. For the sake of brevity we present in graphical format all the results for the first test case with their analyses. In subsequent cases, graphical representations are given only in those cases where the metrics varied significantly. Please note that some of the graphs, such as the graphs for load density and mobility (i.e. maximum speed variation), have origins other than null.

Test case 1

This test investigated communication performance for dissemination of BSMs with a constant rate.

Results

Accepted BSMs delay

The delay values for accepted BSMs as a function of transmission interval, bandwidth, communication service area, load density and nodes mobility are presented in figures 5.7 – 5.18.

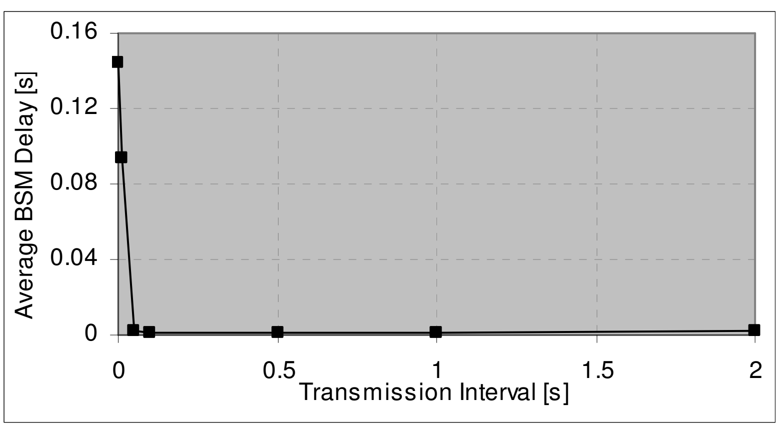


Figure 5.7 Average BSMs delay as a function of transmission interval – test case 1

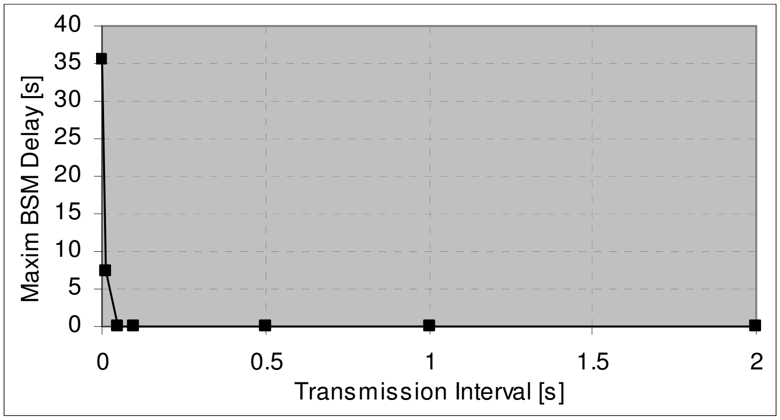


Figure 5.8 Maximum BSMs delay as a function of transmission interval – test case 1

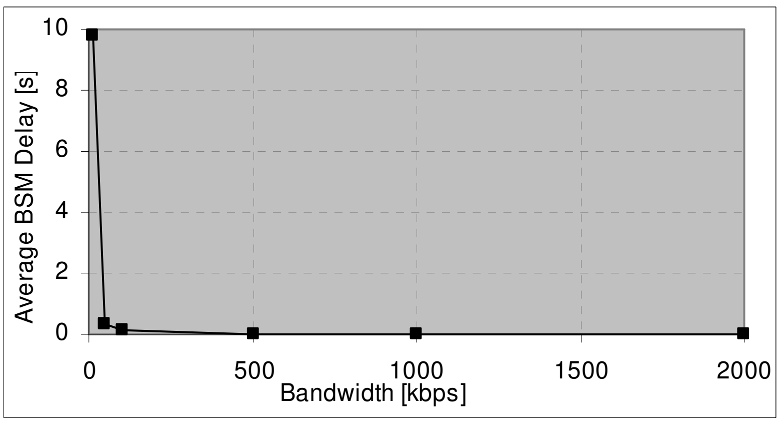


Figure 5.9 Average BSMs delay as a function of bandwidth – Test case 1

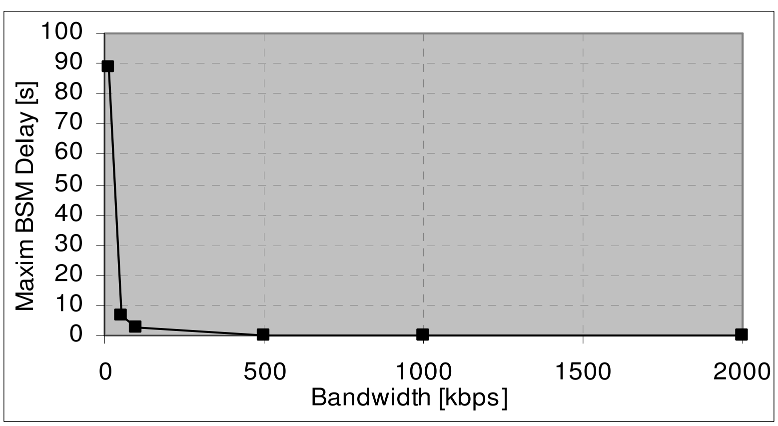


Figure 5.10 Maximum BSMs delay as a function of bandwidth – test case 1

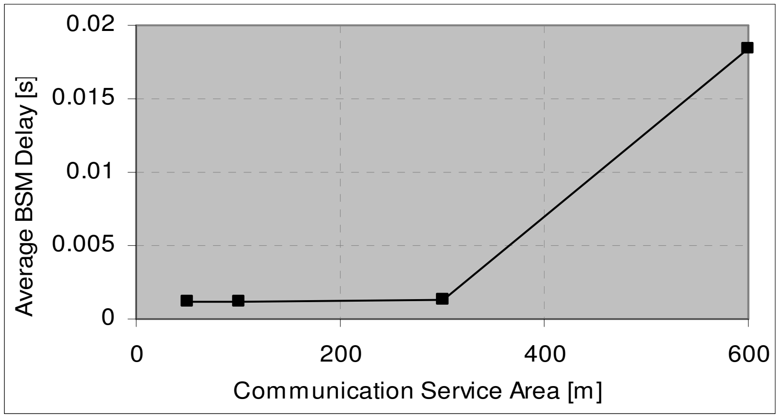


Figure 5.11 Average BSMs delay as a function of communication service area; transmission power 12 dBm – test case 1

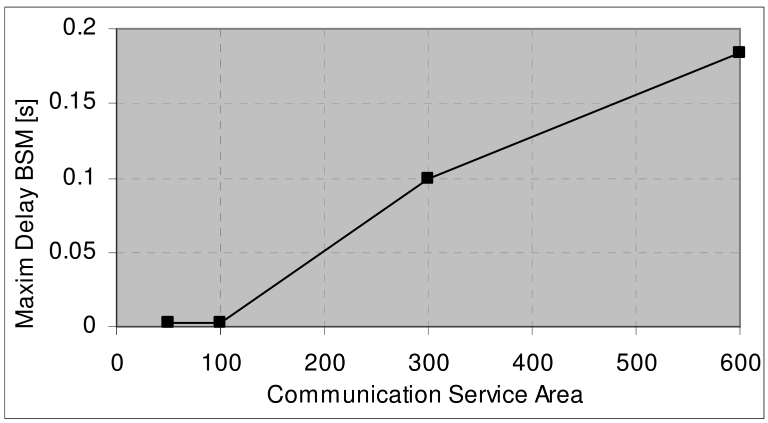


Figure 5.12 Maximum BSMs delay as a function of communication service area; transmission power 12 dBm – test case 1

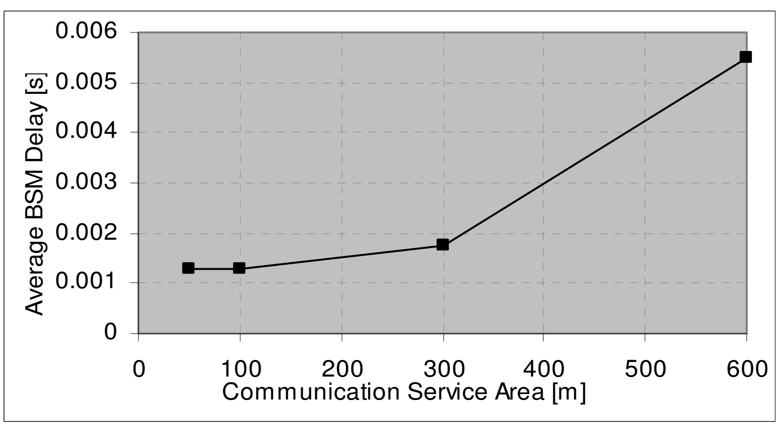


Figure 5.13 Average BSMs delay as a function of communication service area; transmission power 23.5 dBm – test case 1

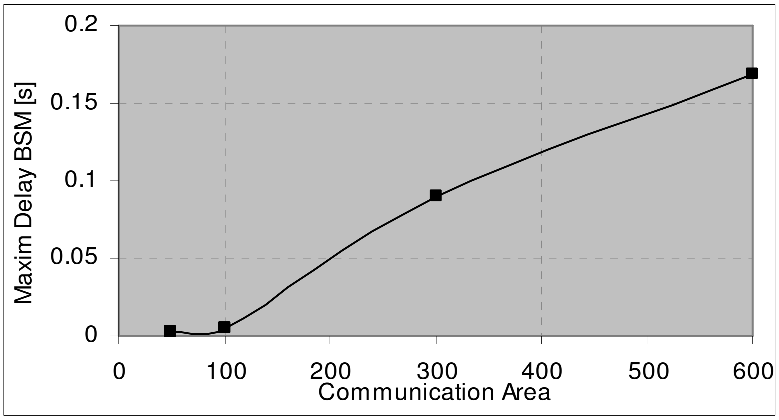


Figure 5.14 Maximum BSMs delay as a function of communication service area; transmission power 23.5 dBm – test case 1

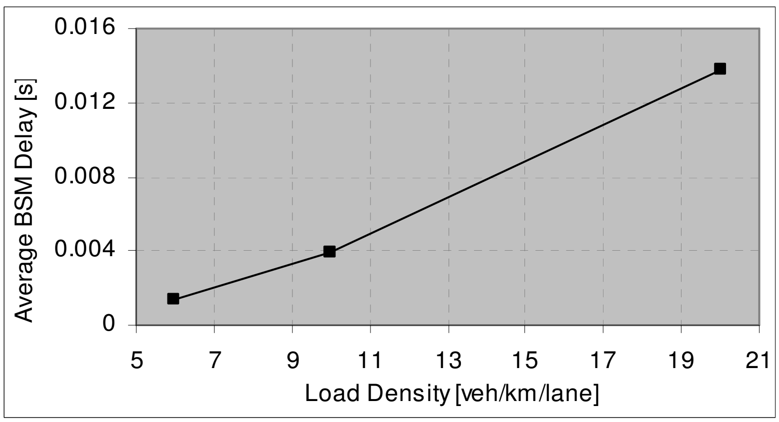


Figure 5.15 Average BSMs delay as a function of network load – test case 1

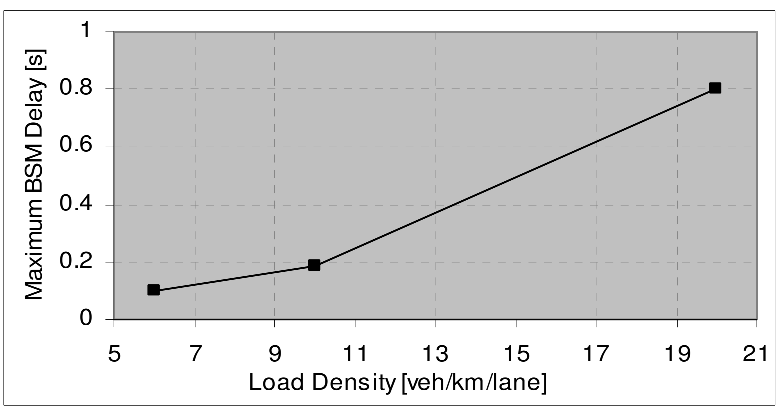


Figure 5.16 Maximum BSMs delay as a function of network load – test case 1

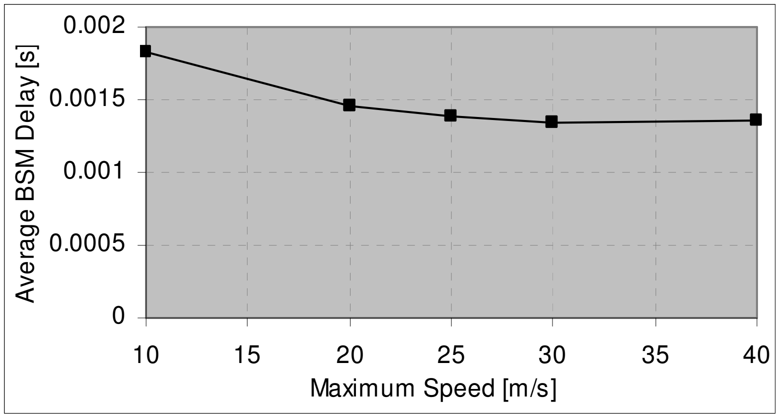


Figure 5.17 Average BSMs delay as a function of velocity – test case 1

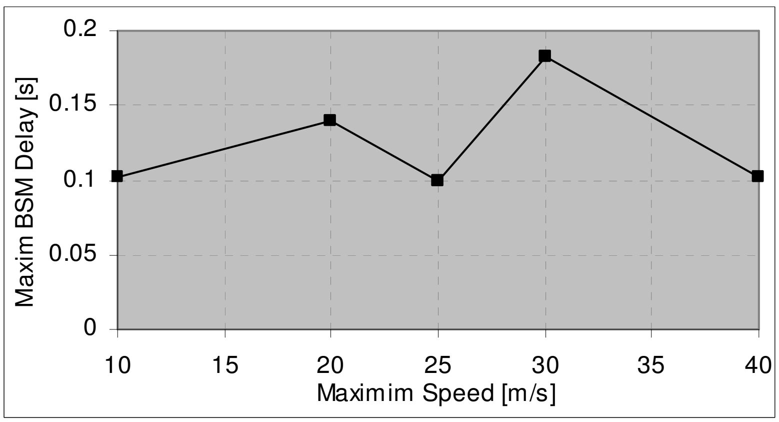


Figure 5.18 Maximum BSMs delay as a function of velocity – test case 1

The delay followed a similar pattern for variation of the transmission interval and the communication system bandwidth. Thus, larger values have been obtained for very small transmission intervals and small bandwidths. For transmission intervals around 0.04 s, the maximum delay was under 1 s. As soon as the transmission interval was higher than 0.05 s the maximum delay values were lower than 0.1 s and had a very limited variation. The higher values for low transmission intervals indicated that the hosts were unable to efficiently acquire and use the transmission medium. Furthermore, the messages seemed to be frequently lost due to collisions. Extensive routing has also been noticed, e.g. in one of the simulation runs a node routed 10384 messages for a transmission interval of 0.001 s, compared to only 1220 messages for a transmission interval of 0.1 s. All these led to an increase of the traffic on the channel and to situations where older messages were received instead of current messages, which were lost. This also induced increased delays in receiving the traffic data.

In the case of bandwidth, the maximum delay was higher than 1 s when the bandwidth was lower than 250 kbps. The metric actually reached tens of seconds for bandwidths of tens of kbps (e.g. 60 s for 10kbps). The maximum delay reached lower values for bandwidths over 210 kbps, and was around 0.1 s for a bandwidth of 500 kbps, and 0.09 s for 2Mbps. This behavior showed that the communication channel was rapidly saturated for small bandwidth values. Thus, the communication should have a bandwidth of at least several hundreds of kbps.

The values of the maximum delay were small for small communication areas and tended to increase as the area was increased. The patterns were similar for both transmission powers used in the tests. When the communication area was higher than 300 m, the maximum delay increased over 0.1 s (e.g. 0.18 s for 600 m for power 12 dBm, and 0.17 s for power 23.5 dBm). This behavior was more visible when looking at the average delay. The results showed that the space limitation of the communication service area lead to an increase of the communication performance, represented here with smaller delay values. They also indicated values around 300 m as a (median) threshold for obtaining small transmission latency. When the communication service area was lower than, or equal to, 300 meters, the average values were quite similar for both transmission powers, with slightly better values for the smaller transmission power (i.e. 12 dBm). However, for values over 300 meters the average delay was much smaller when 23.5 dBm was used as transmission power. This was expected since the larger coverage allowed the distant hosts to directly receive messages. This was not possible when using 12 dBm as the transmission power; the distant hosts received messages only via routing.

The maximum delay values varied significantly for modification of the network load, with higher values for high network loads. A minimum for delay was obtained for a small number of vehicles on the road, which is explained by the low amount of data that needed to be transmitted. By increasing the number of hosts, more communication takes place and the contention for medium increases. This is reflected in larger intervals for accessing the medium. Furthermore, because a large number of messages are transmitted, it is possible for a large number of errors (e.g. collisions) to happen. This leads to the reception of the data via information forwarding, and this induces greater delays. We note that for load values higher than 20 veh/km/lane the maximum delay increased to 0.8 s, a value that we have considered as a critical threshold. However, the absolute variation (i.e. quantitative) was considerably less significant when looking at the average delay. Thus, the average delay was under 0.014 s in all tests, which indicates a rather good median system behavior. Still, even if the obtained delay values might be considered acceptable, we considered that these results indicated the need for improvements.

The mobility of the hosts had little influence on delay. The maximum values were more prone to variations but following a random pattern with 0.08 s as the maximum variation. For instance, the maximum delay was close to 0.1 s at 10 m/s, 25 m/s and 40 m/s, and was 0.18 s at 30 m/s.

The average values of the delay were always much smaller than the maximum values. For certain cases, the average values were even hundreds of times (e.g. 200 times) smaller than the maximum values. Therefore, in several tests we have also looked at the distribution of the delay values over the nodes in the simulation. This indicated that only a very small number of nodes actually exhibited delays close to the maximum value. Thus, it seemed that actually only a small number of hosts experienced difficulties in communicating, whereas the large majority of hosts could communicate in good conditions.

Packet collisions

The packet collisions as a function of transmission interval, bandwidth, communication service area, load density and nodes mobility are presented in figures 5.19 – 5.24.

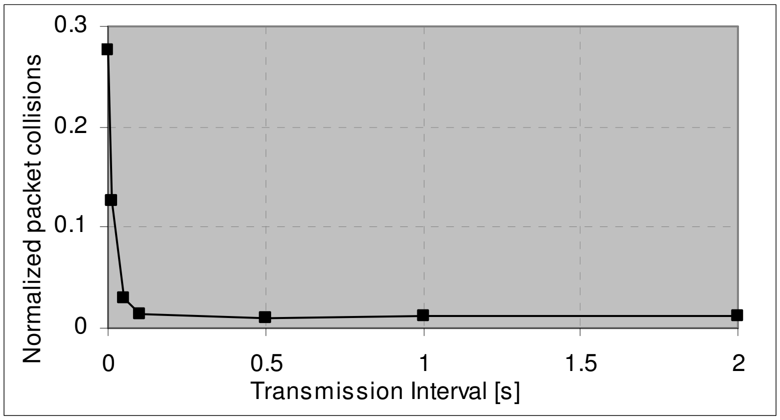


Figure 5.19 Packet collisions as a function of transmission interval – test case 1

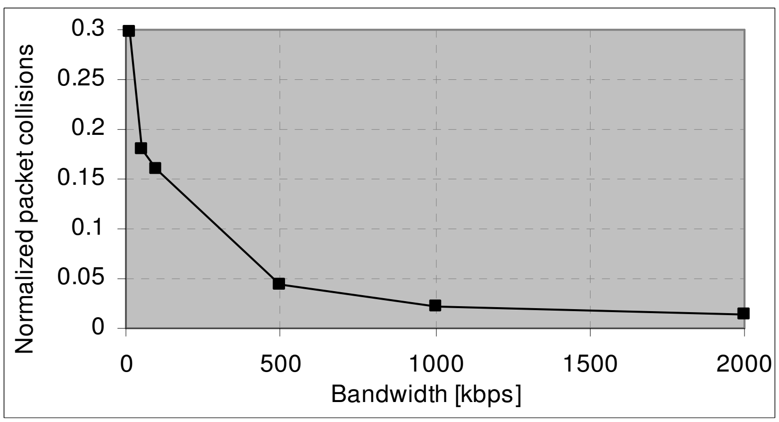


Figure 5.20 Packet collisions as a function of bandwidth – test case 1

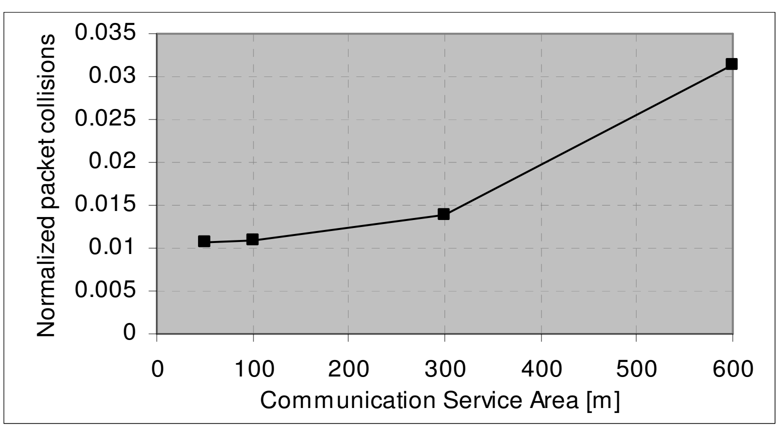


Figure 5.21 Packet collisions as a function of communication service area; transmission power 12 dBm – test case 1

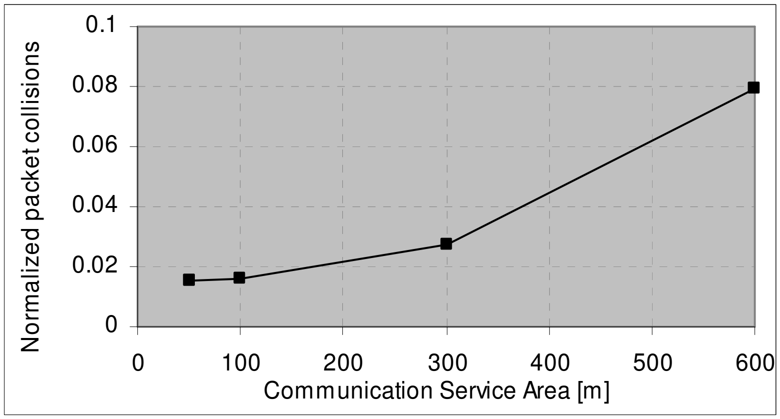


Figure 5.22 Packet collisions as a function of communication service area; transmission power 23.5 dBm – test case 1

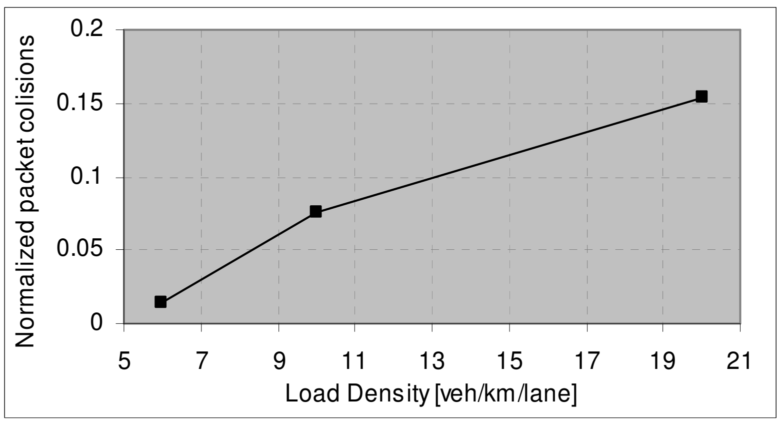


Figure 5.23 Packet collisions as a function of network load – test case 1

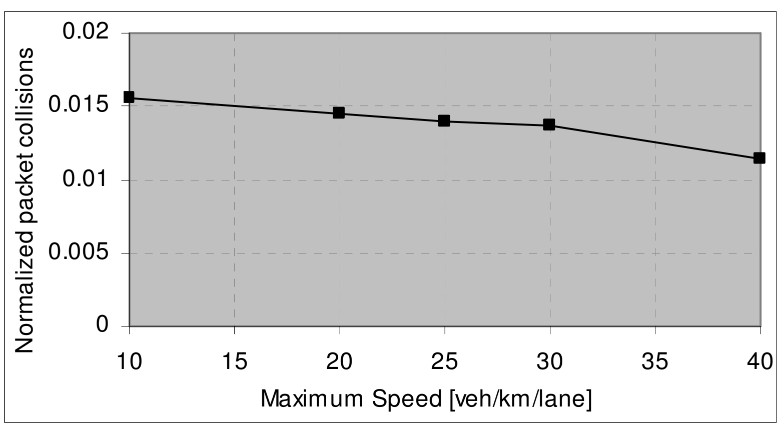


Figure 5.24 Packet collisions as a function of nodes mobility – test case 1

The metric was large for small transmission intervals and then decreased significantly with the increase of the transmission interval. For transmission intervals higher than 0.1 s, a fairly low value of the normalized packet collisions was determined. This is mainly because for small transmission intervals the vehicles tried to send their data often and the packets collided at the receivers. Furthermore, at low transmission intervals the hosts employed routing extensively, which led to a higher channel occupation and a higher probability of packet collisions. These results showed that high efficiency of communication can be obtained when the transmission intervals for basic safety messages is equal to, or higher than, 0.1 s.

A similar behavior was obtained when modifying the bandwidth. As the bandwidth increased, packet collisions decreased and the channel was not saturated anymore. The metric reached quite a low value when the bandwidth was over 500 kbps. This indicated again that a system with a bandwidth of several hundreds of kbps is needed.

The normalized packet collisions increased with the increase of the communication service area, with smaller variations until the area was lower than 300 m, and larger variations for areas between 300 and 600 m. We determined that the number of messages that are routed had risen significantly with the increase of the service area, which led to a higher collision probability. Noticeable differences were obtained when using different transmission powers. For the case of 23.5 dBm, the metric normalized packet collisions was up to 2.5 times higher than when using 12 dBm. This is due to the larger area in which the radio wave propagates, and consequently the increased possibility of collisions as the packets can collide at close as well as distant receivers.

The load density also affects the packet collisions. The increase in the number of the hosts on the road also caused an increase in the number of collisions. This was expected since more hosts competed for the transmission medium when they tried to send traffic data. Consequently, more messages could simultaneously arrive at the radio layer of each node during a simulation run.

As with the BSMs delay, the variation of the mobility of the hosts causes a small variation in the number of collisions.

Send errors

The send errors as a function of transmission interval, bandwidth, communication service area, load density and nodes mobility are presented in figures 5.25 – 5.30.

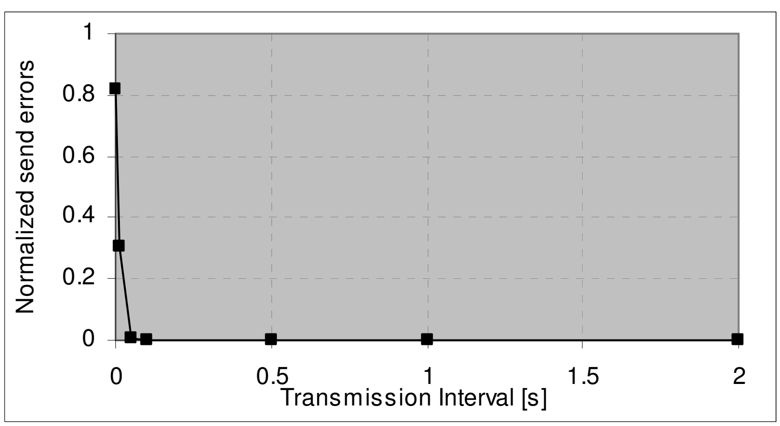


Figure 5.25 Send errors as a function of transmission interval – test case 1

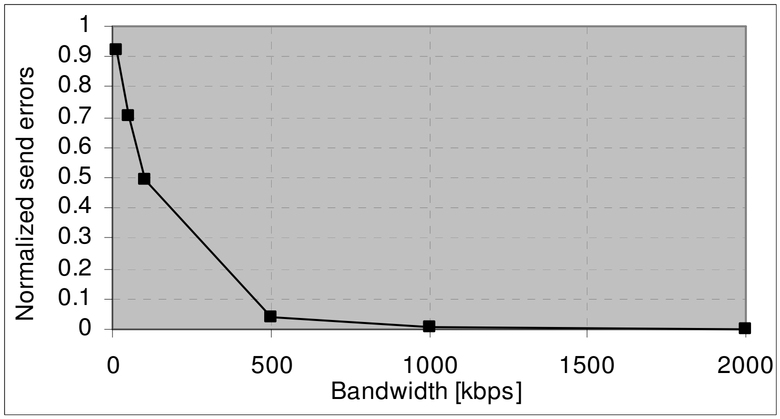


Figure 5.26 Send errors as a function of bandwidth – test case 1

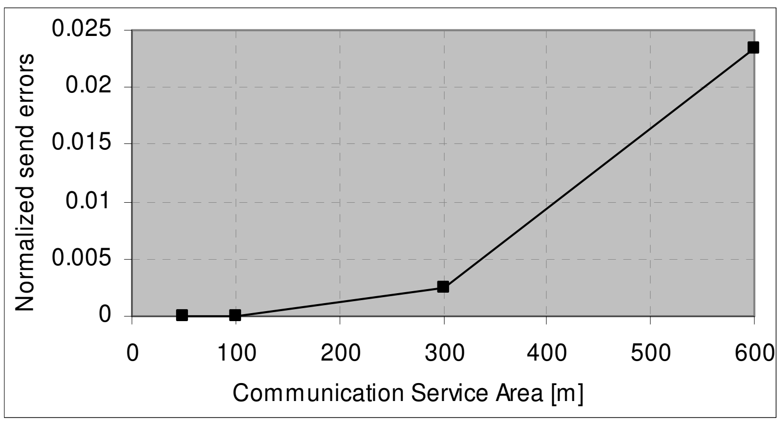


Figure 5.27 Send errors as a function of communication service area; transmission power 12 dBm – test case 1

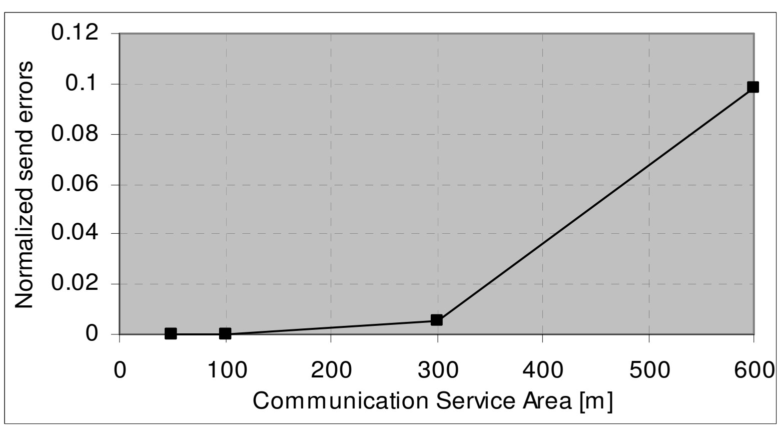


Figure 5.28 Send errors as a function of communication service area; transmission power 23.5 dBm – test case 1

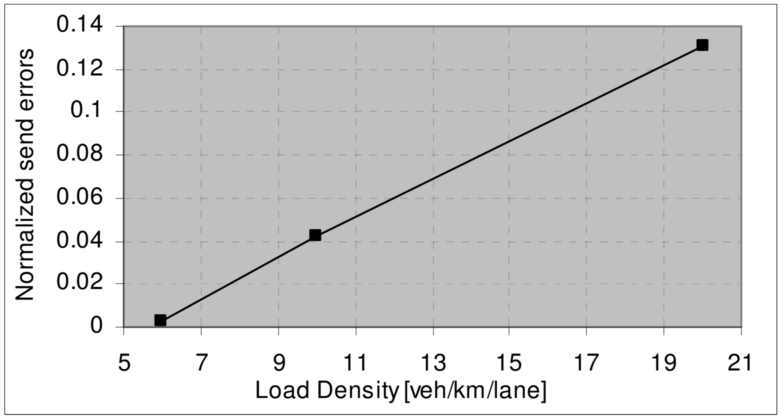


Figure 5.29 Send errors as a function of network load – test case 1

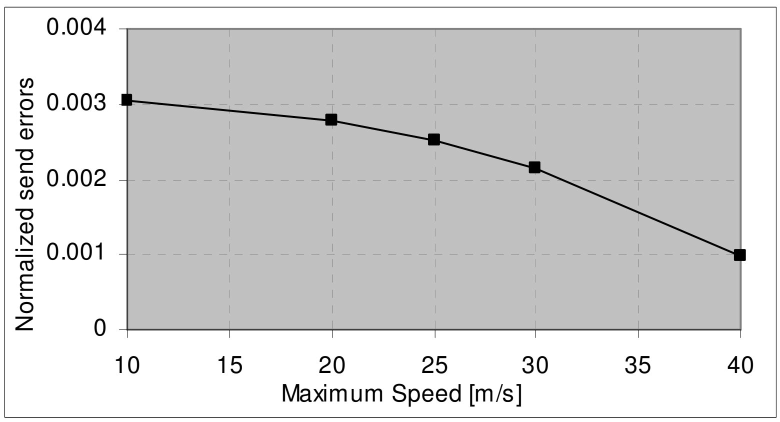


Figure 5.30 Send errors as a function of nodes mobility – test case 1

The values for the normalized send errors were relatively high for transmission intervals lower than 0.01 s. This was because the hosts tried to send their messages very often, and could not access the transmission medium in time because it was busy. (By "in time" we mean that the transmission of a BSM could not be performed until a newer BSM was generated and delivered for transmission on the air interface). As the transmission interval increased, the send errors decreased and reach very low values for intervals higher than 0.05 s (e.g. 0.00254 for 0.1 s).

For low bandwidth values, the send errors were high and did not reached a low value when the bandwidth was lower than 350 kbps. For bandwidths between 500 kbps and 2 Mbps, the values for send errors were very low. This behavior is explained by the channel saturation and the impossibility for the hosts to access the medium in time when the communication channel has low bandwidth. The results indicate that a system with a communication bandwidth of at least 500 kbps would perform best.

The patterns for modifications of the communication areas were similar for the two transmission powers considered: the send errors were higher for larger communication service areas. The metric had quite low values until the service area was lower that 300 m, and increased afterwards. However, the absolute variation was not major. The results for a transmission power of 12 dBm were significantly better than for 23.5 dBm, the send errors being even 4 times lower for the 12 dBm case. The reason is that when a higher transmission power is used, the messages travel further and occupy the medium not only at closer but also at distant hosts. This consequently led to a higher number of hosts that could not access the transmission medium in time.

The network load also affected the behavior of the send errors. Thus, for smaller loads, the send errors were quite low but increase quickly for larger loads. The reasons are similar to those presented for the increase in the packet collisions.

The mobility of the hosts had very little impact on the send errors (i.e. the highest variation was 0.0021).

Information filtering rate

The information filtering rate as a function of transmission interval, bandwidth, communication service area, load density and nodes mobility is presented in figures 5.31 – 5.36.

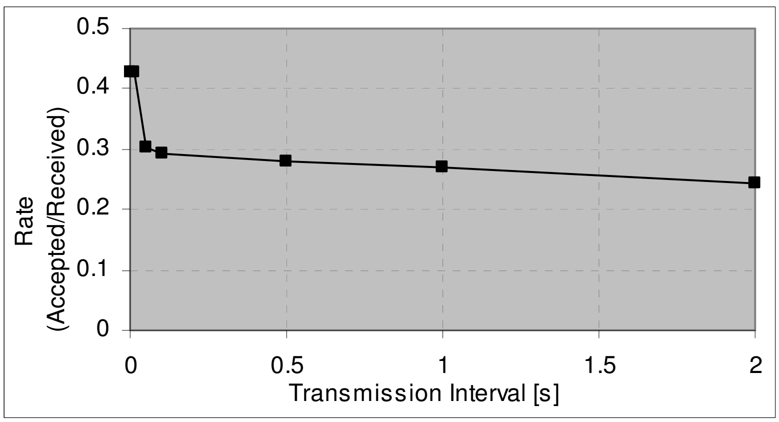


Figure 5.31 Information filtering rate as a function of transmission interval – test case 1

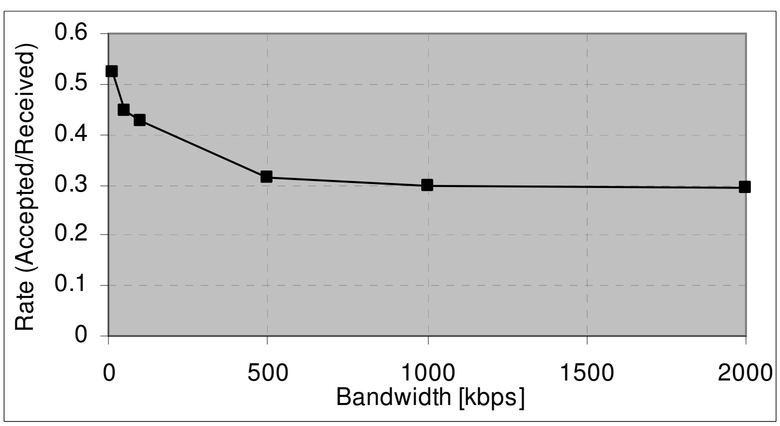


Figure 5.32 Information filtering rate as a function of bandwidth – test case 1

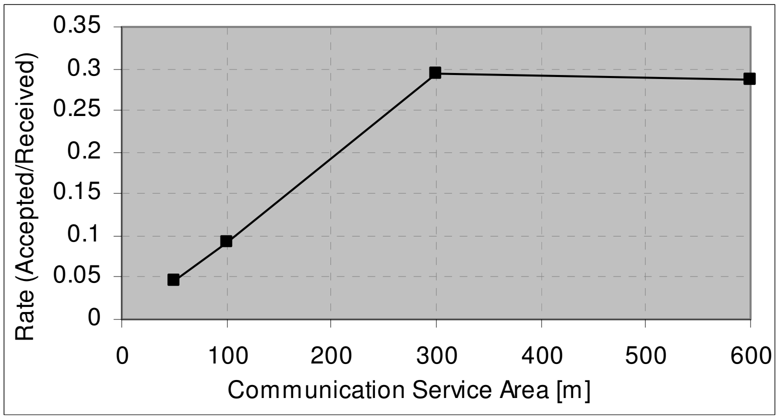


Figure 5.33 Information filtering rate as a function of communication service area; transmission power 12 dBm – test case 1

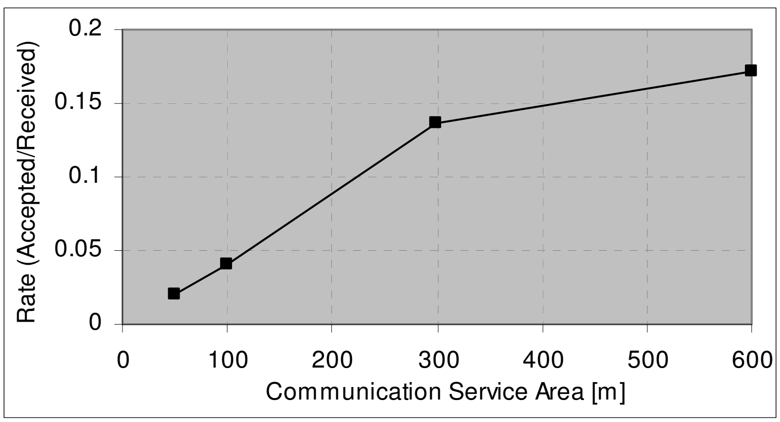


Figure 5.34 Information filtering rate as a function of communication service area; transmission power 23.5 dBm – test case 1

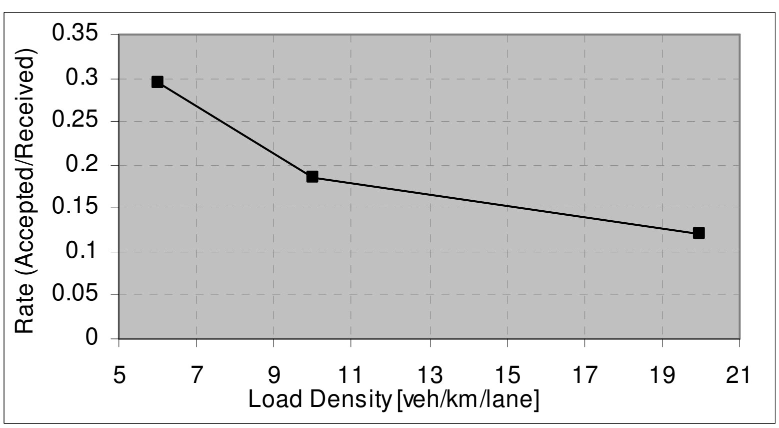


Figure 5.35 Information filtering rate as a function of network load – test case 1

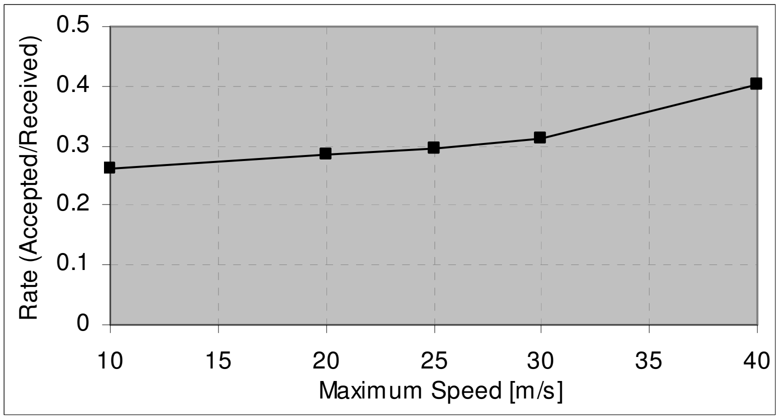


Figure 5.36 Information filtering rate as a function of nodes mobility – test case 1

The information filtering had similar patterns when varying the transmission interval and the communication system bandwidth. The metric exhibited slightly higher values for smaller values of transmission interval and bandwidth. The filtering rate then decreased relatively steeply and had a limited variation for transmission intervals higher than 0.05 s (i.e. 0.25 – 0.3), and bandwidth values higher than 500 kbps (i.e. 0.29 – 0.3). The results indicated that the communication protocol performed a significant filtering of information. On average, only 30% of all received messages were considered to contain useful information and therefore accepted.

The information filtering also varied with the extent of communication service area. The metric had low values for small communication areas (e.g. 0.04 for 50 m), which increased until the communication areas was higher than 300 m, and then varied fairly slowly. The low values obtained for small communication areas are due to the large number of messages that arrived at the hosts, which only accepted messages from nearby hosts. The metric exhibited lower values when testing with 23.5 dBm as a transmission power than when testing with 12 dBm. This was because the sent data in the first case was disseminated in a larger area and therefore a larger number of non-useful messages arrived at the hosts, who discharged them.

The information filtering decreased with the increase of the network load. This is because increasing the network load means more vehicles tend to send and rout messages. Consequently, the hosts received more messages of no interest, i.e. messages with non-useful traffic data or older messages. This caused the filtering mechanism to drop more messages.

The information filtering rate showed a small variation when modifying the mobility of the hosts. Thus, the metric varied between 0.26 – 0.4 for maximum speeds between 10 m/s – 40 m/s.

Evaluation results for test case 1 – final analysis

The results indicated that efficient communication is possible even with the basic settings of the communication protocol that were used in this test case.

The maximum delay values were usually low and very low, a higher value being obtained only when the network was under high stress, i.e. a high network load was used. However, even in this case, the average delay values were relatively low. We also investigated here how the maximum values were distributed over the hosts in the simulations. This investigation revealed that actually only few hosts experienced relatively long delays, whereas the large majority of hosts received the data with low or very low latency. The packet collisions and the send errors were usually small under certain settings of the communication protocol. Larger values for packet collisions have been noticed for high network loads and for large communication areas when the higher transmission power was used. Whereas the first is mostly a problem related to the basic MAC scheme employed in the tests, the second can be solved by using a smaller transmission power and an appropriate communication service area, e.g. 300 m. Larger values for send errors were also obtained for high network loads, which also indicated the inefficiency of the MAC scheme to provide fast access to the channel. The effectiveness of the filtering mechanism, evaluated using the information filtering rate, revealed that usually less than one-third of the received messages were accepted by a host. This indicated a major filtering of messages, which in turn demonstrated the advantage of using such a technique when disseminating information about vehicles in traffic. The communication also coped well with the mobility of the hosts, as small variations of the metrics were acknowledged when modifying the hosts' mobility.

We note that the techniques used for queuing and retransmitting messages had an important role in improving communication quality. Even the basic randomization when routing BSMs led to better quality. However, even if the communication quality was moderately good in this test case, the results indicated the need for investigating further improvements. From the protocol point of view, the transmission method and the routing scheme were indications of possible points of improvement. Furthermore, many of the less positive results were due to the simple MAC scheme that was employed. Even if this scheme was indicated as a possible appropriate alternative for vehicular communication (e.g. [FH02b]), other schemes may be more efficient and may lead to improved performance. We mention that several dedicated schemes for vehicular communication have already been proposed (e.g. [LHS+01, PDO+02, CMR+03]), and new schemes are currently under investigation (e.g. [FH05, YRM05, SMG+05]).

The use of a lower transmission power generally led to better performance. Best results were obtained when the transmission power provided a transmission range close to the extent of the most appropriate value found for the communication service area, i.e. 300 m.

Additionally, we identified appropriate settings for the proposed communication protocol. Thus, values of the transmission interval for basic safety messages equal to, or higher than, 0.1 s led to relatively good results. We note that values such as 0.1 s are also appropriate for keeping the vehicles up-to-date about the traffic situation. With regard to the communication system bandwidth, values over 500 kbps were needed to assure good performance. The advantages of using small communication service areas were shown by the tests. A value of 300 meters was determined as a threshold for fairly good performance. We note that we selected the same value as appropriate from the traffic safety point of view.

The initially selected number of hosts in a local network (i.e. MNH=20) served the functionality of the communication protocol well. This number seemed sufficiently high for a host to maintain data of interest about other hosts. We derived this conclusion by observing the local network's composition (i.e. the level of occupation in the communication system database at each host) at the end of each simulation run. Thus, in almost all simulations, the number of hosts in the local network was lower than MNH (i.e. the databases were not completely occupied).

As a final test, we analyzed in several experiments the composition of the local network of each node at the end of the simulation to identify if these nodes have information about the vehicles that should be of interest. To do so, we defined beforehand, using the characteristics of the vehicles from the trace files and the filtering rules, which vehicles are of interest for each of the nodes. Then, we analyzed the local network database to see if these vehicles are actually registered into it. In all the cases in which this analysis was performed, the matching scored the maximum value, which indicated that the nodes had data about the vehicles of interest.

Test case 2

This test investigated communication performance for dissemination of BSMs with adaptive rate.

Results

The results are presented with regard to the results obtained for the previous test case.

Accepted BSMs delay

The delay values for accepted BSMs as a function of bandwidth and load density are presented in figures 5.37 – 5.40. The results for communication area and hosts mobility were similar both as patterns and values to the constant rate test.

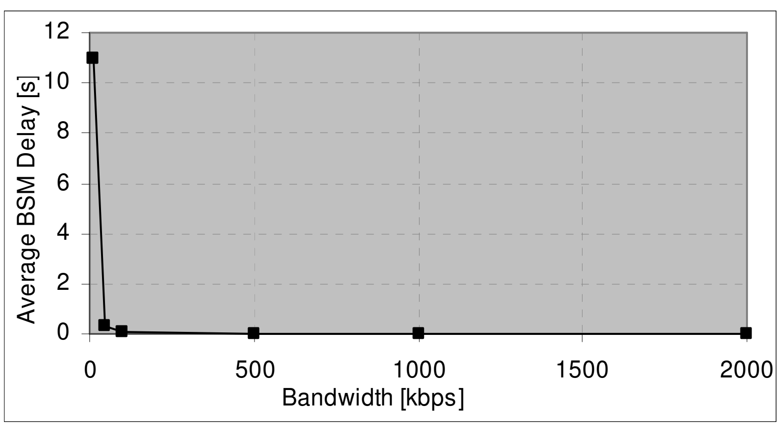


Figure 5.37 Average BSMs delay as a function of bandwidth – test case 2

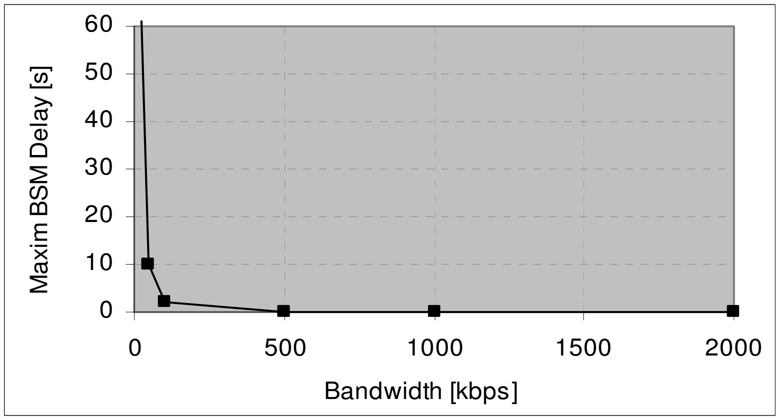


Figure 5.38 Maximum BSMs delay as a function of bandwidth – test case 2

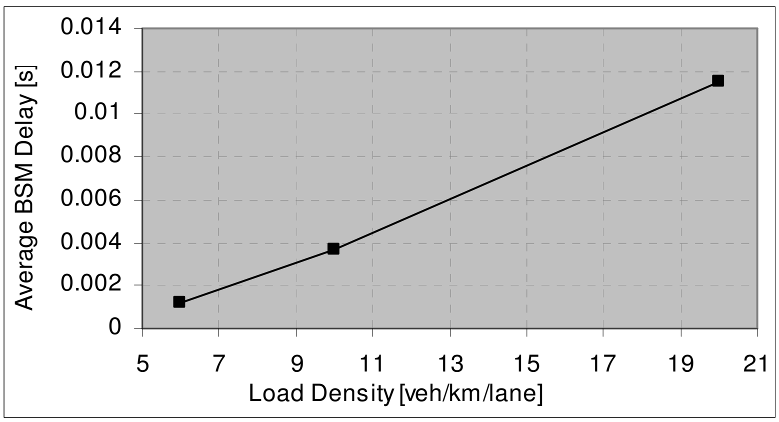


Figure 5.39 Average BSMs delay as a function of load density – test case 2

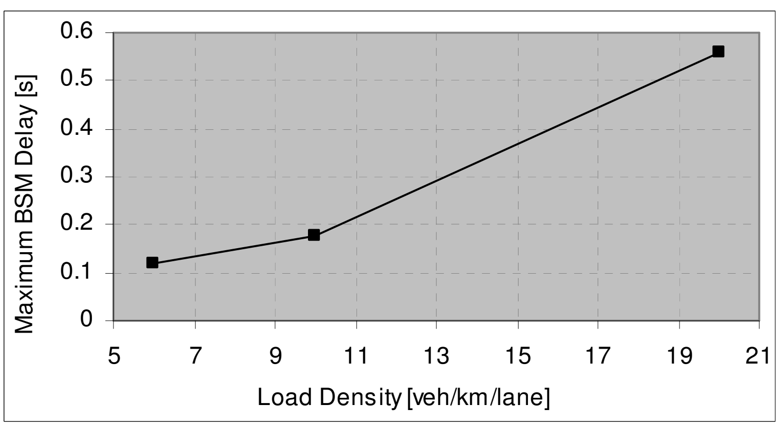


Figure 5.40 Maximum BSMs delay as a function of load density

The delay values followed patterns similar to the previous test case for variation of the communication system bandwidth. The reasons for this behavior are also similar to the previous test. For values less than 200 kbps, the maximum delay was higher than 1 s. For values over 500 kbps, the delay was between 0.1 and 0.12 s.

Patterns similar to the previous test were also obtained for modifications of the network load. However, the delay values were quite different as the highest value for maximum delay was 0.55 s in this case. Also, the maximum value for the average delay was 0.011 s.

The results for modifying the communication area were also very similar to the constant rate approach, with around 300 m as a threshold for better performance.

As with the previous test, the mobility of the hosts did not significantly influence the delay.

Packet collisions

The packet collisions as a function of bandwidth and network load are presented in figures 5.41 and 5.42.

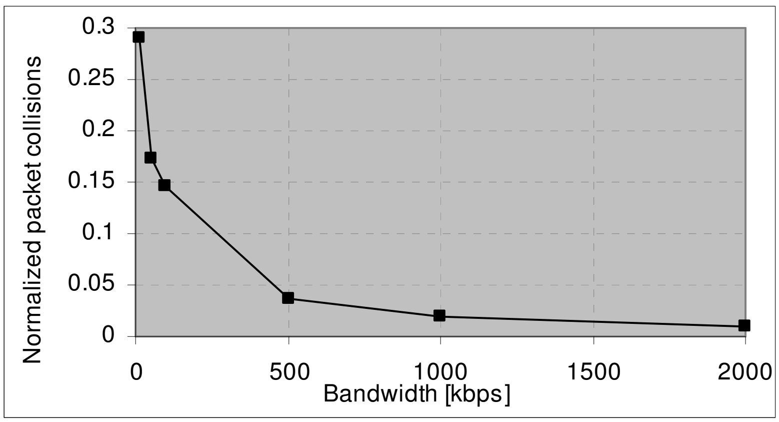


Figure 5.41 Packet collisions as a function of bandwidth – test case 2

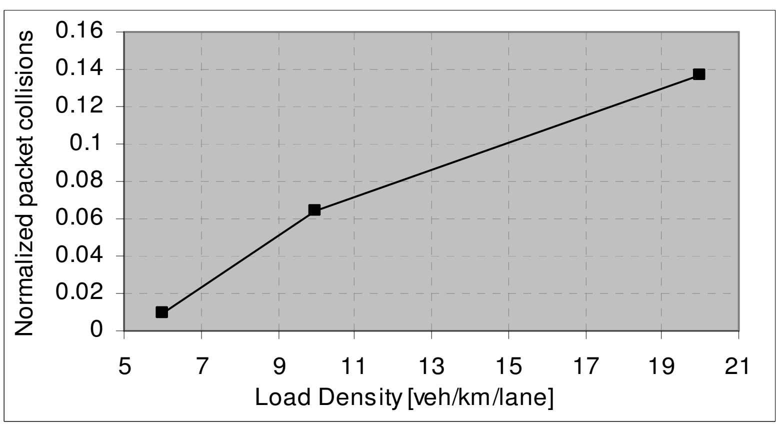


Figure 5.42 Packet collisions as a function of load density – test case 2

The packet collisions followed patterns relatively similar to the previous test when modifying the bandwidth and the load density. The reasons for this behavior of the metric are obviously the same as for the previous test. However, smaller values have been obtained for the adaptive approach. Thus, the values of the normalized packet collisions were up to 1.4 times lower both for the variation of bandwidth and for the variation of the network load. Also, the packet collisions decreased slightly faster with the bandwidth increase, and increased more slowly with the load density increase.

The variation of communication service area and maximum speed also led to patterns similar to the previous test. Again, the obtained values were significantly smaller than the values obtained in the first test case. For communication service area, the packet collisions had values up to 3 times lower. For mobility, the values were up to 3.8 times lower when the velocity was lower than 25 m/s. For higher velocities, the values were similar.

Send errors

The send errors as a function of bandwidth and network load are presented in figures 5.43 and 5.44. Also here, the patterns were similar to those of the previous test but the metric had significantly smaller values. For bandwidth, a reduction of up to 1.6 times was obtained. For network load, a reduction of up to 8.7 times was obtained, with more significant values for lower network loads. The same behavior has been obtained for variation of the communication area and hosts mobility. For load density the reduction was up to 1.6 times, and for communication area the reduction was up to 1.7 times.

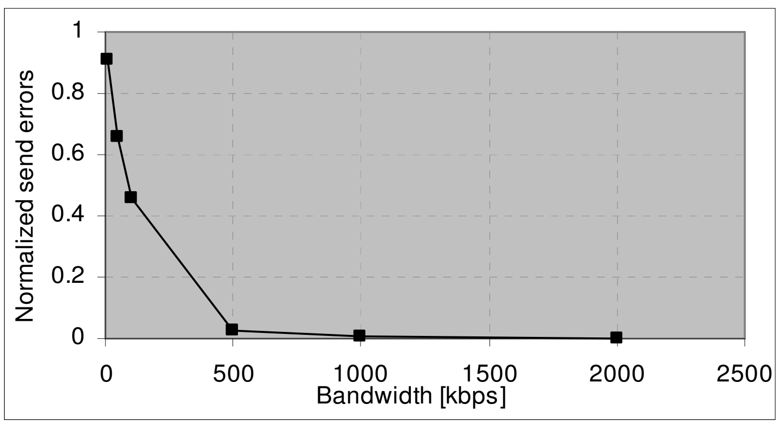


Figure 5.43 Send errors as a function of bandwidth – test case 2

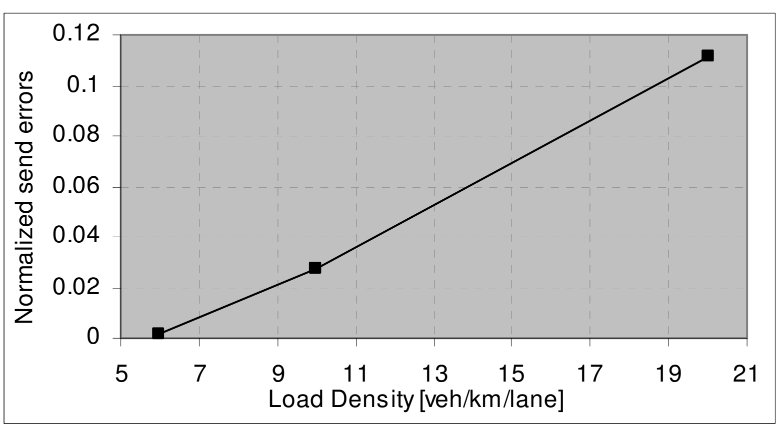


Figure 5.44 Send errors as a function of load density – test case 2

Information filtering rate

The obtained results were very similar to the results obtained within the test using a constant rate dissemination of BSMs. The information filtering was again major, with only around one third of the messages being accepted.

Evaluation results for test case 2 – final analysis

The obtained results indicated that timely and reliable communication is possible using the proposed protocol.

Most of the considerations given for the previous test are also valid for this case, as are the settings of the protocol that lead to good performance. However, the use of the adaptive approach led to significantly better results. Thus, the highest value of the maximum delay, obtained under high network stress, was 1.44 times lower than in the case of using a constant rate for generating BSMs. This value (i.e. 0.55 s) was also reasonably good as related work showed that values of up to 0.6 s can lead to significant improvements in traffic safety [WH98a]. The adaptive approach outperformed the constant approach with regard to collisions and send errors. These metrics were significantly lower in most of the cases when the adaptive approach was employed. The information filtering revealed similar results in both cases. In conclusion, the adaptive approach performs much better and therefore it is more appropriate for meeting the requirements of safety vehicular communication.

Test case 3

This test investigated the influence of BSMs forwarding technique on communication performance. We analyzed possible improvements of communication performance when using the extended approach for forwarding information. For this routing technique, the same decision is used both for filtering and for forwarding BSMs.

Results for the constant rate approach

Accepted BSMs delay

Similar patterns have been obtained in most of the simulations in comparison to the initial approach when the basic technique was used for routing. When using the extended routing technique, slightly lower values of the maximum delay were obtained for modification of the transmission interval, bandwidth, and hosts mobility. Similar values for the maximum delay have been obtained for modification of the communication service area. However, a major difference in the maximum delay values was obtained for modification of the network load. The delay variation for modifications of the load density is presented in figures 5.45 and 5.46. Thus, for the highest load, a decrease of 1.8 times has been noticed when using the extended routing scheme. The absolute maximum value was 0.44 s in this case. As mentioned above, this value can allow for important improvements in traffic safety.

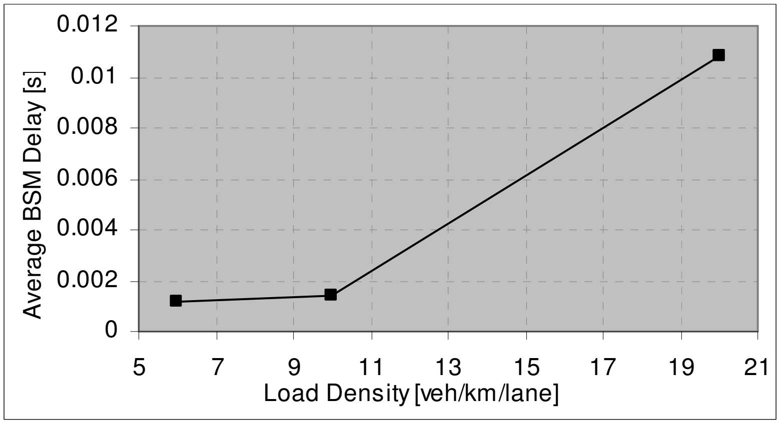


Figure 5.45 Average BSMs delay as a function of load density – test case 3

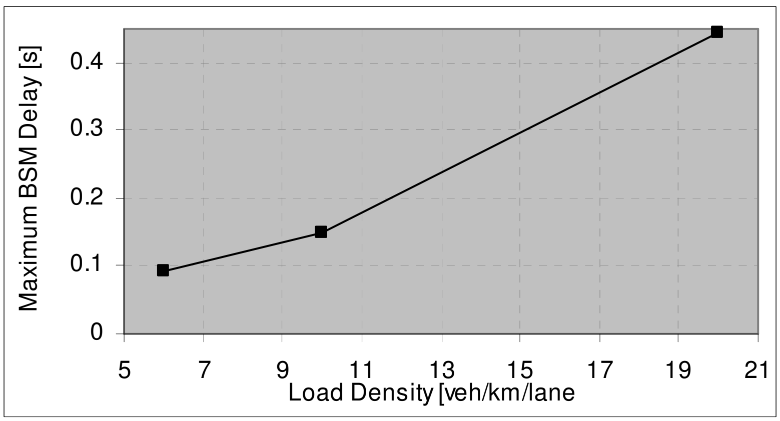


Figure 5.46 Maximum BSMs delay as a function of load density – test case 3

Packet collisions

The packet collisions followed a similar pattern when varying the transmission interval but the obtained values were up to 1.25 times lower. This was mainly due to the smaller number of messages that were routed by the hosts when using the extended approach. This consequently led to a smaller probability of collisions. For example, within one of the simulation runs at a transmission interval of 0.1 s one of the nodes routed 1422 messages when using the basic routing scheme, and only 292 messages when using the extended routing technique.

The bandwidth variation also led to similar patterns, but again with significantly smaller values for collisions. The reduction was up to 2.2 times. The packet collisions also decreased faster with the increase in bandwidth in comparison to the previous case.

The packet collisions as a function of communication service area and load density are presented in figures 5.47 and 5.48. The variation of the communication area was slightly different from the previous case and led to smaller values for all values of the free parameter. The reduction was up to 2.4 times. Larger differences were noticed for service areas higher than 300 meters. We explain this with the reduced number of messages that were routed.

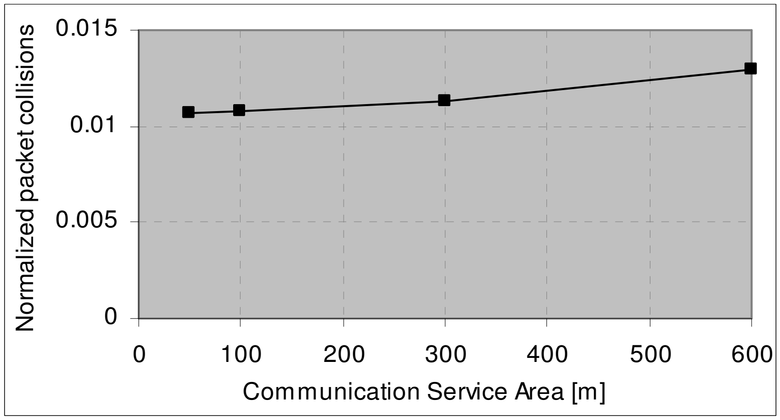


Figure 5.47 Packet collisions as a function of communication area – test case 3

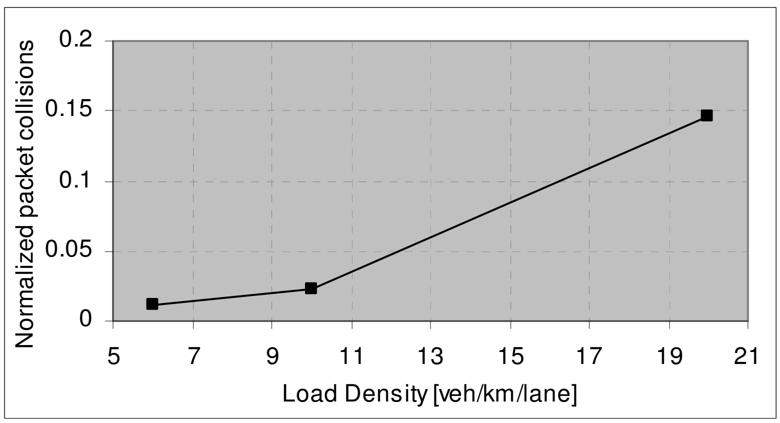


Figure 5.48 Packet collisions as a function of load density – test case 3

The load density also revealed a different evolution, but again with values smaller than for the previous approach. The reduction was up to 3 times.

The mobility of the hosts did not affect the metric much, which remained low for all values of this free parameter. The values were again lower than the values obtained when using the basic routing technique, i.e. the reduction was up to 1.36 times.

Send errors

The send errors followed a similar pattern as in the basic routing approach when varying the transmission intervals of BSMs, but with significantly smaller values. We note that for transmission intervals higher than 0.5 s, many nodes did not experience send errors at all, and the metric was 0 for all nodes when the transmission interval was 2 s. For lower values of the transmission interval (i.e. under 0.5), the send errors were up to 8 times lower than in the previous case. For higher values the differences were even higher, but the actual values of the send errors were quite low for both cases.

The patterns were also similar when varying the bandwidth and the communication service area, but again with much smaller values when using the extended routing, especially for bandwidth values higher than 100 kbps and communication areas higher than 100 m. For bandwidth, the reduction was up to 2.2. For communication area, the reduction was up to 8 times.

The send errors were very low until the load density was lower than 10 veh/km/lane and then increased. However, the values were well under the values obtained for the basic routing approach, i.e. up to 18 times lower.

The mobility of the hosts did not extensively affect the send errors, which were very low in both cases.

Information filtering rate

The values of the information filtering rate were higher than in the case of basic routing when varying the transmission interval, the bandwidth, and the mobility of the hosts. An average value was around 0.5. This is mainly because a smaller number of messages were routed due to the filtering of messages done within the routing scheme.

For variation of the communication area, the values were similar until the area was more than 300 m, in which case the information filtering was higher for the case of the extended routing technique.

When modifying the network load, the patterns were similar in both cases, with slightly higher values for the extended routing technique.

Evaluation results for test case 3 for constant rate approach – final analysis

The results indicated that the use of the extended routing technique provides much better performance for communication. In all the experiments, the performance metrics exhibited better values than when using the basic routing approach. The information filtering had a higher value but still performs efficiently (e.g. 50% of the messages were detected as not useful). It should be noted that a "hidden" information filtering is actually performed within the extended routing technique.

Additional tests using the Ricean fading model

As previously mentioned, we have also performed tests using the Ricean fading model with a K factor of 5. These investigations were done using the constant rate approach and the extended routing technique. As expected, the results were slightly better when testing without a fading model. However, the differences were relatively small between the two cases. The maximum delay was almost the same when varying the bandwidth, the communication service area, the mobility of the hosts and the transmission interval. Similar values were also obtained for modification of the load density, with the exception of the highest network load, when the maximum delay increased, but still within acceptable limits (e.g. 0.58 s). The number of collisions was slightly higher when using the fading model, but not significantly (e.g. 0.0025 for a 20 veh/km/lane network load). The send errors and the information filtering revealed similar values in both cases.

Generally, communication performance was also relatively good in this test, when certain settings (e.g. transmission interval, bandwidth) were used for the communication protocol. This indicated that the communication protocol can accommodate transmission environments that pose different requirements on communication.

Results for the adaptive rate approach

Here, we compare the results obtained when using the adaptive rate approach for disseminating basic safety messages and the basic and the extended techniques for routing them.

Accepted BSMs delay

When varying the bandwidth, better delay values were obtained when using the extended routing technique. The maximum delay was around 1 s when the bandwidth was 100 kbps, which was half of the value obtained for the basic routing. As soon as the bandwidth was higher than 500 kbps, the maximum delay was always under 0.1 s.

For variation of the communication service area, the results were similar for both routing techniques.

When varying the load density, lower values were obtained for the maximum delay when using the extended routing. The maximum was 0.47 s at the highest load tested.

For variation of the mobility of the hosts, the values were quite similar, with a very small improvement for the extended routing case.

Packet collisions

The variation of the bandwidth led to better results for the advanced routing with differences that reached 1.9 times (i.e. for bandwidth of 1 Mbps).

The modification of the communication area led to better results for the use of the extended routing technique. For the largest area considered, i.e. 600 m, the difference was great, i.e. 3.2 times.

The packet collisions were also lower for extended routing scheme when the load of the network was used as a free parameter. The differences were as high as 2.75 times.

An improvement was also noticed when varying the mobility of the nodes. However, in this case the packet collisions were low in all cases.

Send errors

The send errors were lower for the extended routing scheme when using the bandwidth as a free parameter. Better results were obtained for bandwidth values over 100 kbps, where improvements of up to 10.7 times were noticed. Still, for bandwidth over 500 kbps, the send errors were quite low in both cases.

The variation of the communication service area also revealed improvements due to the extended routing technique, especially for areas over 300 m. However, a small number of send errors were noticed in almost all tests.

The modification of the load density led to better results when using the extended routing. For instance, the send errors were up to 14.3 times lower when using the extended routing.

The hosts' mobility variation also revealed better performance for the extended routing. However, in both cases, the number of send errors was again quite small.

Information filtering rate

For both approaches, the metric varied slowly for modifications of the bandwidth, communication area, and mobility, with slightly higher values when using the extended routing scheme. In the case of modification of load density, the variation was steeper, with again higher values for the extended routing technique.

Evaluation results for test case 3 for adaptive rate approach – final analysis

The results indicated that the extended routing technique also provides better performance for communication when using the adaptive approach for disseminating basic safety messages. The most important improvement was in the packet collisions. Also important are the improvements for maximum delay and send errors.

Comparison between the adaptive and the constant rate approaches when using the extended routing technique

In order to be able to provide a complete analysis and identify the best method for exchanging safety data within the vehicular environment we have also compared the case of adaptive rate and constant rate when using the extended routing scheme. We have previously shown that using the basic routing the adaptive scheme outperforms the constant rate scheme. However, we had to see if this would be also the case when using the extended routing technique.

Accepted BSMs delay

The variation of bandwidth and communication service area led to small improvements in several cases for the delay in the case of adaptive dissemination of BSMs.

The variation of load density and mobility of the hosts led to very similar results.

Packet collisions

The variation of the bandwidth led to smaller values for the adaptive approach. The differences for the normalized packet collisions values were higher at larger bandwidths, e.g. 1.48 times at 1 Mbps and 2 times at 2 Mbps. However, the packet collisions had relatively small values for high bandwidths, e.g. 0.0142 for the constant rate and 0.00958 for the adaptive rate when the bandwidth was 1 Mbps.

When varying the communication service area, the number of collisions was up to 2.7 times lower for the adaptive approach. Again, the metric had low values in these experiments.

The modification of the load density revealed also an improvement for the adaptive approach. This was more important for low network loads (e.g. 2 times for 6 veh/km/lane).

Smaller values of the packet collisions for the adaptive approach were obtained for modification of the mobility of the hosts when the maximum speed had values lower than 25 m/s. This was obviously due to the smaller number of messages transmitted using the adaptive approach. For small velocities the differences were high, e.g. 7 times lower value for 10 m/s.

Send errors

Smaller values of send errors were obtained when using the adaptive approach in comparison to the constant rate approach when modifying the system bandwidth. However, we note that for bandwidth values over 500 kbps, the absolute differences (i.e. in units) were less significant and the send errors had very low values in both cases.

When modifying the communication service area, the metric had very low values in all tests. Small improvements have been noticed for the adaptive approach.

As with the packet collisions case, the variation of the network load led to better results for the adaptive approach. The reduction of the send errors was up to 2.4 times. However, the metric had relatively low values within the performed tests, especially for lower network loads.

The modification of the hosts' mobility generated a small number of send errors in all the tests, with better results for the adaptive approach. Again, larger differences were obtained for smaller values of velocities (e.g. 4.77 times less send errors for 20 m/s).

Information filtering rate

Similar results were obtained for both approaches when varying all the free parameters.

Comparative evaluation for the adaptive and constant rate approaches with extended routing - final analysis

In all tests the adaptive approach outperformed the constant rate approach. The most significant differences were for packet collisions and send errors.

Test case 4

In this test, the basic communication performance under the transmission of warning messages was investigated. We use the term "basic communication performance" when presenting results for test cases 4 and 5 to address the following metrics: accepted BSMs delay, packet collisions, and send errors. In addition, we investigated the latency in delivering WAMs and the information dissemination success. The last metric was evaluated by determining if the transmitted WAMs were received by a pre-defined set of hosts.

As previously mentioned, warning messages were set by default to be transmitted in an area larger than the size of a local network (i.e. *default acceptance* field was validated). Consequently, the messages could be received by a large number of vehicles and their dissemination could be performed in large areas. This meant that the warnings could be received by vehicles situated at several kilometers from the vehicle that issued the warning message.

The basic communication performance was quite similar when testing with and without WAMs. The metrics packet collisions and send errors were slightly higher when warning messages were transmitted under a high network load. This was expected as more messages were in the network and the contention for the medium increased. The results indicated that the transmission of warnings did not significantly influence the basic communication performance, when the number of generated WAMs was reasonably small. Under normal conditions this should be the case as vehicles that are notified about a hazard will only forward the announcement and should not produce and send their own announcement.

The WAMs delay as a function of the transmission interval, bandwidth, communication service area, network load and mobility of hosts is presented in figures 5.49 – 5.58.

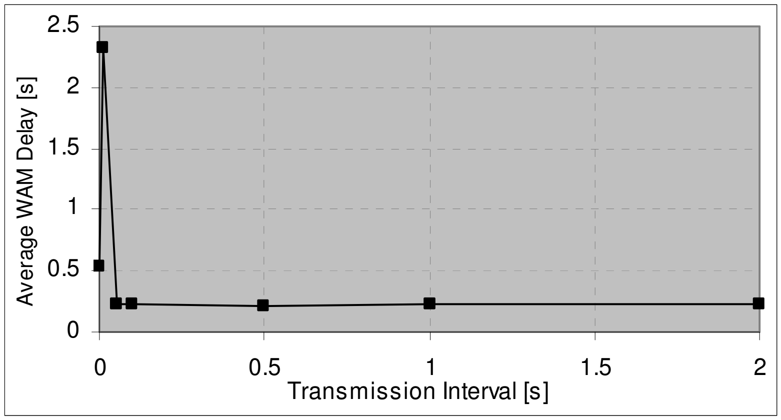


Figure 5.49 Average WAMs delay as a function of transmission interval – test case 4

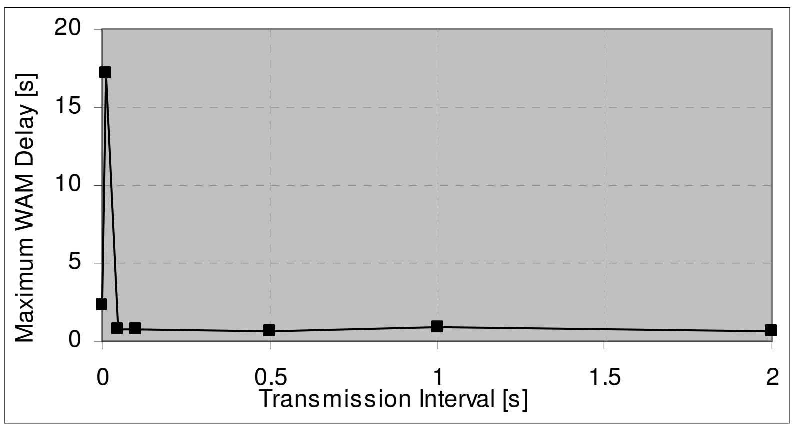


Figure 5.50 Maximum WAMs delay as a function of transmission interval – test case 4

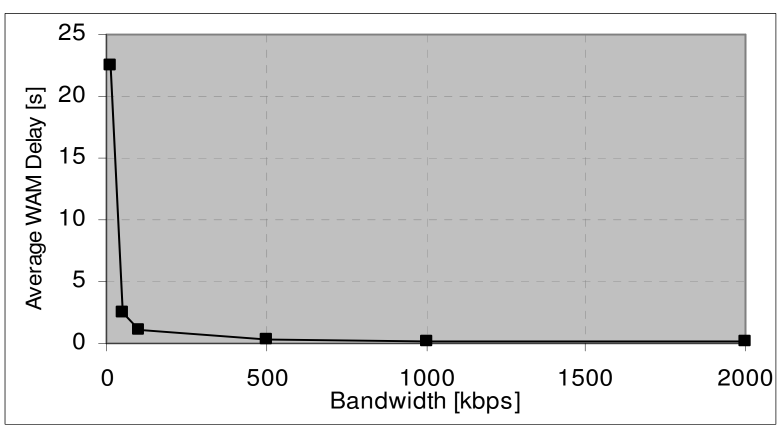


Figure 5.51 Average WAMs delay as a function of bandwidth – test case 4

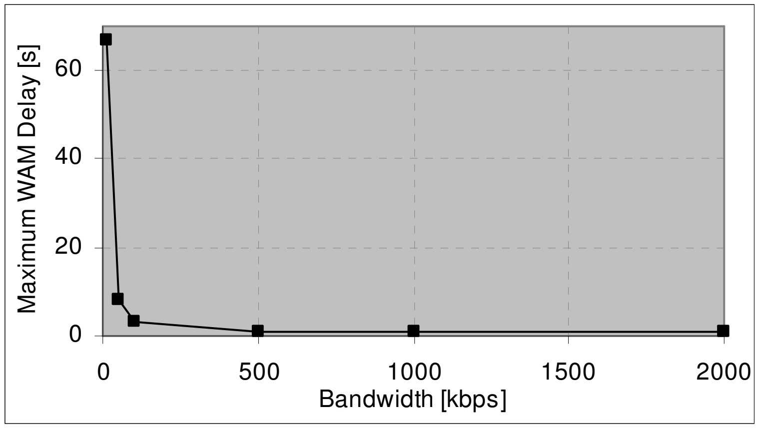


Figure 5.52 Maximum WAMs delay as a function of bandwidth – test case 4

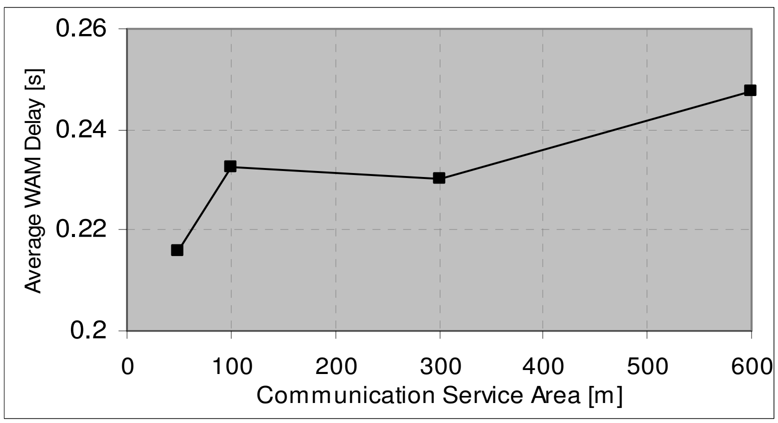


Figure 5.53 Average WAMs delay as a function of communication service area – test case 4

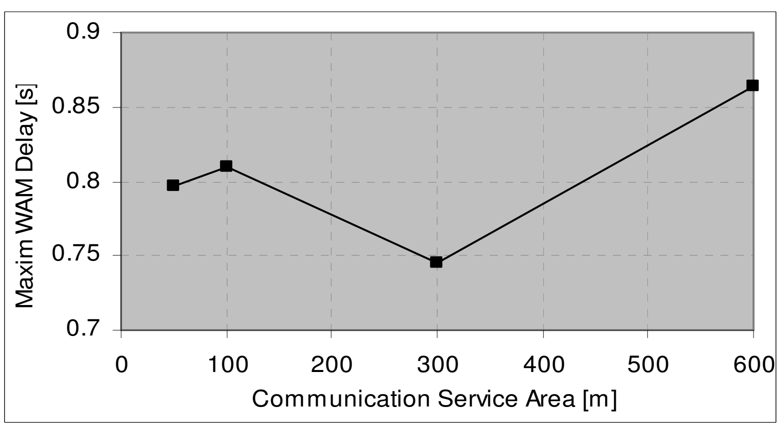


Figure 5.54 Maximum WAMs delay as a function of communication service area – test case 4

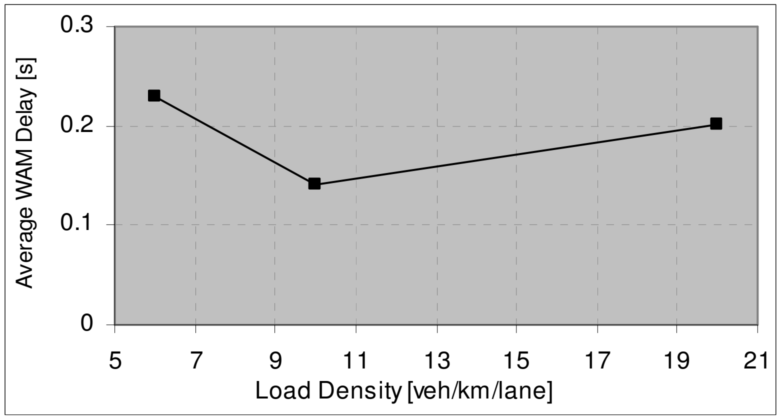


Figure 5.55 Average WAMs delay as a function of load density – test case 4

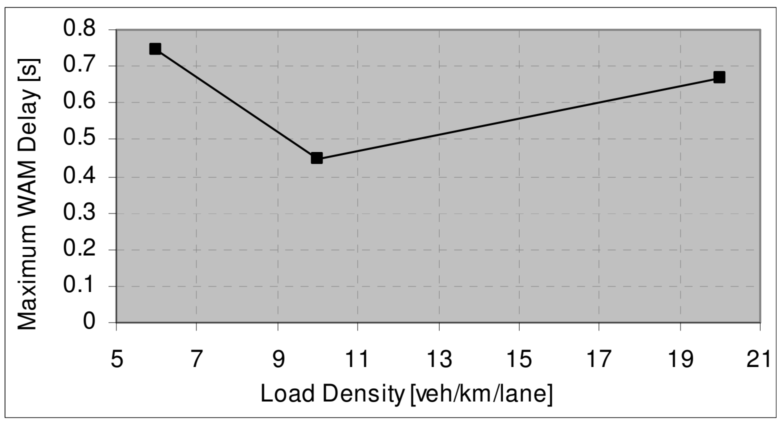


Figure 5.56 Maximum WAMs delay as a function of load density – test case 4

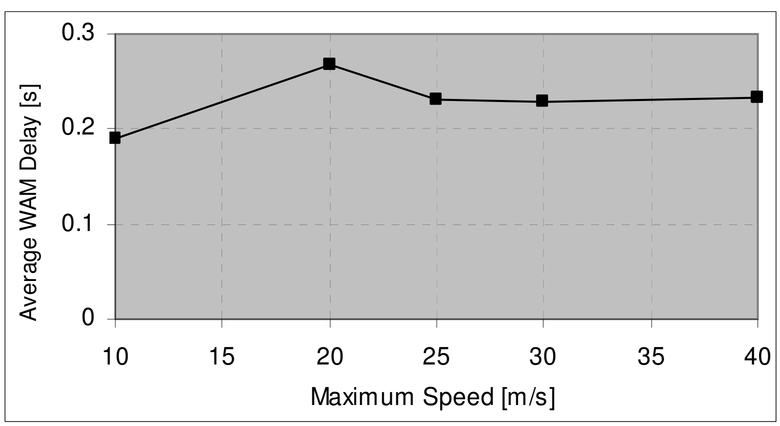


Figure 5.57 Average WAMs delay as a function of mobility of hosts – test case 4

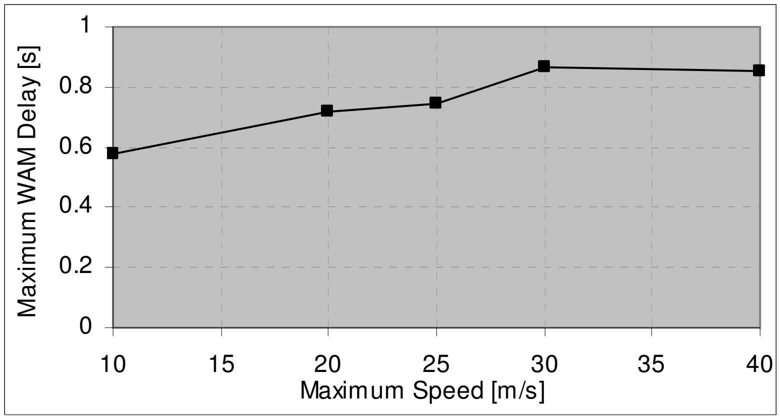


Figure 5.58 Maximum WAMs delay as a function of mobility of hosts – test case 4

The delay of warning messages varied with the transmission interval of BSMs and the system bandwidth, and had large values for very small transmission intervals and small bandwidths. This was mainly due to the hosts' inability to send WAMs in time because the medium was busy. As soon as the transmission interval was higher than 0.05 s and the bandwidth was higher than 100 kbps, the maxim delay for WAMs decreased significantly. The delay then stabilized, with a maximum value of around 0.7 s and an average value around 0.22 s.

The communication area and the mobility of the hosts did not significantly affect the WAMs delay. A minimum was obtained when the communication area was around 300 m.

The variation of the load density led to a limited variation of the delay. The highest value for the maximum delay was obtained for the lowest vehicles density and the best value for an average density (i.e. 10 veh/km/lane). In the first case, a smaller number of vehicles managed to receive and forward the WAMs, which then took a longer time to be disseminated. On the other hand, when many vehicles were on the road, the packet collisions were higher and more messages were lost and WAMs arrived later due to retransmissions.

We investigated the success of disseminating the warning messages by defining a particular group of receivers and analyzed whether they could receive specific WAMs during a simulation run. (Please refer to the test case description for the definition of this group). Our analysis revealed a 100% information dissemination success for all WAMs.

In summary, the latency of delivering WAMs was relatively low, taking into consideration that the messages could be forwarded over several kilometers (e.g. 3.2 km). A value under 1 s was considered appropriate for disseminating such messages at larger distances [BSH00]. This demonstrated the efficiency of the proposed protocol for disseminating emergency traffic data. In addition, the high value of the information dissemination success indicated that messages were successfully received by the hosts in need, which in turn indicated the proposed message dissemination technique is reliable.

The last part of this test was to evaluate the dissemination of warning messages only within the local networks of the senders. As in the other cases, no significant differences were observed in the basic communication performance in comparison to the case of sending only BSMs.

The WAMs delay as a function of the transmission interval, bandwidth, communication service area, load density, and mobility of the hosts is presented in figures 5.59 – 5.68.

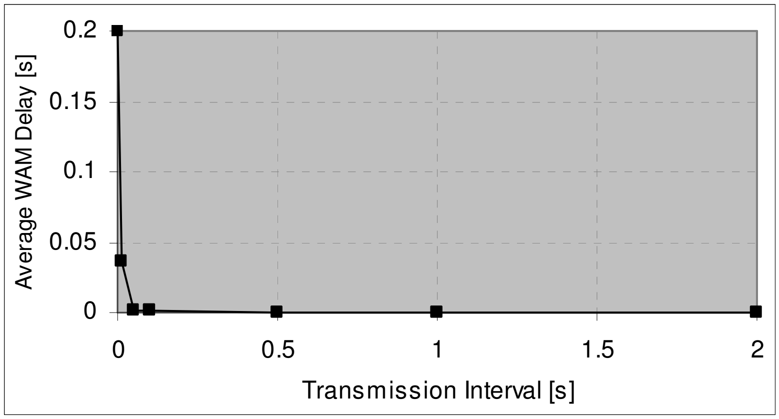


Figure 5.59 Average WAMs delay as a function of transmission interval – test case 4, WAM dissemination within local network

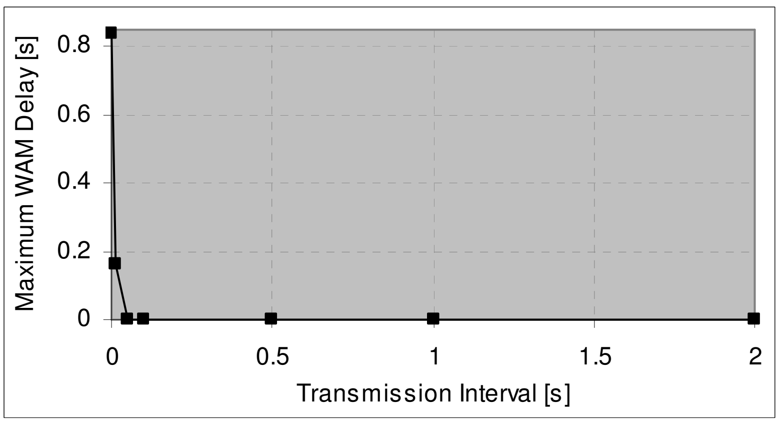


Figure 5.60 Maximum WAMs delay as a function of transmission interval – test case 4, WAM dissemination within local network

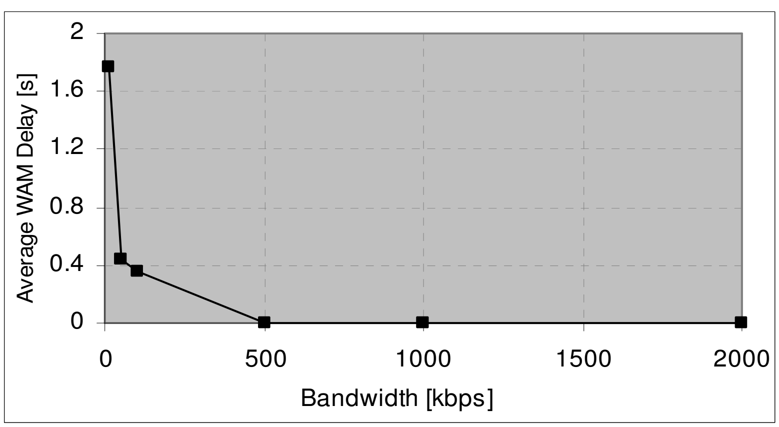


Figure 5.61 Average WAMs delay as a function of bandwidth - test case 4, WAM dissemination within local network

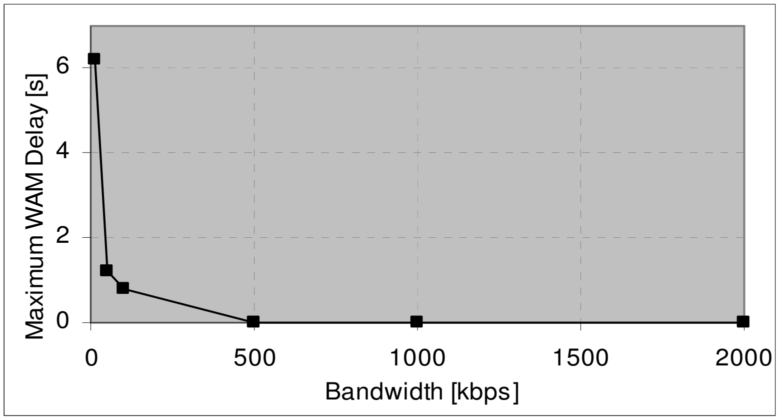


Figure 5.62 Maximum WAMs delay as a function of bandwidth – test case 4, WAM dissemination within local network

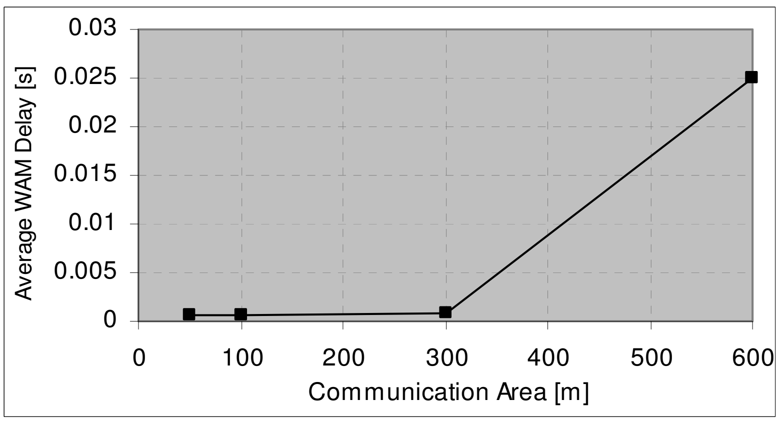


Figure 5.63 Average WAMs delay as a function of communication service area – test case 4, WAM dissemination within local network

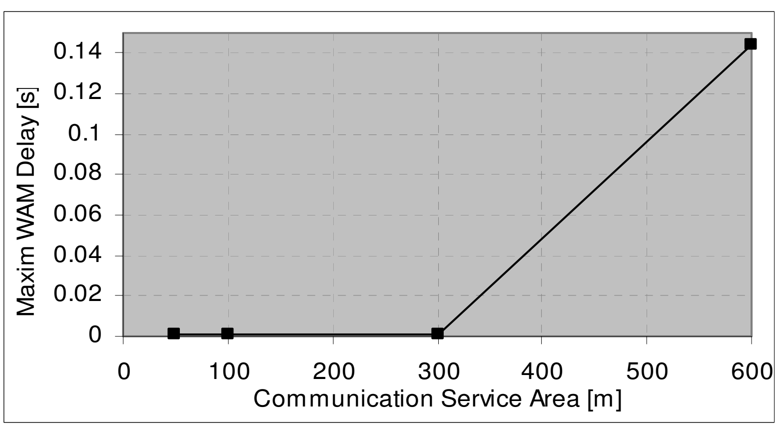


Figure 5.64 Maximum WAMs delay as a function of communication service area – test case 4, WAM dissemination within local network

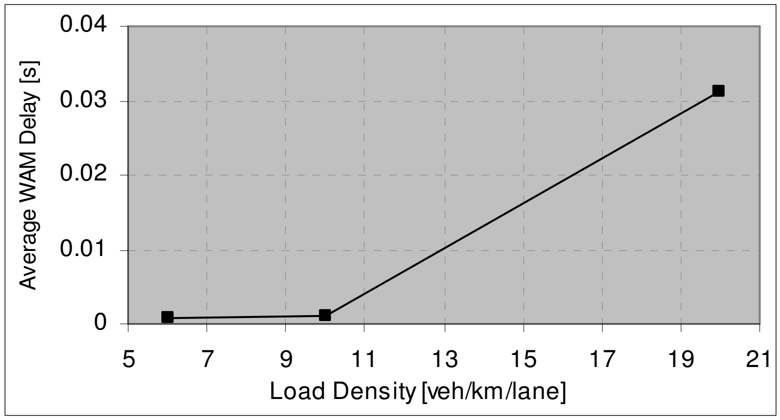


Figure 5.65 Average WAMs delay as a function of load density – test case 4, WAM dissemination within local network

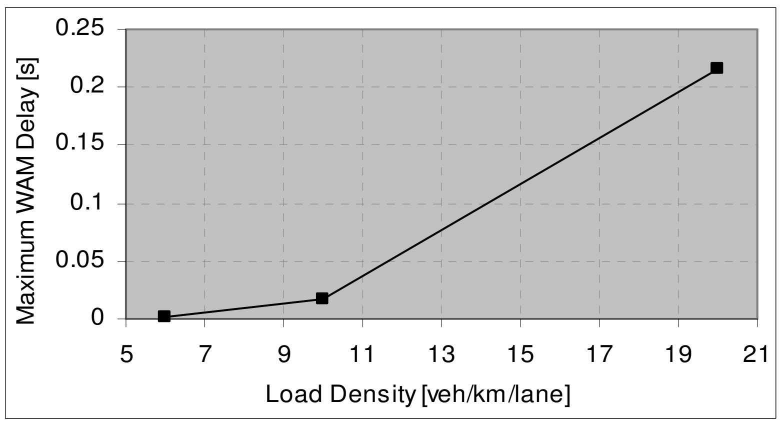


Figure 5.66 Maximum WAMs delay as a function of load density – test case 4, WAM dissemination within local network

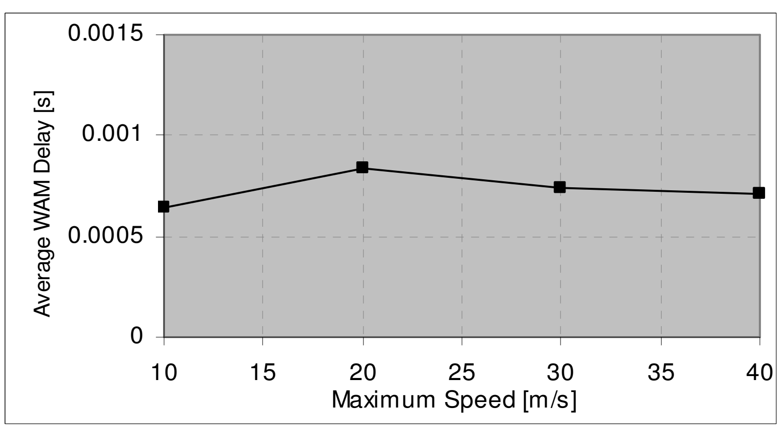


Figure 5.67 Average WAMs delay as a function of mobility – test case 4, WAM dissemination within local network

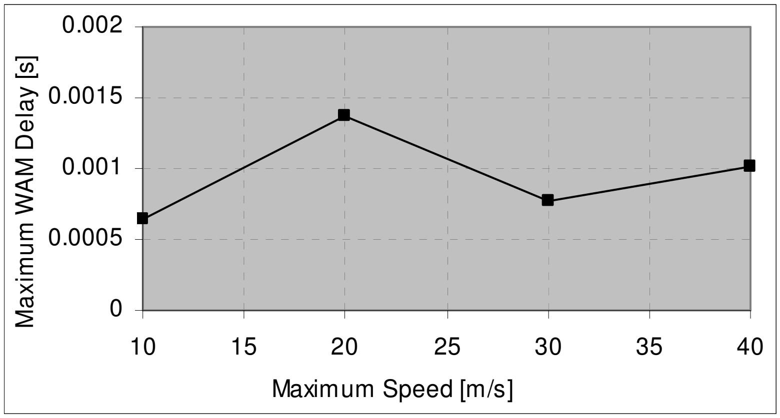


Figure 5.68 Maximum WAMs delay as a function of mobility – test case 4, WAM dissemination within local network

The results indicated that very low values for WAMs delay can be obtained under certain settings of the communication protocol (e.g. for transmission interval higher than 0.01 s and bandwidth values higher than 50 kbps). Even when the network was under high stress, the delay values were low (e.g. maximum 0.2 s and average 0.03 s for 20 veh/km/lane). Certainly, in this case the vehicles that accepted the WAMs were only the members of the same local network, which were close one to another. Therefore, the forwarding of WAMs was much reduced and this also reduced the latency. The information dissemination success was also 100% in this case indicating that the hosts from the same local network were always informed about the dangerous situation indicated in the issued WAMs.

Test case 5

Aspects similar to test case 4 were investigated here for the multiple WAMs transmission approach.

As in the previous test, the basic communication performance was quite similar to the case in which no warning messages were generated. Again, the number of send errors and collisions was slightly higher when WAMs were sent. We also compared the results for the basic communication performance obtained when generating WAMs with single and multiple transmissions. The results were quite similar in both cases, with very small modifications for the multiple transmission case, where the collision and send errors values were slightly higher. However, the differences were small. Also, for a high load density, the maxim delay for BSMs was slightly higher for the multiple transmission approach.

We analyzed the WAMs delay and the information dissemination success. The delay as a function of transmission interval, bandwidth, communication service area, load density, and mobility of the hosts is presented in figures 5.69 – 5.78.

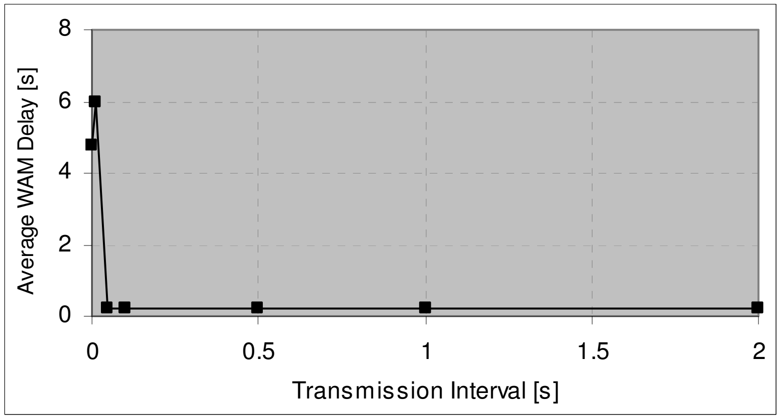


Figure 5.69 Average WAMs delay as a function of transmission interval – test case 5

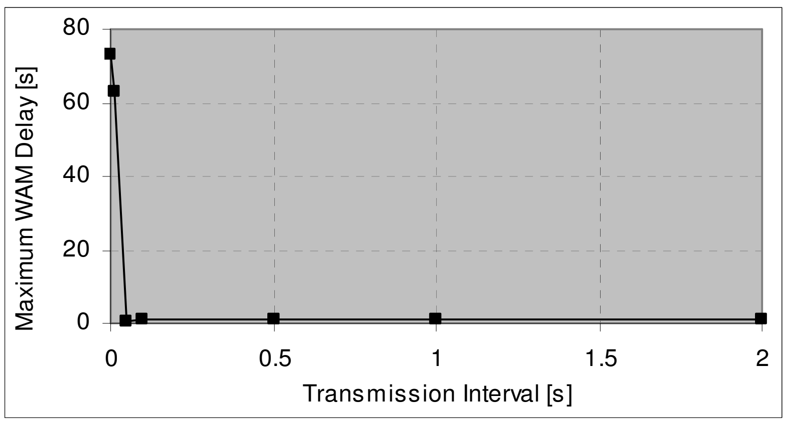


Figure 5.70 Maximum WAMs delay as a function of transmission interval

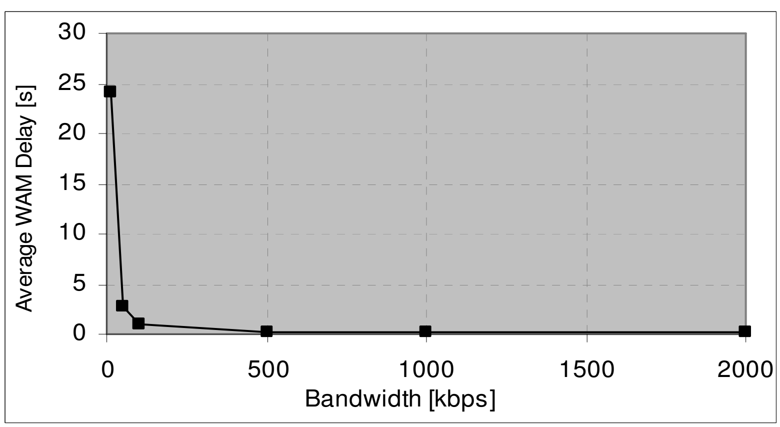


Figure 5.71 Average WAMs delay as a function of bandwidth – test case 5

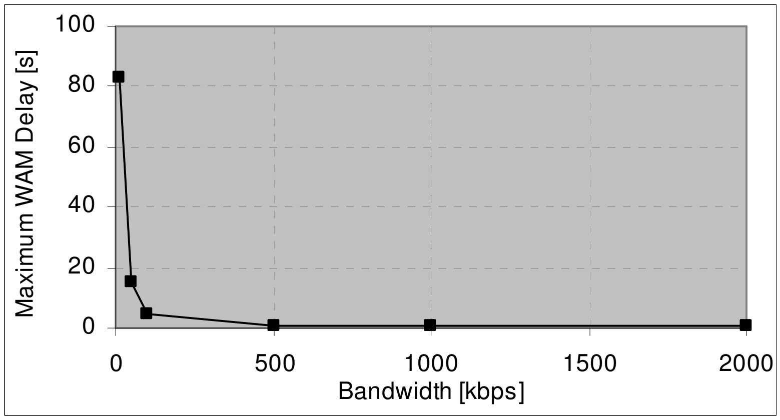


Figure 5.72 Maximum WAMs delay as a function of bandwidth – test case 5

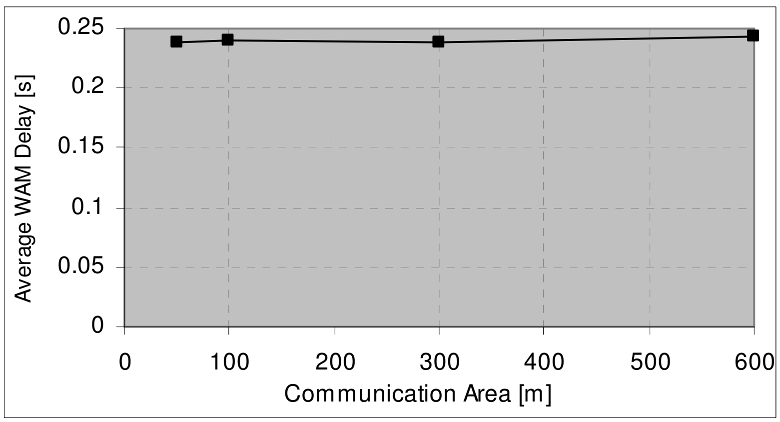


Figure 5.73 Average WAMs delay as a function of communication service area – test case 5

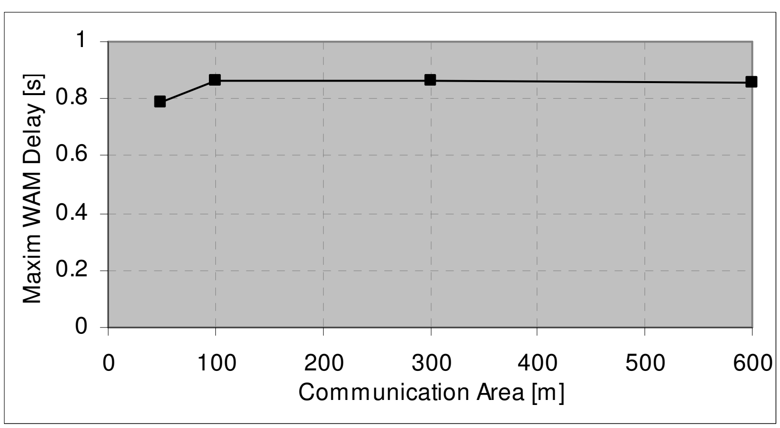


Figure 5.74 Maximum WAMs delay as a function of communication service area – test case 5

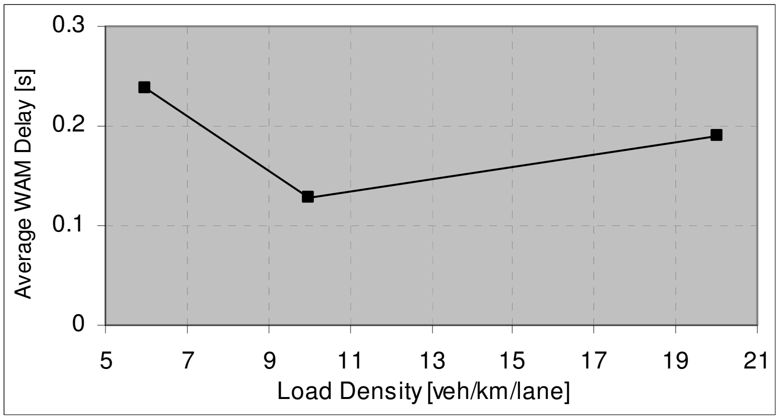


Figure 5.75 Average WAMs delay as a function of network load – test case 5

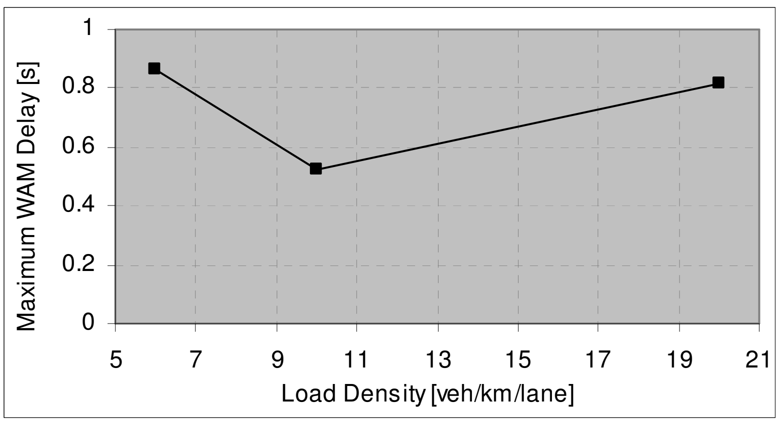


Figure 5.76 Maximum WAMs delay as a function of network load – test case 5

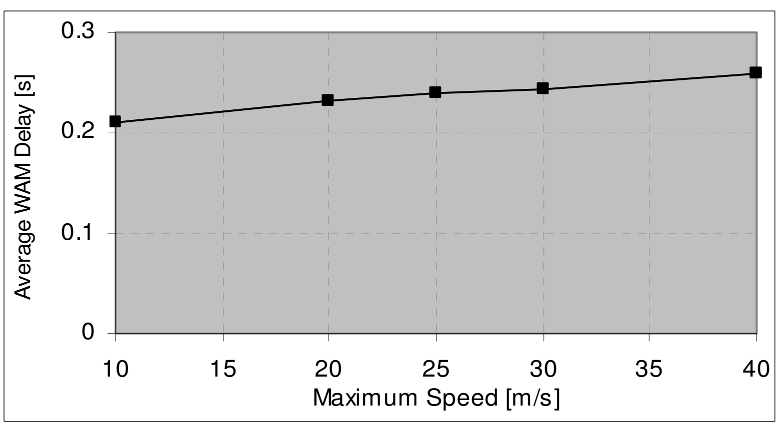


Figure 5.77 Average WAMs delay as a function of mobility of the hosts – test case 5

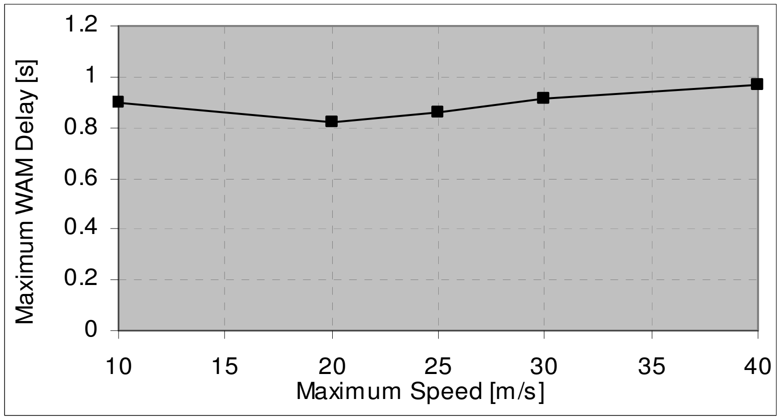


Figure 5.78 Maximum WAMs delay as a function of mobility of the hosts – test case 5

As in the previous test case, as soon as the transmission interval was higher than 0.05 s and the bandwidth higher than 100 kbps, the delay decreased significantly. The metric then stabilized, with a maximum value of around 0.8 s, and a median value of around 0.25 s. The variation of communication service area and hosts mobility did not significantly influence the delay values. The delay exhibited a variation similar to the case of single WAM transmission when modifying the load density due to similar reasons.

In summary, we obtained relatively low delay values under certain settings of the communication protocol. Moreover, the information dissemination success was again 100%, which indicated that this method of sending WAMs was efficient. When comparing the results obtained for the single and multiple WAM transmission approach, the use of single messages usually led to slightly better results, both for the basic communication performance, and for the WAMs delay. Also, the communication performance degrades faster in the case of multiple WAMs transmission since more (warning) messages are generated and routed.

Test case 6

In this test case, a comparison was made between the two proposed techniques for forwarding warning messages, i.e. the random deferring approach, and the deferring approach based on the distance to sender.

The basic communication performances were quite similar for the two approaches. However, when investigating the WAMs delay, differences were noticed. For the initial settings of the approach based on the distance to sender, the maximum delay was higher than when using the random approach. We illustrate these results in figure 5.79 and 5.80 with the graphs for variation of network load. In addition, the approach based on distance to sender led to a lower dissemination success, i.e. 86%. This indicated that some hosts did not receive the needed notifications. A more detailed analysis revealed than in several cases one of the WAMs was received only by half of the vehicles that should receive it.

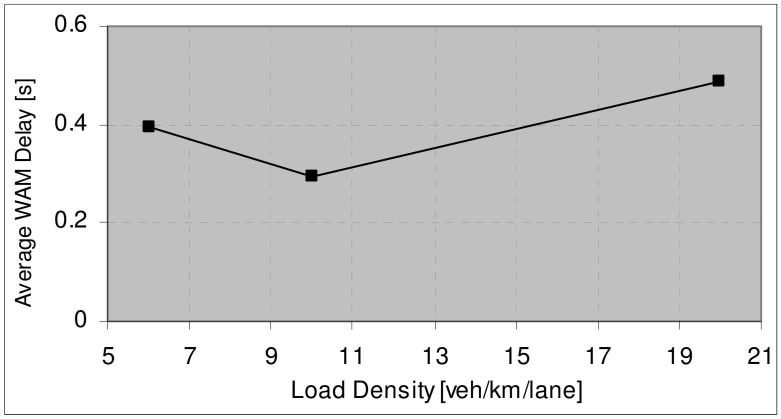


Figure 5.79 Average WAMs delay as a function of network load – test case 6

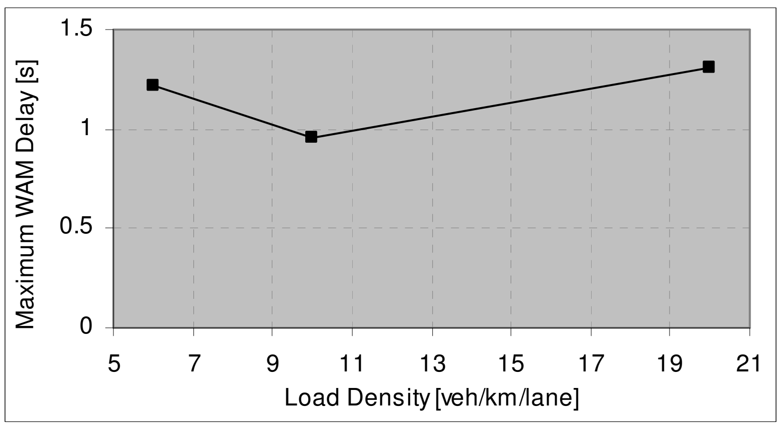


Figure 5.80 WAMs delay as a function of network load – test case 6

However, the performance of the approach using the distance to sender is highly dependant on the parameters used for calculating the deferring time. For instance, using a setting with Tdefer = 0.1 s and Tmax_WAM= 0.5 s led to delay values two times larger than the initial approach. Similarly, using a setting with low deferring intervals, such as Tdefer = 0.01 s and Tmax_WAM= 0.1 s, significantly lower values were obtained for the maximum delay. In this case the delay values were below the values obtained using the random deferring approach. On one hand this indicated the potential of the approach based on distance to sender. On the other hand, no significant modifications to the information dissemination success have been obtained, which indicated the approach to be less reliable. It seems that some of the hosts were unable to avoid the synchronization, or the retransmission dynamic left particular hosts uninformed. Therefore, for this approach to be successfully applied, further improvements are needed. We also note that even the random approach may perform better when using diverse randomization parameters (e.g.. the seed).

Test case 7

In this test we investigated the use of communication to avoid realistic traffic accidents. Thus, we analyzed if the delay that can be obtained for providing specific information to vehicles can satisfy requirements of safety applications. We also investigated if the delivering of this traffic information can be performed in a reliable manner.

VOTS and extended VOTS scenarios

For the VOTS scenario, the WAM delay was very low and the information dissemination success was high (i.e. 100%). Also, basic communication performance metrics such as collisions and send errors were very low or even null. However, in this case only three vehicles traveled and exchanged data. Therefore, the extended scenarios considered a significantly larger number of vehicles. Even in this case the WAM delay had low values and the dissemination success was again 100%. That means that all the vehicles in the simulation received the warning message, including vehicles situated relatively far from the sender (e.g. at 1.6 km). Furthermore, the performance metrics (e.g. send errors, maxim BSMs delay, collisions) indicate good communication quality. In both cases, the latency of delivering the WAM was much lower than the requirements (i.e. as derived using ECAM). The results related to WAM dissemination are presented in table 5.4.

Table 5.4 Results for VOTS and extended VOTS scenarios

Metric	VOTS	Extended VOTS
Maximum WAM Delay [s]	0.000647252	0.178490713
Average WAM Delay [s]	0.000647192	0.083897233
Information dissemination success [%]	100	100
WAM Delay at V1 [s]	0.000647252	0.047498853
WAM Delay at V2 [s]	0.000647133	0.047498735

Basic and extended intersection scenarios

The results were also positive when testing with the basic and the extended intersection scenarios. In the first case very low delay values were obtained and very good communication performance was noticed. Due to the larger number of vehicles on the road, the extended case was more relevant. Even in this case we obtained very low latency in providing the emergency notification and good communication performance. The obtained delay values were again much lower that the requirements. Furthermore, an information dissemination success of 100% for the issued WAM was obtained in both cases. The results related to WAM dissemination are given in table 5.5.

Table 5.5 Results for intersection and extended intersection scenarios

Metric	Basic intersection scenario	Extended intersection scenario
Maximum WAM Delay [s]	0.000647059	0.000647128
Average WAM Delay [s]	0.000647059	0.000647069
Information dissemination success [%]	100	100
WAM Delay at V1 [s]	0.000647059	0.000647059

5.8 Final remarks

The results analysis indicated that when using specific settings of the communication protocol, relatively good performance can be obtained. In addition, the communication protocol can perform well under a wide range of conditions, such as different traffic patterns and vehicles dynamics, varying network load, and modifications of the transmission specifics (e.g. transmission power, fading model). Thus, with appropriate settings of the transmission interval for basic safety messages (e.g. 0.1 seconds), of the system bandwidth (e.g. over 500 kbps), and of the communication service area (e.g. 300 m), timely and reliable communication was possible. The settings that we have derived also proved to be realistic considering the traffic safety requirements (e.g. frequency of updating traffic data, service area), and the capabilities of current communication systems (e.g. bandwidth).

The values obtained for the information filtering rate showed the benefits of using a context-based approach when exchanging traffic information. An improvement of the bandwidth utilization was also noticed when comparing our protocol with a flooding-oriented broadcast protocol (i.e. as defined in [YGK03]) under the same conditions.

The fact that the protocol coped well with the mobility of the hosts indicated that the proposed system can be efficiently used in areas with low and high speed regulations (e.g. on rural and urban roads, and on highways).

Furthermore, the investigations of the system's usability for avoiding accidents confirmed that efficient support to safety systems can be provided by the proposed communication system.

When disseminating basic safety messages, the results indicated that the adaptive approach was the best alternative for providing traffic information. This underlined again the value of an approach where contextual information is used to control vehicular communication. The results also indicated that further developments of the proposed technique, as well as the investigation of other adaptive techniques, are of importance. With regard to the forwarding technique for BSMs, the extended approach far outperformed the basic approach, which recommended its use for routing. This result also indicated the advantages of using context data when performing multi-hop communication between vehicles.

For warning messages, the results indicated that they can be successfully disseminated (in the presence of BSMs) in large areas and with low latency. The singular WAM approach revealed better results than the multiple WAMs approach. Still, the multiple WAMs approach obtained relatively good results and can be successfully employed when needed. The random deferring approach for forwarding WAMs performed better than the approach based on the distance to the sender in terms of information dissemination success. In terms of delay, the results were highly dependant on the settings used by both techniques and no firm conclusion could be derived. Still, the approach based on distance has potential and further investigations are important. The stress on the network due to warnings transmission was limited when a moderate number of warning messages was generated. As previously mentioned, this should be the case when using the proposed system, as many situations that may pose dangers should be determined using the information included in BSMs and should not require the sending of WAMs.

In summary, the results indicated that the proposed communication system is able to provide a high level of support to in-vehicle safety systems. Certainly, improvements to the current version of the system are important, and are part of future work. Such improvements range from improvements of the currently proposed communication and networking techniques to structural modifications. An example of basic improvements is the better encoding of messages to reduce their size and consequently to reduce the load on the communication channel. Another example is the use of alternatives settings for adaptive BSMs dissemination and randomizers that can improve the communication performance. Examples of structural modifications are the use of a more efficient MAC scheme, which would definitely improve the performance, the definition of specializations of the rules employed for information filtering and forwarding, and the development of new adaptive techniques for message dissemination.

6. Related work

Research in vehicular communication can be broadly categorized into three areas: information dissemination, network organization, and MAC techniques. In this chapter we provide an overview of related work in these areas.

6.1 Traffic information dissemination

The network that we propose for organizing the vehicles is fundamentally an ad-hoc network. For disseminating messages in this type of network, extensive efforts have been focused on routing protocols. First we discuss the applicability of such protocols to safety vehicular communication. Further on, we focus on related vehicular communication protocols, which propose specific techniques for data transmission and forwarding between moving vehicles.

Routing in ad-hoc networks and vehicular communication

For forwarding information in ad-hoc networks, both table-driven and on-demand driven protocols have been proposed [RT99].

Examples of table-driven protocols are the Wireless Routing Protocol (WRP) [MG96], and the Destination-Sequenced Distance-Vector protocol (DSDV) [PB94]. These protocols require a host to maintain consistent or up-to-date routing information describing how packets sent by it can reach other hosts in the network. To achieve this, each host maintains routing tables that reflect the host's view of the network. Each host is responsible for notifying the other hosts when a modification of its view occurs, so as to maintain consistency throughout the network.

Examples of on-demand protocols are the Ad-hoc On-demand Distance Vector routing protocol (AODV) [PR99a], the Dynamic Source Routing protocol (DSR) [JM96], and the Temporally Ordered Routing Algorithm (TORA) [PC97]). These protocols create routes only when the sending host needs to transmit data to another host. The establishment of a route is done using route discovery mechanisms that are usually specific to the protocol. Such a route is then maintained until the destination is no longer reachable, or until the route is not needed anymore. A number of variations and extensions of these protocols, which implement various methods for maintaining multiple routes or diverse procedures for route reconstruction and route failure, have been also proposed (e.g. [PR99a, NCD01]).

An important feature of several routing protocols for ad-hoc networks is the use of geographic information (e.g. the location of hosts) for increasing the efficiency of data dissemination [MWH01]. An example is the Location-Aided Routing (LAR) protocol where the destination of a data packet is determined using a combination of the identifier of the destination host and an estimate of the position of this host. The estimate of the host position is based on information about its previous location and previous movement characteristics (e.g. velocity) [KV00]. A host receiving a packet forwards it based on a comparison between its own position and an estimation of the destination host location.

One issue that hinders the applicability of the above-mentioned protocols to vehicular communication is the anonymity of the hosts. In traffic safety applications a vehicle needs to receive information from a number of vehicles in its proximity rather than receiving data from a specific vehicle. Since it is not feasible for a vehicle to maintain the identities of all other vehicles that may receive its data, there is an advantage in not requiring a sender to know the addresses of the receiving vehicles. Certainly, it is possible to provide a host with the identities of other hosts (e.g. in its vicinity) by sending dedicated packets. However, this leads to an overload of communication due to the transmission and forwarding of a large number of packets. It also introduces latency in providing the needed safety data to vehicles. Therefore, routing protocols that require the sender to know the identity of the receiver(s) do not work well for safety vehicular communication.

The vehicular environment is very dynamic as vehicles frequently change their driving orientation and randomly exit and join the roads. Consequently, the vehicular network can often be fragmented. Therefore, the maintenance of a consistent view of the network as required by proactive protocols would be extremely difficult. It would also lead to communication overload and to high delays in data provision since it would be necessary to perform a large number of route updates. The dynamics of vehicular traffic may also hinder the use of protocols that require position estimation when forwarding data, since these estimations can be inaccurate.

We also note that many of the previously proposed routing protocols for ad-hoc networks do not perform well even for non-safety traffic services, such as Internet browsing and low-rate video chat [Wan04a, Wan04b]. Consequently, new routing protocols that are adapted to the traffic environment demands and are focused on supporting infotainment applications have recently been proposed (e.g. [SES+04], [WLH+05]).

Dedicated protocols for vehicular communication

Most of the dedicated protocols proposed for implementing vehicular communication rely on broadcast or directed broadcast for generating messages, and then propose schemes for forwarding these messages among vehicles. Many of these protocols take a reactive approach, and focus on dissemination of notifications about hazards in traffic. In the following, we survey several previous proposals for vehicular protocols.

The communication system presented in [BSH00] and [BH00] was designed to implement a traffic jam notification service on highways. It is based on an ad-hoc distributed communication protocol [BH00], which resides on top of a group membership service [BH02]. When a traffic jam is detected, a virtual group is formed by the vehicles driving in the same direction that slow down significantly. Thus, once a vehicle reduces its speed beyond a predefined threshold, it starts communicating with nearby vehicles by sending messages indicating the existence of a traffic jam. The vehicles receiving such a message wait for a certain time interval, which is dependent on the distance to the sender, and then forward the received message. Each message has a maximum number of hops over which it can be transmitted. The system also determines the size of the traffic jam based on the positions of the vehicles situated at its borders.

The VIBROR system described in [MKO00] and [FMO01] implements a multi-hop transmission scheme for broadcasting traffic information among vehicles. The proposed protocol reduces the retransmission of packets in comparison to flooding-alike protocols, and is based on three main concepts: packet structure, buffering management, and packet construction management. The traffic data is embedded in fixed-size packets and each packet is divided into sub-packets. When a packet is received by a vehicle, all the sub-packets contained in it are stored in a receiving buffer. When a host sends a new packet, this is constructed from a sub-packet containing its own data and other sub-packets containing data describing other hosts. The system assigns priorities to the packets stored in the receiving buffer based on diverse methods, such as the combination of the number of hops and the number of times a packet was retransmitted. When a host constructs and sends a new packet, only the sub-packets with priority higher than a given threshold are included in the sent packet.

The work described in [SFL+00] presents a protocol for highways that implements specific broadcasting techniques. This system takes into consideration the position of the communicating vehicles when forwarding messages. Two approaches are presented by the authors, the Tracking Detection protocol (TRADE), which performs a classification of vehicles based on their relative positions, and the Distance Defer Transfer protocol (DDT), which uses a deferring technique where forwarding of messages is based on the relative distance between the sender and the receiver. The TRADE protocol assumes the vehicles to have previous knowledge of the positions of neighboring vehicles, and performs a selection of particular vehicles for retransmitting messages. When a vehicle has some traffic data to send, it issues a message where it indicates two vehicles that should retransmit this message. These special vehicles are the vehicles situated farthest behind and farthest ahead of the sending vehicle, and previously classified by the sender as traveling on the same road. The process then continues at the receiving vehicles. The transmission of messages is controlled by time-to-live (TTL) counters. The second proposed protocol, i.e. DDT, uses a time-based method for forwarding data and does not require the positions of the neighboring vehicles to be previously available. When a vehicle issues a message, this will also contain its position. Each vehicle that receives such a message computes a deferring time inversely proportional to the distance to the sender. After this time has passed, the receivers assess whether most of their transmission area has been covered by transmissions from neighboring vehicles. If this is the case, they do not retransmit the message. Otherwise, the message is rebroadcast. Similar to the previous protocol, TTL is used for controlling the dissemination area.

A number of vehicular communication protocols using geographic forwarding have also been proposed (e.g. [HBE+01, KSA02, CR03, LHT+03, FMH+03]). The techniques employed for multi-hop communication in these proposals are based on a mapping between the position of the hosts in the network and a database that maps the identities of these hosts to certain locations. To perform such mapping, the main approach is to use digital maps installed in vehicles [LHT+03]. Current problems related to this approach are the difficulty of updating the maps and the possible high cost. Another possibility is to deploy distributed databases within the network [LJC+00]. In this case, when a vehicle needs to send some data, it first sends a query throughout the network to determine the location of the destination. If the destination is found, the data together with an indication of the destination location is sent out through the network. However, for this approach problems related to the maintenance of location servers in the network must be solved [MJK+00]. For all protocols using geographic routing, the vehicles need to know the identities of their one-hop neighbors. When a message containing traffic data is sent by a vehicle to a destination, it is gradually routed through the network, starting with the sender's immediate neighbors and continuing with their neighbors, and so on. These neighboring vehicles forward data using geographic constraints. For example, a simple decision scheme is to send data to the vehicle that is closest to the destination (i.e. greedy position-based routing). If such a vehicle is not found, other strategies for routing, such as the perimeter mode (i.e. delivery of data within an area as in Greedy Perimeter Stateless Routing [KK00]), can be used. Systems implementing vehicular communication using geographic routing are usually intended to provide safety and non-safety traffic applications (e.g. The Fleetnet Project [HBE+01, LHT+03]). Therefore, they usually focus on data dissemination in a large area, where they propose solutions for broadcast, multicast and unicast communication.

The protocol that we present in this thesis uses scoped broadcast and proposes methods for forwarding messages containing traffic safety data. The exchanged data can be used to implement a plethora of safety applications on any type of road. Many of the previously proposed protocols require the use of heartbeat messages. We extend the use of such messages by integrating specific traffic information into regularly transmitted basic safety messages. This data is used by vehicles for organizing the network into virtual clusters (i.e. local networks), and by in-vehicle safety systems for detecting hazards in traffic. Our protocol is a hybrid, providing both proactive and reactive operations. For disseminating information, we use geographic constraints, and employ a context-based approach for deciding whether to accept and forward data. Since safety is our main concern, short-area communication is employed. An appropriate size for this area is determined based both on safety applications' needs and communication performance. Further on, we acknowledge the importance of disseminating specific notifications about emergency situations in large areas, and provide for this possibility in our proposal. Priority schemes such as the scheme proposed in VIBROR are less appealing for our case due to vehicle grouping, and due to the small message size we need to impose on BSMs so as not to overload the communication. Also, a forwarding scheme for BSMs based on distance to sender, such as the one used in TRADE, did not fit our protocol well due to the organization of the vehicles into local networks, where the members aim at having information about one another. Further on, the method employed by DDT, i.e. refraining from retransmission based on analysis of retransmissions from neighboring vehicles, can leave vehicles uninformed [Brie01]. Selective retransmission of warnings with regard to the distance to the sender is appealing for faster dissemination of emergency notifications in large areas. We investigate such technique in our protocol when disseminating WAMs. However, though promising, the technique was not reliable enough. The use of digital maps would certainly contribute to the development of advanced traffic services, and would help us to apply high-precision algorithms for filtering information. However, since such systems may not be available on such a large scale in the near future due to cost issues, we also provided alternatives methods by specifying algorithms that use only the position and movement data of vehicles as input parameters.

6.2 Network organization

Until recently, there has been little focus on developing procedures for organizing vehicular networks. However, techniques for managing vehicles are essential in order to obtain scalable and reliable communication, and we envision that the field will develop significantly in the future. In this area work has mostly been done on group management for vehicles. Thus, in [BH00] a group management service for sustaining communication in case of traffic jam notifications is proposed. This service performs and maintains the aggregation of vehicles into neighboring groups based on information included in small messages that are regularly sent by vehicles (i.e. *Hello* messages). These messages contain the identity of a vehicle and its position, and the vehicle grouping is used to control the dissemination of a notification about a traffic jam through the network. Reference [MKC+01] introduces a general framework for proximity group communication, where mobile communicating hosts in an area are grouped according to their position and functional aspects. Possible traffic applications that are mentioned are grouping vehicles that approach a traffic light, and grouping vehicles that should give right of way when an ambulance is approaching. However, the work presents only the general idea and does not provide details on how to implement these services. The work in [CC05] proposes an organization of the vehicular networks into groups using two methods: stationary and dynamic. The stationary approach considers the roads to be previously divided in fixed areas. When vehicles enter these areas, they belong to the group associated with the area. The dynamic approach proposes vehicle grouping based on radio coverage. Vehicles that are in each other's transmission range form a group. Improvements to this simple approach are grouping close vehicles into cells and grouping vehicles in a vector on the basis of distance to sender.

Our work can be also categorized as belonging to the group membership area. The vehicles are grouped into local networks according to their current interest in traffic safety. The information needed for organizing the network is provided regularly, and we make use of position data and other contextual information when defining the network organization and management. The vehicles are then able to dynamically organize the network, which allows support for various traffic safety applications. Using fixed clusters is an appealing alternative to dynamic networking. However, this would require some authority to do extensive work on all roads, as such clusters would need to be defined everywhere there is traffic, and their definition would need to take into consideration a variety of aspects such as the road type, the driving conditions and the communication properties (e.g. range). These clusters would need to be updated at certain intervals, as the traffic conditions can change over time (e.g. weather – dense fog in certain periods). Additionally, the vehicles would need to be aware of all existing clusters as they might travel in large areas (e.g. different countries). Even if fixed clusters are defined, there is no guarantee that the vehicles in the group associated with a cluster will be able to communicate with each other. Therefore, even in this case some technique for information forwarding must be developed. Considering these issues, we employed only a pseudo-static formation of clusters by the fixed hosts. As also mentioned by the authors, our work can be considered complementary to the work in [CC05] for the dynamic approach, as our local networks can be built on top of the dynamically formed groups in [CC05]. We note that the networking technique that we propose did not need such previous grouping of vehicles, but it can make use of it if it exists.

6.3 MAC schemes for vehicular communication

Efficient MAC schemes are essential for developing high-performance communication for vehicles. This area has recently received a great deal of attention.

Investigations of classic MAC schemes for vehicular use have been conducted, and extensions to them have been proposed. For example, [WH98b] proposed a CDMA scheme where the channel access is controlled using the relative location of vehicles, which is supplied by magnetic sensors installed on roads. In a number of other works, e.g. [Ver97, TAF00, KTT+02, FH02b] or [SON+02], assessments of the applicability of schemes such as p-persistent and non-persistent CSMA, ALOHA and R-ALOHA to inter-vehicle communication have been made.

In [YRM05] two extensions to CSMA were proposed for controlling the dissemination of warning messages. The first scheme uses backoff time spacing for differentiating messages with different priorities (e.g. messages from closer vehicles have high priority, and messages from distant vehicles have low priority). The second scheme implements a polling mechanism, where the receiving vehicle polls only vehicles that are waiting to send messages indicated dangerous situations. These vehicles are polled only if they are located within a certain distance from the receiver. The polling operation is done by sending an out-of-band tone on a dedicated channel.

Dedicated MAC schemes for vehicular communication have also been developed. Schemes using slot reservation mechanisms for UTRA-TDD were proposed in the Fleetnet project [LHS+00] and the CarTalk2000 project [BCC+03]. Position-based schemes, where medium access is coordinated using the location of the vehicles, were also investigated (e.g. [NH00+, BV01, KMR+03]). These schemes require the division of the geographic area into cells that have associated dedicated communication channels. The vehicles that enter a cell can then communicate only on the associated channel(s). We note that the idea is similar to the network organization using fixed clusters and therefore suffers from similar drawbacks.

The IEEE 802.11a MAC scheme is currently the de facto scheme for the Direct Short Range Communication (DSRC) standard [BTD06], which provides support for road-to-vehicle communication and for one-hop vehicle-to-vehicle communication. However, this scheme seems to provide moderate quality for implementing certain safety applications such as collision avoidance (e.g. [YEH+04]), and it is expected that improved schemes will be produced [CC05]. A comprehensive analysis of the drawbacks of IEEE 802.11-based schemes and potential improvements was given in [ZR03].

In our work we used one of the basic schemes (i.e. non-persistent CSMA) proposed for inter-vehicle communication when performing the evaluation. However, the results clearly indicated that this scheme could not assure high-quality communication, and the use of more efficient schemes needs to be further investigated.

6.4 Direct Short Range Communication (DSRC)

Dedicated Short Range Communication (DSRC) is a suite of specifications initially proposed for vehicle-to-road communication, and recently extended for vehicle-to-vehicle communication [AST03]. DSRC specifies the MAC layer, the link layer and the radio layer for vehicular communication systems. The basic standard specifies three types of channels: for vehicle-to-vehicle communication, for road-to-vehicle services, and for (communication) control. The North American DSRC program proposed a large variety of applications that can be supported by DSRC [ZR03]. These are both safety applications and non-safety applications such as traveler information and rich media content delivery.

However, DSRC does not address multihop communication or network management [CC05]. Our system is complementary to DSRC and can be implemented using the specified DSRC components. The context-based protocol that we have proposed provides multihop communication and may be used for augmenting DSRC functionality when implementing safety applications. Furthermore, the organization of vehicles into local networks can help to improve communication performance (e.g. by controlling dissemination area), and can ease operations such as unicast and multicast as the local network's members have data about each other. The proposed communication system also integrates road-to-vehicle communication and may be extended to accommodate services proposed to make use of DSRC.

7. Concluding remarks

This chapter presents final remarks on the work in this thesis. Future research directions are also discussed.

7.1 Final remarks

High casualty rates and extensive property damage make traffic safety a critical problem for society. The importance of this problem has sparked research into developing systems that could help reduce the severity of crashes, or even completely avoid collisions between vehicles. However, although important improvements in traffic safety have recently been achieved, the number of collisions with severe consequences is still unacceptably high. Therefore, safety systems that can provide better service to the driver must be developed. Safety vehicular communication is a promising technology for supporting active safety systems. This technology allows the collection of data that cannot be acquired using other technologies proposed for safety systems. It extends the perception of the vehicles, and allows them to correctly identify dangers in complex traffic situations.

Designing the support system for active safety systems is challenging due to multiple factors that must be considered. In this work we aimed at providing a generic method that helps the designer focus on important design aspects, leading to a detailed system design. The risk of overlooking certain key factors, such as accident development, is that the resulting solution may not be applicable in various traffic situations. We refer to [YLZ+04] for a system that can provide an efficient dissemination of emergency notifications in case of rear-end accidents. However, the system cannot be successfully applied to intersection collisions. The design method that we propose is certainly general and can be further specified. However, the current results of analyses, as well as the analysis tools (e.g. ECAM) can be useful in developing other support systems and extending the currently proposed system. They can also be useful in investigating other aspects related to traffic. For instance, we employed ECAM for analyzing the possibility of avoiding intersection accidents that involve drivers of a specific type, namely elderly drivers [SCA+04, SCA06]. In this thesis we illustrate a specification of the general design method with analyses of the communication as the enabling technology for active safety systems. We define properties of the traffic environment in order to derive requirements for communication systems that provide support to exchange of safety data among vehicles. We also study the operation mode of active safety systems and analyze accident scenarios in order to identify specific requirements that apply to safety communication. When analyzing accident scenarios, we also investigate the limitations of safety systems based on communication. For instance, inter-vehicle communication may be less effective in lane departure accidents. We note that the same limitations apply for radar, but not for vision as the enabling technologies. Therefore, the ideal safety system would augment communication-based mechanisms with other technologies. Active safety systems that integrate several enabling technologies can be highly effective.

Several communication approaches can be applied for disseminating data among vehicles in traffic. We analyzed various approaches in order to estimate the level of support each could provide to safety communication. We also conducted a deeper investigation of the design components of the communication system, which resulted in specific features that we integrate in our proposal.

Besides fulfilling strict requirements of safety applications such as collision warning, the communication system needs to fulfill requirements imposed by the particular properties of the vehicular environment. In this work, we advocate the use of these unique properties for building systems that are adaptable to the traffic situation. Two techniques were used to achieve this behavior in the communication system. First, we propose a method of organizing the vehicular network by the use of contextual information. Using this method, the vehicles form and maintain virtual clusters according to their current interest in traffic. This allows the vehicles to be able to constantly organize a network that reflects their needs. Second, we develop a context-based protocol for disseminating safety information to vehicles. An anonymous scoped broadcast protocol is used for delivering specific messages, since the destinations of these messages may not be known to the senders. The receivers then need to identify the messages that contain data of interest. To achieve this, they apply a context-based information filter. We propose here a filtering mechanism based on rules derived from accident situations and guidelines for active safety systems. A set of rules was used as a proof of concept within a prototype implementation of the communication system.

Our protocol mainly takes a proactive approach, where vehicles are regularly provided with safety information. We argue for the effectiveness of this approach in improving traffic safety, since in this case the safety system is able to identify possible dangers well in advance and efficiently act towards avoiding them. Two basic methods can be taken for data delivery in proactive protocols, the fixed rate approach and the adaptive rate approach. We investigate the performance provided by each, and provide an example of the adaptive rate approach with an adaptation mechanism based on the velocity of the vehicles. We also investigate different methods for forwarding information. We subsequently propose a basic routing method based on the distance to the sender, and then extend it to improve the communication performance. Similarly to the information filtering, the routing techniques use context information.

Further on, we enhance the communication protocol with a reactive operation mode because there are situations when traffic safety can benefit from the issuance of specific notifications to warn vehicles in traffic. Also in this case, we investigate different methods for generating and forwarding warnings.

For implementing the communication protocol and integrating it within a vehicle, we propose a vehicular communication platform.

The traffic environment is complex and contains situations that can put very different demands on communication. Therefore, we investigate the performance of the proposed communication system under various conditions. We also investigate the system applicability in helping to avoid specific accidents. A GloMoSim-based simulation system was used for performing the simulations. Realistic traffic traces were generated by traffic simulators that we have developed. We evaluate system performance using delay, packet collisions, send errors, and dissemination success for warning messages. We also investigate the efficiency of the information filtering and specific settings of the communication system. We then assess if the settings that are appropriate for obtaining high-quality communication are realistic by comparing them against safety applications' demands and the capabilities of current communication systems. The results indicate the adaptive approach employed for the proactive operation mode as most suitable for delivering safety data. They also indicate that forwarding and filtering of information are essential in obtaining good performance. For instance, the use of a basic routing protocol resulted in a system with marginal performance for the maximum latency, which may be difficult to use for informing particular vehicles in time. When the routing mechanism was extended with a technique similar to message filtering, the system performance was dramatically improved. For the retransmission of warning messages, the experiments showed potential for an approach based on the distance to sender, but also revealed that such techniques might not provide the needed level of reliability. Thus, when we applied a deferring technique based on distance to sender, it was possible to obtain low delays for delivering warning messages under specific settings, but some of the vehicles in need did not receive these notifications. This indicated that improvements are needed for such techniques to function satisfactorily. A simpler approach using a flooding-oriented technique for retransmitting warning messages led to better results. These results also indicated that vehicular communication based on contextual information needs to be carefully designed in order to represent the traffic characteristics. The filtering of information was significant in all cases, which indicated that important improvements in information management, i.e. elimination of useless and misleading data, can be obtained when using contextual information for management of the communication. The communication performance degrades with the network load, which indicates the need for more efficient MAC schemes and the importance of further investigation of transmission and forwarding techniques. We recall that the MAC scheme that we have employed was previously proposed for vehicular communication. However, the evaluation results indicated this MAC scheme to be able to provide only moderate quality.

To summarize, safety communication is an essential part of future active safety systems. In this thesis we propose a method for designing communication and networking techniques for use in safety vehicular communication. These techniques make use of contextual information for controlling the communication between vehicles in traffic, which improves the management of information and results in good communication performance. Thus, timely and reliable provision of safety data to vehicles can be realized using the proposed communication system.

7.2 Future work

Many aspects of the work presented in this thesis can be extended. Several directions are presented in the following.

Communication and networking

Medium Access Control

Investigation of more efficient MAC schemes for data exchange in the vehicular environment is important. Research can also go deeper into this area with the goal of proposing new access schemes. This is because even the scheme proposed for DSRC is considered only as a provisory solution [CC05], as it cannot provide the needed level of quality. The performance study on DSRC in reference [YEY+04] showed that this scheme may achieve low latency for one-hop communication, but cannot currently fulfill reliability requirements, as a large number of neighboring vehicles (i.e. more than 40%) may remained uninformed due to information loss.

Information Dissemination

Improved versions of the techniques for transmitting and forwarding data are also important subjects for further investigation. We have shown that adaptive transmission of BSMs and efficient routing can have a significant impact on the communication performance. The adaptation method proposed here can be considered as generic, and further specializations can be developed. Moreover, schemes that adapt the transmission rate with regard to the road the vehicles travel on, or with regard to more specific traffic situations should also be investigated. For instance, for vehicles traveling on divided highways, a combination of the driving orientation, the number of vehicles in a local network, and the relative distance between vehicles can be used. Thus, if a vehicle traveling in one direction has only distant neighbors, i.e. neighbors situated at the border of the communication service area, the transmission rate can be reduced.

Forwarding of information in case of low penetration rate of the system also needs to be investigated. This is to assess whether or not the protocol can work efficiently in this case and to identify eventual extensions.

Information Filtering

Information filtering remains an open issue. In this work we have given examples of the advantages of using contextual information for controlling the communication and we defined and used a set of rules for filtering received data. However, this is a proof-of-concept and even if these rules generally apply for most traffic situations, it is important that further investigations of rules be performed. Aspects such as position inaccuracies, vehicles traveling on parallel roads, and amount of vehicles that can be considered dangerous should be studied in more depth.

Network organization

Since network organization considerably influences the system performance, it is of interest to explore alternatives. It would also be interesting to investigate how the network organization could help to improve the communication performance by performing certain operations such as controlling access priorities. Also of interest is to investigate how the network organization can support the deployment of diverse traffic applications, such as applications that make use of multicast and unicast communication.

Testing and implementation

The improvements in traffic safety for different deployment rates of the communication system are of interest for investigation. Certainly, in this case the initial assumptions regarding the operation of the safety system and the driver interaction with the system will influence the results. Still, using relevant research results in traffic safety it should be possible to estimate the level of improvement.

A prototype of the current version of the communication system or an improved future version using on-market devices is planned for development. By employing field tests, more information can be gathered about the performance of the system in real operations. However, this may require the use of devices that do not really satisfy quality requirements imposed by the vehicular environment. This is because such devices may not be available. For example, DSRC devices are not currently on the market and WLAN cards, which are most likely to be employed in field tests, usually provide low quality when used for inter-vehicle communication [CC05]. We also note that a large number of vehicles would be needed for performing a realistic assessment of the feasibility and reliability of the proposed communication system. This is because testing with two or three vehicles, like in previous studies [e.g. [SBS+02, KKR+04, CC05]) can only provide indications of data delivery latency, packet collisions or throughput. However, such tests address a specific situation where interference will most probably be low. Also, indications about the efficiency of the information filtering and the impact of the network organization on the communication performance can be obtained only when testing with a larger number of vehicles.

The implementation of the proposed communication and networking techniques using DSRC components would also be worthwhile to investigate in more detail.

Other directions

The protocol that we propose is directed toward safety applications. However, we envision the possible use of the basic concepts for providing other types of vehicular communication such as infotainment. To enhance the protocol with such functionality, new techniques for sending and forwarding data need to be developed. Provision of different traffic services using inter-vehicle communication is of interest to the community, and relevant research has already been performed in this direction (e.g. [Wan04b, WLH+05]).

Another possible direction addresses the modeling of accidents and the derivation of requirements on the support system for active safety systems using temporal logic. We see here a need for extending the ECAM reasoning system with more advanced models of vehicle dynamics, driver behavior and safety systems operation modes. The definition of a set of fluents and events that generally apply to a large variety of traffic scenarios is also of interest. By using such a set, a standard framework for analyzing accidents and deriving requirements for supporting technologies for safety systems can be provided. We also see the possibility of investigating the use of the ECAM system for predicting the occurrence of accidents.

Security and privacy are issues of concern in vehicular networks and we have identified various security requirements. However, we focus rather on the functionality of the communication protocol in this thesis, and security remains an open issue.

Appendix A: Algorithms for derived parameters

The decision mechanisms that implement the information filtering make use of primary and derived parameters. The derived parameters are determined using primary parameters that were previously extracted from received basic safety messages or were provided by systems located on a subject host. In Chapter 4 we introduced the algorithms for determining the derived parameters. This appendix gives details on these methods.

A1. Membership of two hosts to the same road

Let us consider two hosts, H1 and H2, which travel on a road as presented in figure A1.1. The gray vehicles in the figure represent the current position of the hosts and the white vehicles with dotted lines represent the previous positions of the hosts. The dotted arrows indicate the movement of the vehicles between the two points in time.

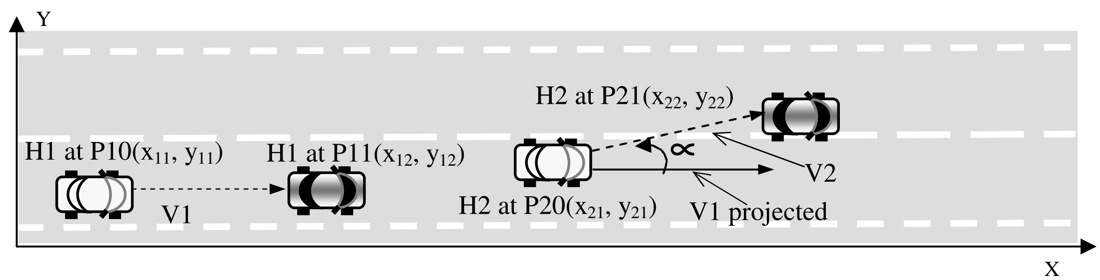


Figure A1.1

We use a bidimensional representation (X and Y) of the movement vectors of the hosts. The angle α between the movement vectors of the considered hosts can be calculated as:

$$\alpha = \arccos\left(\frac{V1 * V2}{|V2||V1|}\right) \text{ where } V1 = \begin{bmatrix} x_{12} - x_{11} \\ y_{12} - y_{11} \end{bmatrix} \text{ and } V2 = \begin{bmatrix} x_{22} - x_{21} \\ y_{22} - y_{21} \end{bmatrix}.$$

In the previous equation, |X| represents the module of vector X and we have used "*" to indicate the dot product of two vectors. We used the classical equation for Euclidean distance when calculating the module of a movement vector based on two successive position indications. Thus:

$$|V1| = \sqrt{(x_{12} - x_{11})^2 + (y_{12} - y_{11})^2} \text{ and } |V2| = \sqrt{(x_{22} - x_{21})^2 + (y_{22} - y_{21})^2}$$

Furthermore, the dot product of the movement vectors is calculated as:

$$V1 * V2 = (x_{12} - x_{11}) * (x_{22} - x_{21}) + (y_{12} - y_{11}) * (y_{22} - y_{21})$$

The angle α in the above equation is calculated in radians and needs to be translated in degrees. Thus, α [degree] = α [rad] *180/π. If α is close to 0 or 180 degrees, then the hosts H1 and H2 are considered to be on the same road. Otherwise, they are considered to travel on different roads. We have considered 10 degrees as the maximum deviation (from 0 or 180 degrees).

A2. Relative positioning of two vehicle hosts

The relative positioning of two vehicle hosts indicates if one of the hosts is ahead of or behind the other. This parameter is evaluated when the hosts are traveling with opposite headings. An example is illustrated in figure A1.2, where two hosts H1 and H2 are represented at two successive moments in time.

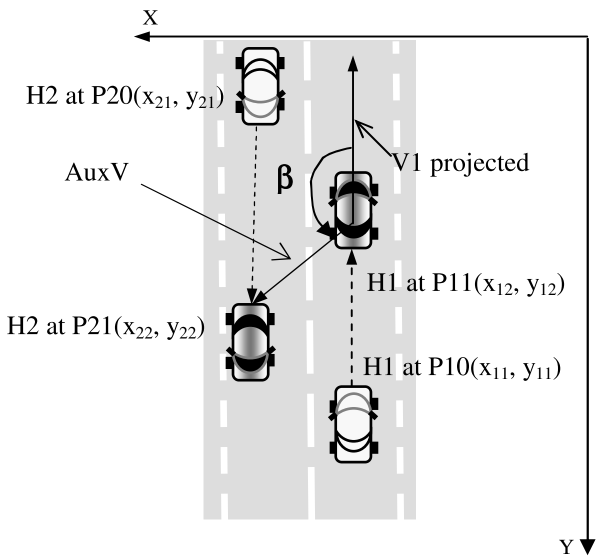


Figure A1.2

The gray vehicles represent the current position of the hosts and the white vehicles represent the initial position. The dotted arrows indicate the movement of the vehicles. We also used a bidimensional representation (i.e. X and Y) of the movement vectors. The angle β indicated in the figure was evaluated as follows.

$\cos\beta = \frac{AuxV * V1}{|AuxV||V1|}$, where $V1 = \begin{bmatrix} x_{12} - x_{11} \\ y_{12} - y_{11} \end{bmatrix}$ and $AuxV = \begin{bmatrix} x_{22} - x_{12} \\ y_{22} - y_{12} \end{bmatrix}$

The angle β is then translated in degree and is compared with a threshold value of 90 degree. If β is lower than this threshold, the host H2 is considered to be ahead of host H1. Otherwise it is situated behind H1.

A3. Detection of route contention at an intersection

Route contention indicates the possibility that two vehicles will meet at an intersection. We considered two vehicle hosts H1 and H2 that travel on different roads as presented in figure A 1.4. We estimated if these vehicles might meet using their positions (e.g. P21 and P11), their orientations with regard to the horizontal axis (i.e. angles θ1 and θ2), and their velocities (i.e. VH2 and VH1). We note $\lambda_2 = \tan\theta 2 = \frac{y_{int} - y_{22}}{x_{int} - x_{22}}$ and $\lambda_1 = \tan\theta 1 = \frac{y_{int} - y_{12}}{x_{int} - x_{12}}$

If λ1= λ2 then H1 travels on a path parallel with H2 and they cannot meet at any time point. If λ1≠ λ2 then:

$$y_{int} - y_{12} = \lambda_1 x_{int} - \lambda_1 x_{12}$$
$$y_{int} - y_{22} = \lambda_2 x_{int} - \lambda_2 x_{22}$$

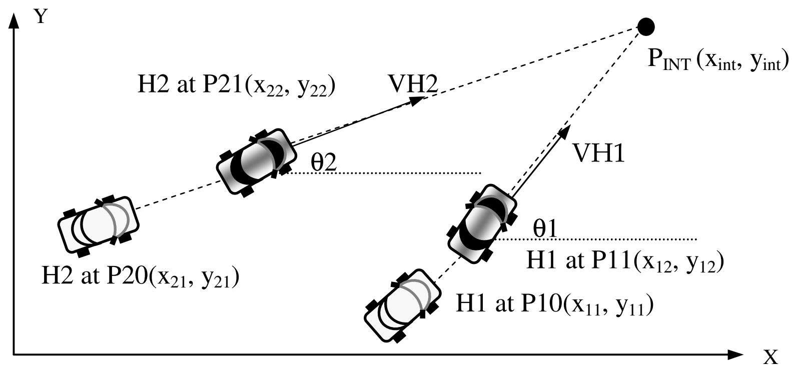


Figure A1.4

Thus, the estimated coordinates of the possible intersection point are:

$$x_{\text{int}} = \frac{1}{\lambda_1 - \lambda_2}\left[\lambda_1 x_{12} - \lambda_2 x_{22} + (y_{22} - y_{12})\right]$$

and

$$y_{\text{int}} = \frac{1}{\lambda_1 - \lambda_2}\left[\lambda_1 \lambda_2 (x_{12} - x_{22}) + \lambda_1 y_{22} - \lambda_2 y_{12})\right]$$

The vehicles can meet at the intersection point P_{INT} only when they approach this point. This is the case if the following conditions hold at the same time:

[C1] $\frac{x_{\text{int}} - x_{12}}{x_{12} - x_{11}} > 0$ and [C2] $\frac{x_{\text{int}} - x_{22}}{x_{22} - x_{21}} > 0$

The vehicles can meet at the intersection point only if they reach it at approximately the same time. The distances to the predicted intersection point for H1 and H2 are calculated as follows:

$$P_{11}P_{INT} = \left[(x_{\text{int}} - x_{12})^2 + (y_{\text{int}} - y_{12})^2\right]^{1/2}$$

$$P_{21}P_{INT} = \left[(x_{\text{int}} - x_{22})^2 + (y_{\text{int}} - y_{22})^2\right]^{1/2}$$

The estimated times *t1* and *t2* when H1 and H2 are supposed to reach the intersection point are:

$t_1 = \frac{P_{11}P_{INT}}{VH1}$ and $t_2 = \frac{P_{21}P_{INT}}{VH2}$

However, the vehicles have a certain length and can collide when both of them arrive at the same moment at the intersection point, or when one arrives at the intersection point and the other is passing through it. Therefore, we introduced a time interval when the vehicles might meet at the intersection. We call this interval *Intersection_time_threshold* and use this approximation when comparing the time moments *t1* and *t2*. Thus, the vehicles are considered in danger of meeting at an intersection when $|t1-t2| \leq$ *Intersection_time_threshold*

To specify a value for the Intersection_time_threshold we consider the usual length of a vehicle to be between Lmin = 3 meters and Lmax = 7 meters. We also consider a minimum speed value of Vmin = 8 km/h (e.g. urban intersection) and a maximum speed value of Vmax = 140 km/h (e.g. highway junction) for a vehicle. Then, the longest period needed by a vehicle to completely pass through the intersection point can be calculated as Lmax/Vmin and is around 3.2 sec. Consequently, we selected 3 seconds as the value for Intersection_time_threshold.

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