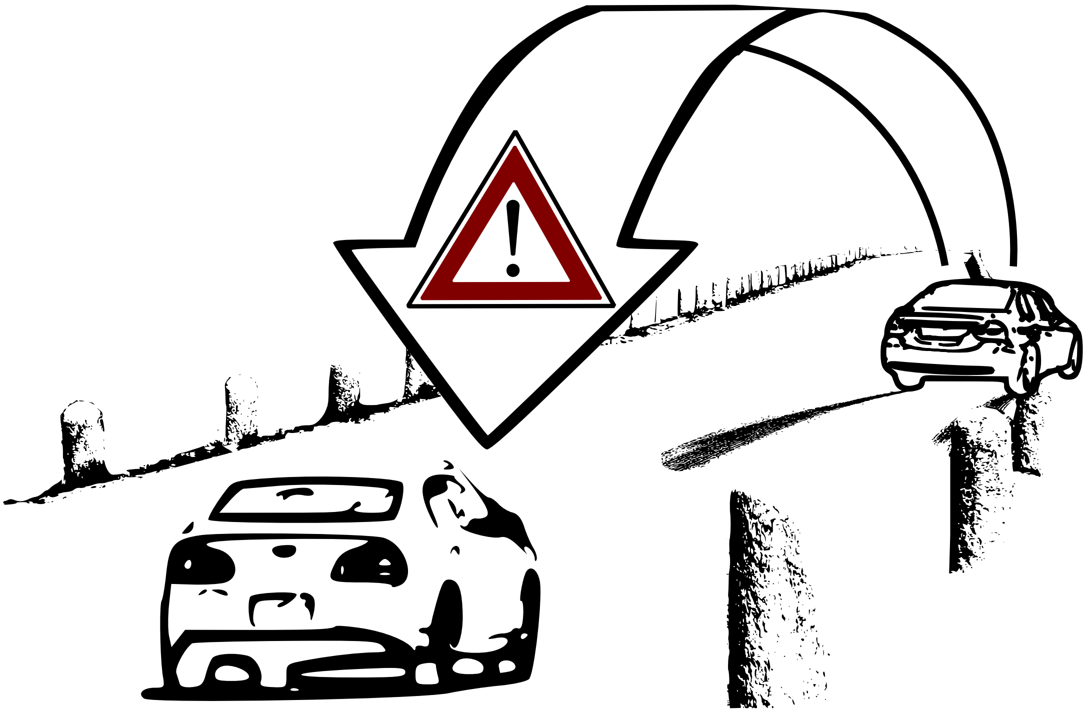
Moritz Killat

The Impact of Inter-Vehicle Communication on Vehicular Traffic



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The Impact of Inter-Vehicle Communication on Vehicular Traffic

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Dissertation

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Moritz Killat

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Erster Gutachter: Prof. Dr. Hannes Hartenstein
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Zweiter Gutachter: Prof. Dr. Christian Bettstetter
Universität Klagenfurt

Zusammenfassung

Von einer direkten drahtlosen Kommunikation unter Fahrzeugen des täglichen Straßenverkehrs verspricht man sich, die Straßenverkehrssicherheit sowie die Straßenverkehrseffizienz zu erhöhen. Diese Dissertation untersucht, wie sich das Potential von Anwendungen, die intensiven Gebrauch von Fahrzeug-Kommunikationsnetzen (engl. *Vehicular Ad Hoc Networks (VANETs)*) machen, in Bezug auf eine reduzierte Anzahl von Unfällen und auf einen erhöhten Verkehrsfluss abschätzen lässt. Zu diesem Zweck nimmt die Arbeit eine auf die beiden Ziele abgestimmte Modellierung von VANETs vor, entwickelt darauf aufbauend Simulationswerkzeuge und ermöglicht somit eine Leistungsbewertung des Systems in Simulationsstudien.

Im ersten Teil der Arbeit steht die Verkehrssicherheit im Fokus, deren Verbesserung anhand der Anzahl vermiedener Unfälle gemessen wird. Eine solche Bewertung schlägt sich in einem dreistufigen Prozess nieder: (a) der Bereitstellung von Verkehrsinformationen durch VANETs, (b) deren Bewertung und Verarbeitung in der Anwendung und (c) die Konsequenzen der Aktivierung der entsprechenden Anwendung auf den Straßenverkehr. Die Arbeit nimmt zunächst eine Potentialabschätzung vor und geht von einer vollständigen Verfügbarkeit der benötigten Informationen aus. Unter dieser Annahme wird das Problem der Unfallvermeidung modelliert, indem unfallträchtige Verkehrssituationen rechtzeitig identifiziert und somit vermieden werden können. Die Modellierung erfolgt zunächst durch einen Markovschen Entscheidungsprozess mit absorbierenden Systemzuständen und offenbart dabei eine Komplexität des zugrundeliegenden Problems aufgrund derer dieser Ansatz zwar als methodisch reizvoll, für eine praktische Umsetzung aber als zu aufwendig erkannt wird. Unabhängig von dem Komplexitätsproblem ist die Validierung einer zum Einsatz kommenden Unfallvermeidungsstrategie unabdingbar. Zur Bewertung einer solchen Strategie bemüht die Dissertationsarbeit Simulationsstudien, für deren Durchführung das Konzept eines Verkehrsunfalls in bestehende Simulationswerkzeuge integriert werden muss. Die Dissertation schlägt entsprechende Modifikationen für das Fahrzeug-Folgemodell von Wiedemann vor, integriert diese in den Verkehrssimulator VISSIM und bewertet eine Sicherheitsstrategie in Überholmanövern mittels Simulationsstudien. Die Ergebnisse weisen einen ansteigenden Erfolg der untersuchten Sicherheitsanwendung mit zunehmender Verfügbarkeit von Fahrzeuginformationen auf und zeigen gleichzeitig, dass das Ziel eine vollständige Information

über die gegenwärtige Verkehrslage sein muss.

Im zweiten Teil der Arbeit werden VANETs hinsichtlich ihrer Auswirkungen auf die Verkehrseffizienz untersucht. Der Blickwinkel auf das System verschiebt sich dabei von der Betrachtung einzelner Fahrzeuge hin zu ganzen Verkehrsströmen und deren Charakterisierung in Bezug auf den Verkehrsdurchsatz. Für VANETs konnten Simulationsstudien dieser Art bislang insbesondere aufgrund der Skalierungsprobleme von diskreten ereignis-basierten Kommunikationssimulationen nicht durchgeführt werden. Die Dissertation entwickelt deshalb ein mathematisches Modell der Paket-Empfangswahrscheinlichkeit, das anhand von Simulationen statistisch validiert wird. Eine Verknüpfung des Modells mit dem Verkehrssimulator VISSIM und die Bereitstellung eines Applikationsmoduls ist dann den gestellten Anforderungen gerecht geworden. In abschließenden Simulationsstudien zeigt die Arbeit, wie mittels VANETs verbreitete Geschwindigkeitsanweisungen sich auf den Verkehrsdurchsatz auswirken. Die Simulationsstudien umfassen dabei bis zu 3 000 kommunizierende Fahrzeuge und weisen einen Beschleunigungsfaktor von bis zu 1 500 gegenüber vergleichbaren strikt ereignisbasierten Simulationsansätzen auf.

Abstract

The idea of introducing communication technology to road traffic is appealing for its promises to increase vehicular traffic safety and vehicular traffic efficiency. In communication networks established over radio equipped vehicles, so called *Vehicular Ad Hoc Networks (VANETs)*, applications are assumed to support a decrease of accidents and an increase of traffic throughput. The goal of this thesis is to enable an impact assessment of such applications. The thesis provides a modeling of the system tailored to the two envisaged goals, develops simulation tools and thus allows for performance studies by simulation means.

In the first part, the thesis addresses an impact assessment of traffic safety reflected in the number of occurring accidents. Such an evaluation is structured in three parts: (a) provision of vehicular traffic information by VANETs, (b) evaluation and usage of information by a respective application and (c) the effect of the considered application on road traffic. The thesis firstly aims at revealing the potential of the system and therefore assumes the communication system to provide all information required by a safety application. Under this assumption, the thesis addresses part (b) of the evaluation process by modeling the problem of identifying accident-prone traffic situations by means of an Markov Decision Process with absorbing system states. This methodology proves to be a valuable approach to model traffic safety applications but simultaneously reveals implementation bottlenecks due to complexity reasons. From these observations the thesis infers the need for simplified safety algorithms which (as any other algorithm) require validation by simulation means. Therefore, the concept of a traffic accident is incorporated to the Wiedemann mobility model and implemented into the traffic simulator VISSIM, thus allowing for part (c), the impact assessment of the application on road traffic. In a simulation study, the thesis assesses a safety application designed to prevent accidents in overtaking maneuvers. The results indicate a decreasing number of accidents with increasing information on surrounding vehicles and suggest that complete information on the traffic situations needs to be the aimed at goal.

In the second part, the thesis turns towards an impact assessment of VANETs on vehicular traffic efficiency. This perspective changes the scale of the modeling view from individual vehicles to traffic flows comprising thousands of vehicles and their effect on the traffic throughput. Up to now, VANET simulation studies of such scale could not be performed because of scalability problems resulting from a discrete-event simulation approach of communication behavior. The thesis therefore devises a mathematical model on the probability of packet reception which is validated against simulation results. Incorporated into the traffic simulator VISSIM and linked to a module hosting the application logic, the proposed model allows for the envisaged large-scale studies of VANETs. In a concluding simulation experiment the thesis investigates the effect of a speed advice disseminated via a VANET on the resulting traffic throughput. Compared to a pure discrete-event simulation approach, the proposed methodology has shown a speedup factor of up to 1 500 in a scenario comprising 3 000 communicating vehicles.

Vorwort

Es trifft wohl nur sehr selten zu, dass man eine Forschungsarbeit als abgeschlossen erachtet. Stattdessen sieht insbesondere der Autor neue, sich aus den ursprünglichen Fragestellungen ergebene Fragen, für deren Zuwendung jedoch der Rahmen des ursprünglichen Ziels bei weitem gesprengt werden würde. Insofern handelt es sich oftmals bei einer veröffentlichten Arbeit vielmehr um eine Momentaufnahme des beruflichen Schaffens denn eines Abschlusses. Die vorliegende Arbeit verschafft einen Überblick über Fragestellungen, mit denen ich mich in meiner Zeit als wissenschaftlicher Mitarbeiter in der Forschungsgruppe Dezentrale Systeme und Netzdienste (DSN) am Institut für Telematik der Universität Karlsruhe (TH) auseinander gesetzt habe. Was sie nicht leistet, für mich aber von nicht minderer Bedeutung ist, ist ein Überblick über die Menschen, die mich in dieser Zeit begleitet haben und die wesentlich zum Gelingen dieser Arbeit beigetragen haben. In diesem Vorwort möchte ich versuchen, wenn auch mit viel zu wenigen Worten, diesen Menschen zu danken.

In erster Linie gilt mein Dank meinem Doktorvater Herrn Prof. Dr. Hannes Hartenstein. Nicht nur sein Angebot, das mir ermöglichte eine Stelle als wissenschaftlicher Mitarbeiter zu besetzen, sondern noch viel mehr die Arbeitsweise, die er vorlebt und das Umfeld, das er pflegt, bildeten den Ausgangspunkt dieser Arbeit. Seine Mischung aus offerierten Freiräumen und gezieltem Lenken, aus Denkanstößen und kritischem Hinterfragen ist einzigartig, inspirierte mich immer wieder auf ein Neues und lässt mich mit Freude auf die vergangenen Jahre zurückblicken. Ich habe in diesen Jahren gelernt, neue Denkweisen angenommen und Seite an Seite mit einem großen Menschen arbeiten dürfen. Danke Hannes.

Ich möchte mich auch bei Herrn Prof. Dr. Christian Bettstetter für die Übernahme des Korreferats meiner Arbeit, sowie bei Frau Prof. Dr. Martina Zitterbart und Herrn Prof. Dr. Ralf Reussner für die Begleitung meiner mündlichen Abschlussprüfung bedanken. Ebenso gilt mein Dank dem Graduiertenkolleg 'Information Management and Market Engineering (IME)' in dem ich drei Jahre mit Kollegen unterschiedlichster Fachrichtungen forschen durfte. Auf der Professorenseite möchte ich hier insbesondere Herrn Prof. Dr. Karl-Heinz Waldmann nennen, ohne dessen Unterstützung wesentliche Teile meiner Arbeit in der Form nicht hätten realisiert werden können.

Einen Großteil der Zeit habe ich in den vergangenen Jahren mit meinen Kollegen der DSN-Forschungsgruppe verbracht. Zwar befinden sich allesamt auf

fußballerischen Irrwegen, fachlich aber auf der Überholspur und menschlich habe ich gar neue Freunde hinzugewonnen. In chronologischer und alphabetischer Reihenfolge gilt mein Dank zunächst Dr. Jochen Dinger, Felix Schmidt-Eisenlohr und Dr. Marc Torrent Moreno, den DSN-Mitarbeitern der ersten Generation. Neben unseren Freundschaften konnte ich mich stets glücklich schätzen immer wieder Rat, Verständnis und Inspiration in zahlreichen Gesprächen finden zu können und die Zeit in nicht enden wollenden Paper-Nächten vergessen zu machen. Den später zu der Forschungsgruppe gestoßenen Mitarbeitern sei aber nicht minder gedankt. Mit Thorsten Höllrigl, Frank Schell, Dr. Jérôme Härri, Natalya An, Oliver Jetter, Konrad Jünemann, Sebastian Labitzke, Jens Mittag und Tessa Tielert verbindet mich weit mehr als ein kollegiales Miteinander. Ihr Blickwinkel auf meine Fragestellungen eröffnete mir abermals einen klareren Blick auf das vorliegende Problem. Der DSN-Gruppe kann nicht vollständig gedankt werden ohne Astrid Hopprich zu erwähnen, die mit ihrer immer vorhandenen Hilfsbereitschaft mir zahlreiche Aufgaben abnahm. Bevor sie zu uns gestoßen ist, durfte ich oft auf die Hilfe von Brigitte Armbruster, Ina Dvorak, Astrid Natzberg, Dorothea Wagner und Doris Weber zurückgreifen, bei denen ich mich an dieser Stelle auch ganz herzlich bedanken möchte.

Neben meinen unmittelbaren Kollegen hatte ich das große Glück während meiner Arbeit auf die Infrastruktur der Gruppe um Frau Prof. Dr. Martina Zitterbart zurückgreifen zu können. Ich profitierte nicht nur von deren hervorragender Ausstattung, sondern genoss die freundschaftliche Atmosphäre, das technische Know-how und die Jura Kaffeemaschine. Letztere besiegelte meine Verbindung zu Detlev Meier, der wie Frank Winter und Gentiel Mussgnug mir stets zu Hilfe war, wann immer ich Unterstützung auf technischer Seite benötigte. Mein Dank gilt aber insbesondere auch Peter Baumung, Michael Conrad, Thomas Gamer und Christian Hübsch mit denen ich weit mehr teile als das Büro nebenan.

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Neben schon bereits erwähnten, möchte ich mich auch bei Lars Rohnstock und bei meinem Vater bedanken, die meine Arbeit Korrektur gelesen haben. Bei letzterem und bei meiner Mutter gilt mein Dank natürlich noch viel weitreichender, als es diese paar Zeilen hergeben würden. Ich danke Euch für Eure Unterstützung über all die Jahre, für Euer offenes Ohr in meinen schwierigsten Situationen und für das fortwährende Gefühl des Daseins. Zu guter Letzt, aber eigentlich an erster Stelle, möchte ich meiner Freundin Nina danken. Danken, für das Zu-mir-stehen, wenn die gemeinsame Zeit knapp war, danken für Deine Wärme, wenn ich nur zum Schlafen nach Hause kam und danken für Deinen Zuspruch, wenn meine Zuversicht schwand. Ohne Deine Unterstützung und Deinen Rückhalt hätte ich diese Arbeit nicht vollenden wollen.

Moritz Killat, Karlsruhe im September 2009

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List of Symbols

A	set of actions
$\mathcal{A}$	an application
a_i	fitting parameters
α	discount factor
B_ϵ, $B_{\hat{R}}$	number of bits required for ϵ and $\hat{R}$, respectively
d	distance in meter
δ	vehicular traffic density
f	transmission rate
h_i	polynomial fitting functions, $h_i : \mathbb{R}^+ \rightarrow \mathbb{R}^+$
$h_i^{(j,k)}$	coefficients subject to fitting functions h_i
$\mathcal{M}$	empirical model
μ	mean
P	transition law
π	policy function, $\pi : S \rightarrow A$
π^*	optimal policy function
Pr	probability
$\widetilde{\text{Pr}}$	approximated probability
ψ	transmission power
q	probability
r	reward function, $r : (S, A) \rightarrow \mathbb{R}^+$
$\hat{R}$	maximum reward
S	set of system states
σ^2	variance
SSE	sum of squared errors
U	update operator, $U : \mathbb{R}^+ \rightarrow \mathbb{R}^+$
U_π	update operator applying policy π
V	value function, $V : S \rightarrow \mathbb{R}^+$
$V^{(n)}$	value function gained after n successive applications of operator U
V_π	value function when policy π is applied
X	stochastic process
ξ	communication density

The following three definitions are taken from [Jam92].

Banach space: A vector space whose scalar multipliers are the real numbers and which has associated with each element x a real number $\|x\|$, the norm of x, satisfying the postulates: (1) $\|x\| > 0$ if $x \neq 0$, (2) $\|ax\| = |a| \cdot \|x\|$ for all real numbers a, (3) $\|x + y\| \leqslant \|x\| + \|y\|$ for all x and y, (4) the space is complete.

Bounded linear transformation: A linear transformation T between normed vector spaces is bounded if there exists a constant M such the $\|T(x)\| \leqslant M\|x\|$ for each x.

Eigenvalue: For a linear transformation T on a vector space V, an eigenvalue is a scalar λ for which there is a nonzero member $v \in V$ for which $T(v) = \lambda v$.

Spectral radius:[Put05] Let T be a linear transformation and let $S(T)$ denote the spectrum of T (for a matrix, the set of its eigenvalues [Jam92]) then the spectral radius of T is given by $\sup_{\lambda \in S(T)} |\lambda|$.

1
Problem Statement and Overview of Thesis

1.1 A brief history on vehicular ad hoc networks

1.1.1 First attempts

Already in the 1970s researchers were fascinated by the idea of radio-equipped vehicles that mutually exchange traffic information to improve driving conditions. Probably the first research project worldwide on this topic, the Comprehensive Automobile Traffic Control System (CACS) project, was initiated in Japan in 1973 [Kaw90]. Essentially, the CACS project pursued four objectives: (a) reduction of road traffic congestion, (b) reduction of exhaust fumes caused by traffic congestion, (c) prevention of traffic accidents, and (d) enhancement of the public and social role of automobiles. From an implementation point of view, the key to attaining the objectives was seen to be in the provision of additional information to the driver, thereby promptly alerting of danger and giving notice about alternative routes to circumvent traffic congestions. As required technical means, CACS conceived mobile communication techniques integrated into vehicles and facilitating communication among vehicles and road-side infrastructure. Such a communication network spanning over vehicles and road-side infrastructure was envisioned as being capable of

1. strengthening a driver's awareness of the current traffic situation and thereby improving **vehicular traffic safety**, and

Original picture by **Matt Hintsa** (permission granted)

Figure 1.1: Inter-vehicle communication enables the driver of the white vehicle in the foreground to obtain information from farther distances (yellow) than what basic sensors (dark green) or advanced sensors (light green) can provide.

2. creating an effective tool for centralized road operators to release stressed traffic conditions and thereby to improve **vehicular traffic efficiency**.

The aforementioned goal is exemplarily visualized in Figure 1.1: from the perspective of the white vehicle in the foreground, the driver's horizon of awareness is expected to exceed basic sensor information (colored dark green) and the driver's perception (light green) to include farther distances (yellow) provided via inter-vehicle communication.

Some years later Europe (Prometheus, 1986) and the USA (PATH, 1986) likewise started research initiatives to explore potential benefits of communication enabled vehicles. The research programs demonstrated the successful application of communication systems to vehicular traffic in platooning experiments, where succeeding vehicles exchanged information on acceleration and braking behavior [Tsu05]. The available communication technology at that time required the research programs to apply communication technology based on infrared or millimeter waves, restricting the communication capabilities to line-of-sight conditions. One may conclude that advancements in the communication technology were required to exploit the full potential of communication-enabled vehicular traffic.

1.1.2 Renaissance at the end of 1990s

At the end of the 1990s, the availability of low-cost wireless local area network (WLAN) transceivers and of satellite-based positioning system (GPS) for civilian use leveraged research initiatives in Europe, Japan, and the USA, respectively.

The term *Vehicular Ad Hoc Networks (VANETs)* was coined to indicate the decentralized and self-organizing nature of the communication networks; synonymously, researchers also often refer to *inter-vehicle communication* or *vehicle-to-x communication*, where the latter specifically takes account of the communication-to-roadside infrastructure. The communication technology now generally operating in the 5.8/5.9 GHz band enables the capabilities of broadcast communication exceeding previous boundaries of direct, neighboring communication links. Additionally, the availability of positioning information associates received information with geographically distant transmitters. Many research programs in Europe (e.g., FleetNet, PReVENT, eSafety), Japan (ASV 2/3/4), and in the USA (IVI, VII, IntelliDrive) adapted to the advancements in technology and refocused on the initial goals envisaged 30 years ago.

From a communication point of view, the latest research initiatives have focused on establishing requirements for assumed VANET applications. Traffic safety applications, for instance, may likely depend on a fast exchange of information in a robust manner when danger has been detected. Therefore, optimizations on communication metrics, like the probability of packet reception over distance or the delay of successful packet delivery, have constituted the primary communication design goals. These goals appear challenging if one considers the available bandwidth of 10 to 20 MHz currently assigned or foreseen for VANET communications [HL08] and the potentially high number of communicating vehicles all accessing the channel in a distributed manner. However, essentially these goals are quality-of-service measures on the network and transport layer of the classical communication stack. An assessment of the potential benefits of VANETs on their goals, namely vehicular traffic safety and vehicular traffic efficiency, requires quality-of-service measures in the perceived application domain. So far it has not been demonstrated if the application of VANETs reduces the number of traffic accidents or if it contributes to an increased traffic flow in everyday vehicular traffic. We thus pose the motivating questions of this thesis:

1. *How many accidents can be avoided if VANETs are applied?*

2. *Which information distributed via VANETs increases the traffic flow and to which extent?*

These questions might be too ambitious and indeed the thesis will not answer them. But the thesis fundamentally discusses how an impact assessment of VANETs on vehicular traffic safety and on vehicular traffic efficiency can be carried out.

1.2 Problem statement

General answers to the motivating questions are hard to find since the potential impact of VANETs likely depends on the given traffic situation. An assessment consequently requires evaluating the influences in many differing traffic situations. However, the danger and the costs of testing a preliminary immature system impede real-world experiments on the road. From an engineering perspective, the availability of a modeling tool set is necessitated to create different traffic scenarios and to observe potential improvements of using VANETs in evaluation metrics, like traffic accidents or traffic throughput.

A modeling approach, however, is challenging since the joint impact of many influencing factors needs to be considered. For demonstration reasons, we consider a conceived use case of VANETs: the number of accidents in overtaking maneuvers is assumed to be lowered if the driver of the overtaking vehicle is warned of faster approaching vehicles. An assessment of this use case depends on various details in the considered scenario setup: reaction behavior and delay of humans, position and speed of vehicles, reception delay of transmitted warning messages, and weather conditions present only a small number of factors that may change the outcome of an experiment. For clarity reasons, we seek structures that organize the myriad of influencing factors.

Communication experts typically distinguish between a modeling of the network and the corresponding communication protocols on the one hand, and a modeling of distributed applications operating on the communication system on the other hand. In VANETs, however, the aspect of mobility additionally gains particular importance: it changes conditions of the communication system and frequently is the trigger of operations of VANET applications. We adapt this separation of application, communication, and mobility and consider a modeling based on the following three building blocks.

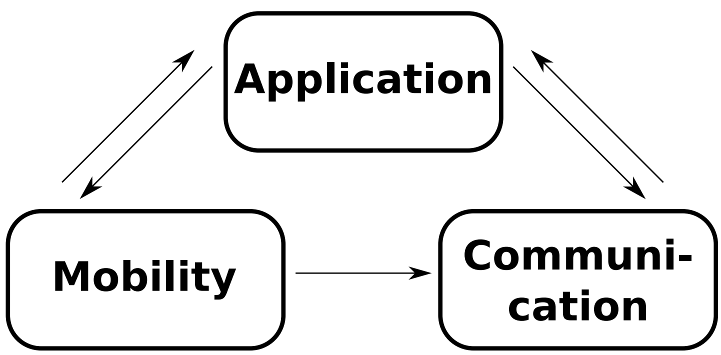


Figure 1.2: Fundamental building blocks required to model the 'inter-vehicle communication system'. An arrow from A to B indicates that A influences B.

The **application** building block models the application of VANETs and the context in which they operate. The application typically originates from use cases that define the events in the considered scenario and the proposed reaction taken by an informed driver. The application block thus observes traffic conditions, triggers the dissemination of information, evaluates received information, and suggests consequences to the driving behavior. Therefore, the functionality of the building block is determined by changes of the traffic scenario (defined in the mobility block) and by the set of available information on the scenario (determined by the communication block).

The **mobility** block represents spatial changes to the scenario's constellation. At first glance, this concerns the movement of the vehicles, their acceleration and braking behavior, and their compliance with traffic rules, like traffic lights, for instance. On closer inspection, more details become important: physical properties of the vehicles, the road surface quality, weather conditions changing the grip of vehicles, and perhaps most importantly the human factor introducing false estimations and anticipations about the current traffic situation. Roughly summarizing, this building block comprises the influencing factors that determine the characteristic of the current vehicular traffic.

This building block influences the application building block by creating use-case-specific traffic events that cause activity in VANET applications. On the other hand, it may become influenced by the application, since a VANET application can suggest changes to the driving behavior to achieve improved traffic conditions. Likewise, the mobility block determines the performance of the communication system, which depends on the spatial positions of sender and receivers.

The **communication** block models the communication system. Depending on the information obtained from the mobility block, it determines which transmissions triggered by the application block are received at which point in time and by which recipients. Therefore, the communication block can represent various implementations of communication strategies. A strategy is not necessarily restricted to a communication protocol but may likewise reflect the used communication technology or the choice of configuration parameters such as, for example, the transmission power. The decision about received information and the respective point in time is then returned to the application block for evaluation.

To consider every modeling detail at the same time is not manageable. But is it required? Regarding the aforementioned use case on overtaking maneuvers, precise information on the geographical position of vehicles may turn out to be decisive. However, when VANETs are used to provide information on current traveling times, a deviation of a few meters probably does not cause notable changes to the evaluation in the end. In this sense, the separation of building blocks is sensible, since each building block can be individually adapted to the needs of the evaluation, despite the revealed dependencies among the building blocks. Nevertheless, the key problem remains and demands an appropriate tailoring of one (or more) blocks to the envisaged application domain. Essentially, we need to find a level of detail in each respective building block that meets the requirements of the aimed evaluation study. If such a level is identified, we can build models which, incorporated into simulation tools, allow for an approach to the motivating questions posed at the end of Section 1.1.2 by simulation means.

1.3 Objectives and contributions

The thesis considers the application of VANETs to improve vehicular traffic safety and vehicular traffic efficiency. For each application domain, we pose requirements for the respective building blocks and evaluate the suitability of available models to meet the demands. We develop new models and propose simulation tools that facilitate an assessment of *the impact of inter-vehicle communication on vehicular traffic*. The following Sections 1.3.1 and 1.3.2 provide an overview of the respective contributions.

1.3.1 Vehicular traffic safety

The potential benefit of VANETs on vehicular traffic safety is reflected in a reduced number of traffic accidents. An accident itself, however, is a very rare incident, only occurring if a very specific constellation of events comes together at the same time. In Germany, for instance, an accident involving injuries only happened every 2 000 000 driven kilometers in 2007 [BfS08]. Hence, a replication of an accident situation, and thus an evaluation of the potential benefits of VANETs, requires a detailed representation of the influencing factors. For the identified building blocks, we thus infer the following requirements.

1. Communication
   If additional knowledge of the traffic situation has the potential to prevent accidents from happening then it is imperative to know at which point in time the information became available for which traffic participant. We thus require a detailed modeling of the communication network that provides precise information on packet receptions and packet reception times. These requirements are already met by available simulation models for the network simulator NS-2 [CSEJ+07].

2. Application
   Assuming the communication system was capable of providing every vehicle with all available information, the true potential of VANETs on traffic safety could only be explored if we knew how to best use the information. The thesis provides an analytical investigation of optimal driving decisions and concludes with the need to fall back on relaxations to the problem due to reasons of complexity. The nature of relaxations and the possibility of associated malfunctioning makes an assessment indispensable in the end.

The thesis therefore aims at evaluating safety applications regarding their ability of estimating the probability of ensuing accidents through simulation means.

3. Mobility
   Available simulation models on vehicular traffic have proven their capabilities of replicating the movement behavior of vehicles. However, the rare incident of an accident is typically not considered in the simulators and thus leaves a significant gap for the goals of the vehicular traffic safety studies. This thesis therefore suggests an extended mobility model that allows for the introduction of the imperfection of human beings, thereby provoking traffic accidents.

The thesis concludes the discussion on vehicular traffic safety with a simulation tool, having incorporated the results of the respective building blocks. In a simulation experiment, the impact of inter-vehicle communication is demonstrated with the crucial example of careless overtakings and the ensuing avoidance of accidents, depending on the degree of information received by the endangered car/driver system.

1.3.2 Vehicular traffic efficiency

As indicated by Kawashima in 1973 [Kaw90], a communication network that incorporates vehicles and road-side infrastructure can create an effective tool for a centralized traffic control center to take influence on the traffic performance. Compared to traffic safety studies, the evaluation unit thereby scales up to traffic flows and their performance in the network. Since traffic flows comprise a multitude of vehicles, the overall behavior of which is assessed, individual inaccuracies are accepted if the parameters describing the behavior of the traffic flow prove statistical significance. A key requirement to the building blocks therefore becomes scalability and, from the perspective of a traffic control center, 'in time' evaluation results.

1. Application
   Optimizing traffic flows in a large-scale network poses a hard problem to a traffic control center. However, the aspect of locality may likewise be considered if VANETs are used to solve encapsulated optimization problems independently from the entire street network. An example is given by the application of speed advices which are intended to adapt the speed of a traffic flow to the capacity of a road. Such a measure can be applied locally without affecting the complexity of the remaining street network. The thesis will deal with these local problems and therefore does not struggle with scalability problems in the application block.

2. Mobility
   Available mobility models distinguish in their capabilities between to the

considered level of details on the one hand, and the accompanying scalability on the other hand. However, even the detailed mobility models that we have considered for traffic safety studies are able to simulate a couple of thousand vehicles under real-time conditions. Hence, we will also make use of them to study the envisaged applications on vehicular traffic efficiency.

3. Communication
   Available simulation models, which precisely replicate the performance of the communication system, require a computational effort that violates real-time constraints already at a small-scale of communicating nodes. 'Real-time' in this sense, refers to the equality of simulated scenario time and the necessarily required computation time. However, possible accelerations of the computation time gained through a neglect of communication details cause false provisions of information among the vehicles and thus distort the outcome of the evaluation study. The thesis therefore suggests a hybrid simulation approach, which interlinks a detailed simulation of the application and mobility blocks with a mathematical (and thus computationally efficient) representation of the communication block. The key requirement, an accurate mathematical representation of the communication system, has not been proposed so far and is therefore developed in this thesis.

As a result of the discussion, the thesis proposes a hybrid simulation tool. In concluding simulation studies, the tool proves its suitability to assess the application of VANETs for an improved vehicular traffic efficiency.

The contributions of this thesis have been previously published in:

- M. Torrent-Moreno, M. Killat, H. Hartenstein: *The Challenges of Robust Inter-Vehicle Communications*, in Proceedings of the 62nd IEEE Semiannual Vehicular Technology Conference (VTC-Fall), pp. 319-323, Dallas, USA, 2005 ([TMKH05])

- M. Killat, H. Hartenstein, K.-H. Waldmann: *Communication and Control: Joint Treatment of Application-Specific Behaviour and Communication Constraints in VANETs*, in 'Information management and market engineering', Universitätsverlag Karlsruhe, pp. 125-138, 2006 ([KHW06])

- M. Killat, F. Schmidt-Eisenlohr, G. Göbel, T. Kosch, H. Hartenstein: *On the accuracy of coupling a mobility and a communication simulator for VANETs*, in Proceedings of the 4th International Workshop on Intelligent Transportation (WIT), pp. 137-142, Hamburg, Germany, 2007 ([KSEG+07])

- M. Killat, H. Hartenstein: *Vehicular Ad Hoc Networks: How to Show the Impact on Traffic Safety?*, in Proceedings of the 65th IEEE Semiannual Vehicular Technology Conference (VTC-Spring), pp. 659-663, Dublin, Ireland, 2007 ([KH07])

- M. Killat, F. Schmidt-Eisenlohr, H. Hartenstein, C. Rössel, P. Vortisch, S. Assenmacher, F. Busch: *Enabling efficient and accurate large-scale simulations of VANETs for vehicular traffic management*, in Proceedings of the fourth ACM International Workshop on Vehicular Ad Hoc Networks (VANET), pp. 29-38, Montreal, Canada, 2007 ([KSEH$^+$07])
- F. Schmidt-Eisenlohr, M. Killat: *Vehicle-to-Vehicle Communications: Reception and Interference of Safety-Critical Messages*, in IT – Information Technology, volume 50, number 4, pp. 230-236, 2008 ([SEK08])
- M. Killat, T. Gaugel, H. Hartenstein: *Enabling Traffic Safety Assessment of VANETs by Means of Accident Simulations*, in Proceedings of the 19th IEEE Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Cannes, France, 2008 ([KGH08])
- J. Mittag, F. Schmidt-Eisenlohr, M. Killat, J. Härri, H. Hartenstein: *Analysis and Design of Effective and Low-Overhead Transmission Power Control for VANETs*, in Proceedings of the fifth ACM International Workshop on Vehicular Ad Hoc Networks (VANET), pp. 39-48, San Francisco, USA, 2008 ([MSEK$^+$08])
- M. Killat, H. Hartenstein: *An Empirical Model for Probability of Packet Reception in Vehicular Ad Hoc Networks*, in EURASIP Journal on Wireless Communications and Networking, Volume 2009, Article ID 721301, 12 pages, 2009 ([KH09])

1.4 Overview of the thesis

This thesis is devoted to the problem of vehicular traffic safety addressed in Part I and of vehicular traffic efficiency discussed in Part II.

Part I: Vehicular Traffic Safety

Chapter 2 provides a more detailed introduction to vehicular traffic safety.

Chapter 3 addresses the application building block and studies a problem underlying many safety applications by analytical means.

Chapter 4 provides an overview of available models to be used for the communication and for the mobility building block.

Chapter 5 firstly closes the identified gap of missing accidents in the models discussed for the mobility block. Subsequently, a simulation tool is presented that allows for traffic safety studies. In a concluding simulation experiment, the chapter assesses the performance of a basic traffic safety application in the domain of traffic accidents when a varying amount of knowledge about the traffic situation is provided.

Chapter 6 finally concludes the first part and summarizes the proposed contributions.

Figure 1.3 visualizes the building blocks to be discussed in Part I of this thesis colored in black.

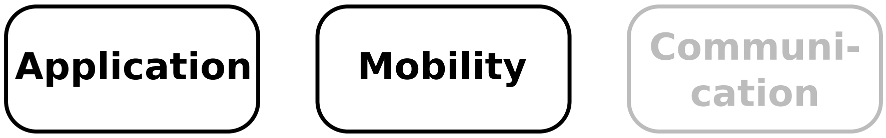


Figure 1.3: Black-colored building blocks are discussed in Part I.

Part II: Vehicular Traffic Efficiency

Chapter 7 introduces the problem of analyzing the impact of VANETs on vehicular traffic efficiency and reveals scalability concerns for the Communication building block.

Chapter 8 surveys the literature for simulation tools designed to account for a large number of communicating nodes. Additionally, this chapter provides an overview of available analytical models on wireless communication networks according to the IEEE 802.11 standard.

Chapter 9 presents and evaluates an empirical model that provides the probability of packet reception over distance based on changing parameters of the scenario layout.

Chapter 10 then incorporates the developed model into a hybrid simulation architecture and conducts simulation studies assessing the influence of VANETs on vehicular traffic efficiency.

Chapter 11 recapitulates the discussion and highlights the presented contributions.

Figure 1.4 visualizes the building blocks to be discussed in Part II of this thesis colored in black.

Figure 1.4: Black-colored building blocks are discussed in Part II.

Finally Chapter 12 summarizes the addressed problems and the proposed contributions and reports on the conclusions that can be derived from this thesis' results. The thesis concludes with an outlook on further perspectives on modeling and simulating the system of 'inter-vehicle communication'.

Part I

Impact on Vehicular Traffic Safety

2
Introduction

2.1 European perspective on road traffic safety

In 2001 the European Commission published a White paper on the 'European transport policy for 2010' [Eur01]. A major concern in this publication addresses the annual number of vehicular accidents and in particular fatalities. A package of measures has been proposed which shall decrease the number of fatalities yearly by 7.4 % thus attaining a reduction of 50 % in 2010 compared to the 53 909 fatalities in the reference year 2001. The package of measures covers a broad spectrum from a harmonization of penalties in the member states to a tightened legislation of the working conditions of commercial drivers. An important contribution to the reduction of fatalities is expected by the technological progress. Since 57 % of fatal accident victims are car occupants, the European Commission fosters the development of safety-related capabilities of vehicles [Com]. For this purpose, the Commission and the motor vehicle industry launched the *eSafety* initiative in 2002 which has the aim to accelerate the development and deployment of 'Intelligent Vehicle Safety' systems. In parallel, further research support has been initiated by the European Commission firstly in the scope of the Sixth and later continued in the Seventh Research Framework Progam (FP7) and is expected to bring forward activities in the field of road safety.

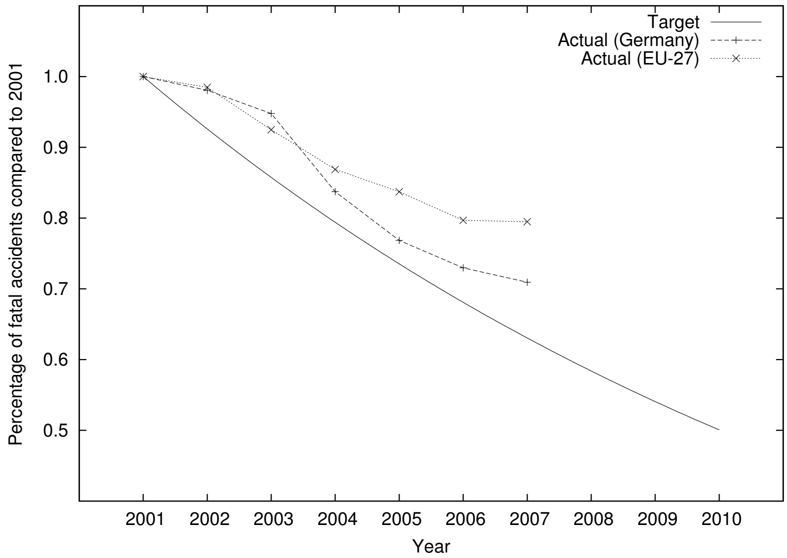


Figure 2.1: Normalized number of traffic accidents involving fatalities based on the reference year 2001. Currently the European member states (Germany chosen as selected example) miss the targeted goal proposed by the European Commission (source: [Com08]).

2.2 The role of vehicular ad hoc networks

However, without new technological achievements the adherence to the reduction plan from 2001 is put into doubts. This statement is based on the fatality statistics of the European Union which is partly illustrated in Figure 2.1. Obviously, a continuously decreasing number of fatalities can be observed in the European Union and, as a case study, in Germany from 2001 to 2007 but, likewise, the progress reveals exceedance of the targeted goal throughout the years. A supposed continuation of the numbers does not suggest that the fatalities will be halved in 2010 unless a 'breakthrough impact' would be experienced. VANETs are expected to contribute to such an impact. The possibility to provide an additional source of information to the driver is supposed to lead to a more attentive driving behavior and to less severe accidents. In fact, according to the records of the German police in 2007, 87 % of the accidents with injuries happened because of a misbehaving driver. Approximately 20 % of the accidents are due to a wrong driver behavior in overtaking, turning, etc. situations [Bun08] in which additional information on the traffic situation, provided via a VANET, could potentially prevent an accident from actually happening. According to the same statistics, 8.3 % of all accidents with injuries happened because of weather conditions, slippery roads or animals on the road; on detection, such information can be conveyed via a VANET to approaching vehicles.

2.2.1 Expectations on vehicular ad hoc networks

The two presented sample statistics cover the major goals of VANETs regarding traffic safety as they are pursued from today's perspective:

(a) to alert vehicles in the surroundings whenever hazardous situations have been detected and

(b) to increase each vehicle's awareness of surrounding vehicles in order to prevent dangerous situations to occur.

In this part of the thesis we put our focus on the latter mentioned goal and investigate the impact of an increased awareness of the traffic situation on road traffic safety.

2.3 Assessing the impact of an increased awareness

In the scope of this work, awareness is related to the amount of information which a driver obtains on traffic participants in her or his surroundings. Knowledge on their presence including their geographical position, speed, etc. is meant to be evaluated by a supporting system and presented to the driver in order to aid a correct perception of the traffic situation. An evaluation of the supposed beneficial impact on road traffic safety then requires a three step process answering the following questions:

(a) Which information is provided?

(b) Which actions are taken based on the provided information?

(c) How do taken actions affect road traffic safety?

Following the modeling of essential building blocks introduced in Chapter 1, a discussion of the raised questions takes place in (a) the communication, (b) the application and (c) the mobility block (according to the numbering of the questions).

Our discussion firstly aims at revealing the potential of vehicular ad hoc networks, specifically, the potential of an increased awareness provided via VANETs on traffic safety. This focus requires an optimal behavior of the building block application, at best provided with all required information from the communication block and the resulting impact reflected in the domain of the mobility block. In detail, we proceed in the building blocks as follows.

Communication
Since the set of 'all required information' needed by the application block depends on the implemented application itself, we consider an ideal communication system providing an upper bound of information on vehicles in the surroundings.

The communication block thus provides an immediate delivery of each transmitted message at each intended recipient.

Application

Based on the provided information set, we analytically define the problem of distinguishing a safe from a dangerous traffic situation. From the presented definition we can then infer that an optimal solution to the problem suffers from the underlying complexity. Consequently, the building block needs to be treated by means of approximations which, as a matter of fact, address relaxations of the actual problem.

This result will change the orientation of the traffic safety discussion: instead of investigating the potential of the system, we turn towards an impact assessment of safety applications by simulation means. As a paradigm for safety critical situations, in which VANETs could play an important role, we have selected overtaking maneuvers on motorways. Based on the information gained from other vehicles in the neighborhood in terms of location we consider a simple heuristic algorithm which will already reveal the full potential of accident avoidance by inter-vehicle communications.

As a consequence thereof, we need to digress from afore taken assumption of an ideal communication system which is required to study the potential of VANETs on traffic safety. Instead, we assess the performance of the safety application under varying conditions represented in the communication block covering the full range from ideal conditions to no receptions at all.

Mobility

The mobility block takes two roles in the considered evaluation study: (a) it determines the shape of the vehicular network and thereby provides essential input data (i.e. positions of the communicating nodes) to the communication block. (b) It provides a metric in terms of numbers of accidents which allows to eventually assess the success of a safety application. The thesis surveys available mobility models and identifies the difficulty of non-existing traffic accidents. Therefore, we propose a mobility model which includes the occurrence of accidents happening in the particular situation of overtaking maneuvers.

Based on the results of the discussion in the respective building blocks, in this part of the thesis a simulation tool is developed which allows to assess safety applications based on inter-vehicle communication on road traffic safety. In a concluding simulation study we demonstrate the suitability of the simulation tool and study the performance of a safety application designed to prevent accidents in overtaking maneuvers.

2.4 Structure of Part I of this thesis

The discussion of the previous section is reflected in the remainder of this part of the thesis as follows.

In **Chapter 3** we address an optimal behavior in the application block by looking at a decision control problem tailored to road traffic safety: having information on a vehicle's surrounding we rank traffic situations by means of the expected elapsing time until an accident will occur. The optimal application would then suppress driving actions which lead into assumed dangerous traffic situations. As mentioned before, the results of the discussion will show that a solution to the problem cannot be determined due to complexity reasons. Hence, we turn towards an assessment of safety application by simulation means.

Chapter 4 therefore surveys the literature and discusses previous modeling attempts on the communication and on the mobility building block. We come to the conclusion that an appropriate modeling of the communication system already exists but the state of the art of vehicular mobility representing is not adequate when traffic safety studies are concerned.

Hence, the thesis firstly proposes in **Chapter 5** an improved mobility modeling for specific traffic situations, then incorporates the presented model into a simulation framework and concludes with a simulation study, which evaluates the performance of a basic safety application.

Finally, **Chapter 6** summarizes the presented discussion and achievements and points to some open issues.

3
Formal View to a Decision Control Problem

In this chapter we deal with the building block application which is responsible for the evaluation of available information and for potential suggestions how to react in order to increase traffic safety. Essentially, we are looking for an answer to the motivating question of this chapter: *If we assume an ideal communication system in which every transmitted message is received at all intended recipients, how much impact on traffic safety could actually be attained?* In other words, we ask for the true potential of the inter-vehicle communication system. The sole availability of additional information (provided via VANETs), however, does not increase traffic safety; therefore, one needs to know which usage of information actually improves traffic safety. The question for the potential of the system then requires knowledge on an *optimal* usage, i.e. it demands an optimal traffic safety application. In this thesis, we consider an optimal traffic safety application according to the following definition.

Definition 3.1. *Optimal traffic safety application*
An optimal traffic safety application corrects the driving behavior if and only if the current driving behavior leads into a dangerous traffic situation.

The definition allows to draw the implicit conclusion that the application keeps silent whenever the current driving behavior does not lead into a dangerous traffic situation. Fuzzy, in this sense, remains the understanding of a *dangerous* traffic situation. In the scope of this thesis, we conceive 'dangerous' in the sense of 'accident has happened' which is truly the extreme.

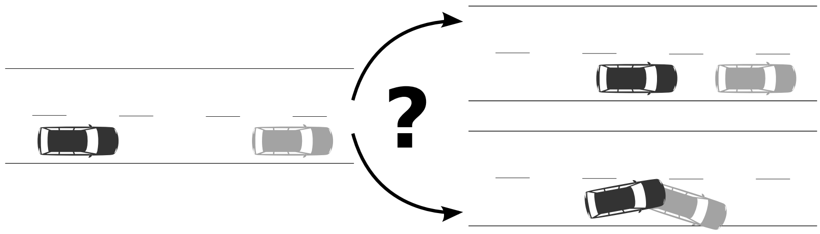


Figure 3.1: Is the left shown traffic situation safe or dangerous? If it leads to the bottom right situation it should be conceived dangerous. For the upper left situation, the considered time horizon does not allow to issue a judgment.

An optimal traffic safety application would not only allow to assess the impact of inter-vehicle communication on traffic safety but also contributes to the design process of the underlying communication system. Answers to open issues like the required quality of the communication system may be found by comparison of a decreasing communication quality with a simultaneously increasing number of accidents. Developers of the communication system would thus be informed whether additional effort to improve conditions is at all of use.

3.1 How to assess a traffic situation?

3.1.1 Traffic situations and their evolvement

In principle, the purpose of traffic safety applications is to avoid dangerous traffic situations actually to happen or, if this is not possible anymore, to alleviate their consequences. As a fundamental requirement such applications depend on a measure which ranks traffic situations in some scale from dangerous to safe. *How does such a measure look like?* Given a photo snapshot of a traffic situation we can infer its dangerousness if it shows an accident. For all of the remaining situations, however, an assessment is not obvious. The traffic situation illustrated on the left in Figure 3.1, for instance, does not appear dangerous at first sight, but we cannot rule out that it could turn into a dangerous situation in the very next moment. In fact, if the traffic situation evolves to the bottom right situation, we would certainly assess the situation to be dangerous; on the other hand, with an upcoming situation like shown on the upper left we still cannot make a final assessment but know that an accident will not occur in the very next moment. An assessment of a situation is obviously closely related to the evolvement of traffic or, to be more precise, to its *expected* evolvement. 'Evolvement' thereby refers to a sequence of successive traffic situations over a considered time scale and horizon.

What is a traffic situation? Regarding Figure 3.1, we intuitively distinguish the three traffic situations because of the varying geographical position of the vehicles. However, many additional information is not illustrated which, if considered, would offer more possibilities to separate one situation from the other.

The amount of details considered in the definition of a traffic situation also effects aforementioned expected evolvement. Assume the black vehicle in Figure 3.1, for instance, to be significantly slower than the gray colored vehicle, then a definition of traffic situations considering the speed of vehicles would not suggest an expected evolvement as illustrated on the right. Without considering the factor speed in the definition of system states, however, the expected evolvement needs to take account of situations in which the black vehicle is notably faster than the gray car. A lack of details obviously causes an increasing variance in the expected evolvement and thus complicates an assessment of traffic situations at the end. Too many considered details, on the other side, lead to numerous traffic situations which can hardly be managed anymore. Apparently, the definition of a traffic situation is subject to a tradeoff problem.

3.1.2 Valuation of system states

Nevertheless, with a chosen definition of traffic situations and their expected evolvement, the elapsing time until an accident is expected to happen may serve as a measure to provide a ranking on the system states. Such a valuation of system states can be computed by means of a Markov Decision Process as been demonstrated by Dolgov and Laberteaux [DL05], for instance. They mapped traffic situations and their evolvement to system states and state transition probabilities, the two fundamental ingredients of a Markov Decision Process. Their definition of a system state has been based on the (discretized) geographical position of vehicles those number has been upper bounded by three. The transitions among system states have been derived from the modeled mobility of vehicles which, according to the speed of vehicles, steadily moves the cars an appropriate number of discretized spatial units ahead. Dolgov and Laberteaux also assumed a discretization in time and thus updated the position of vehicles in fixed intervals. The computation of the expected time to collision for each system state and the thereby gained valuation of system states, finally, led to a control strategy aiming at avoiding collisions among the vehicles. In a concluding simulation experiment, a decreasing number of accidents when the gained strategy is applied has demonstrated the feasibility of the approach in principle.

3.1.3 Overview of this chapter

This thesis will adapt Dolgov and Laberteaux's proposal. We firstly introduce the fundamentals of a Markov Decision Process and then extend their suggested modeling. We introduce a modeling considering absorbing system states which enables a more accurate specification of the decision problem of safe or dangerous traffic situations, respectively. We then exemplify the application of a Markov Decision Process with absorbing system states in a toy example. Subsequently, we transfer the successfully demonstrated concept to a vehicular environment: we contribute an advanced modeling of system states and transition probabilities and derive a valuation for some system states. This chapter then concludes by pointing to arising difficulties which demand the application of simulation tools.

3.2 Markov Decision Process

3.2.1 Fundamentals of MDPs

For the considered problem of distinguishing safe from dangerous traffic situations we assume a relaxation of the general definition of a Markov Decision Process (MDP)[1]. We conceive an MDP to be a time-discrete stochastic process, denoted $(X_n)_{n\in\mathbb{N}}$, on a finite set of system states and a finite set of actions. Formally speaking, an MDP is represented by the tuple $M = (S, A, p, r, \alpha)$ with the following meaning.

1. S, a finite set of system states.
2. A, a finite set of actions.
3. p, a transition law from (S, A, S) to $[0 \ldots 1]$. Depending on the chosen action a the transition law gives the probability $p_{s,s'}(a)$ to move from the present system state s to the next system state s'. For each action a, the transition law is a probability distribution and thus fulfills the conditions $p_{s,s'}(a) \geqslant 0$ and $\sum_{s'\in S} p_{s,s'}(a) = 1,\ \forall s \in S$.
4. r, a positive bounded reward function from (S, A) to $\mathbb{R}^+$, where $\mathbb{R}^+$ includes all positive real numbers and 0.
5. $\alpha \in \mathbb{R}$, a discount factor with $0 < \alpha \leqslant 1$.

Figure 3.2 illustrates a transition step of an MDP: the stochastic process is at time stage n in system state s, $X_n = s$, chooses an action a and moves with probability $p_{s,s'}(a)$ to system state s' in the next time period. As a result of having chosen action a in system state s the process receives a reward $r(s, a)$. If neither a reward function nor an action set is considered, i.e. the transition law is independent from the action set, the MDP is denoted a *Markov Chain*. The Markovian property is due to the fact that the probability of going from system state s_n to system state s_{n+1} within one time step is independent from previous visited system states, i.e.

$$\Pr\left(X_{n+1} = s_{n+1} \mid X_0 = s_0,\ X_1 = s_1, \ldots,\ X_n = s_n\right) = \Pr\left(X_{n+1} = s_{n+1} \mid X_n = s_n\right).$$

A **policy** is a function $\pi : S \to A$ from the set of system states to the set of actions which represents a strategy selecting action $\pi(s)$ whenever system state s is encountered[2]. Differing policies let the stochastic process X_n accumulate differing rewards in the transition steps due to the dependency of the reward function

[1] A general and comprehensive introduction to MDPs is exemplarily given in [Put05].

[2] The standard literature on MDPs calls this a *stationary* policy.

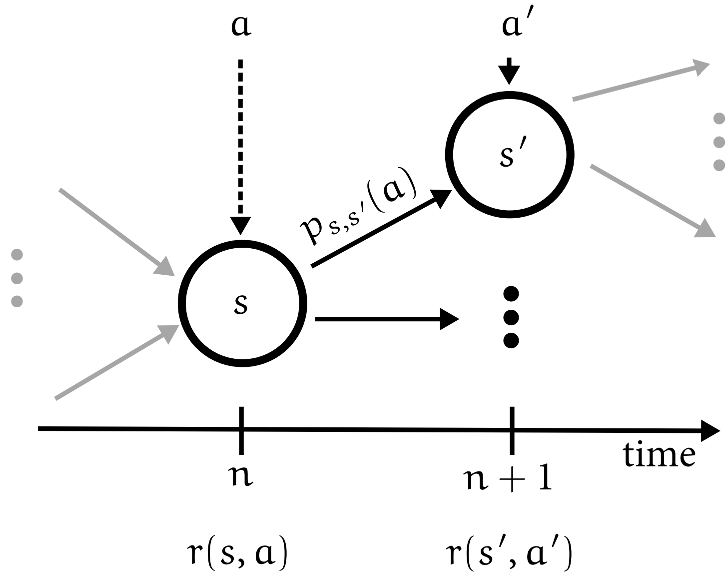


Figure 3.2: Illustration of a transition step of an MDP

and of the transition law on the selected action. The reward function thus serves as an instrument to evaluate policies at the end. The literature on MDPs discusses differing optimality criteria to compare policies such as an optimization of the average received reward per transition step or an optimization of the total reward collected after n transition steps, for instance. This thesis will interpret a reward unit as a time unit which at least elapses before an accident is expected to happen. Hence, our aim is to maximize the total reward, i.e. to prolong the occurrence of an accident as long as possible.

We assess a chosen policy function π by means of the **total discounted reward criterion**. The criterion considers an infinite number of transition steps and accumulates the successively received rewards discounted by the factor α, i.e. $\sum_{n=0}^{\infty} \alpha^n r\left(s_n, \pi(s_n)\right)$. From a mathematical perspective, a discount factor $\alpha < 1$ is generally required to guarantee convergence of the infinite sum[3]. Let $E_\pi\left(\sum_{n=0}^{\infty} \alpha^n r\left(X_n, \pi(X_n)\right)\right)$ denote the expected total discounted reward which considers all possible realizations of the stochastic process X_n when the policy function π is applied. Then the **value of a system state** s based on the policy π is given by

$$V_\pi(s) = E_\pi\left(\sum_{n=0}^{\infty} \alpha^n r(X_n, \pi(X_n)) \mid X_0 = s\right) \tag{3.1}$$

with s being the initial system state visited by the process at time stage 0. Moreover, the computation of Equation 3.1 for all initial system states $s \in S$ provides a ranking on S based on the applied policy π.

[3]The discussion in Section 3.2.3 will deal with a special case for which $\alpha = 1$ is possible.

The value of a system state s is given by the instantaneous reward received for selecting action $\pi(s)$ in the current system state s and by the discounted value of future taken system states. We present this relationship by the following conversion of Equation 3.1

$$\begin{aligned}
V_\pi(s) &= E_\pi\left(\sum_{n=0}^{\infty}\alpha^n r(X_n,\pi(X_n)) \mid X_0 = s\right) \\
&= r(s,\pi(s)) + \sum_{s'\in S} p_{s,s'}(\pi(s))E_\pi\left(\sum_{n=1}^{\infty}\alpha^n r(X_n,\pi(X_n)) \mid X_1 = s'\right) \\
&= r(s,\pi(s)) + \sum_{s'\in S} p_{s,s'}(\pi(s))\alpha\, \underbrace{E_\pi\left(\sum_{n=0}^{\infty}\alpha^n r(X_n,\pi(X_n)) \mid X_0 = s'\right)}_{V_\pi(s')} \\
&= r(s,\pi(s)) + \alpha\sum_{s'\in S} p_{s,s'}(\pi(s))V_\pi(s') \qquad (3.2)
\end{aligned}$$

which results in Equation 3.2 known as *Bellman's equation*.

As aforementioned, we interpret a received reward as a time unit which at least elapses before an accident is expected to happen. Therefore, our focus is on a maximization of each system state's value. In this sense, we consider π^* to be an **optimal policy** function if and only if for any arbitrary policy function π, $V_\pi(s) \leqslant V_{\pi^*}(s), \forall\, s \in S$ holds. Hence, regarding Bellman's equation (cf. Equation 3.2) we conclude that if π^* is an optimal policy then there is no other policy π which assigns actions to system states yielding a greater value of system states than π^*, i.e. for all system states s

$$V_{\pi^*}(s) = \max_{a\in A}\left\{ r(s,a) + \alpha\sum_{s'\in S} p_{s,s'}(a)V_{\pi^*}(s')\right\} \qquad (3.3)$$

holds. We conclude with the coherence of optimal policy π^* and optimal valuation of system states V_{π^*}. Given the optimal policy π^* we can derive the optimal valuation V_{π^*} by solving the system of linear equations

$$V(s) = r(s,\pi^*(s)) + \alpha\sum_{s'\in S} p_{s,s'}(\pi^*(s))V(s') \qquad (3.4)$$

and given the optimal valuation of system states V_{π^*} we obtain the optimal policy by the argument solution to

$$\pi^*(s) = \arg\max_{a\in A}\left\{ r(s,a) + \alpha\sum_{s'\in S} p_{s,s'}(a)V_{\pi^*}(s')\right\} \qquad (3.5)$$

for all system states $s \in S$. If either the valuation or the policy is known, the respective other can easily be derived.

3.2.2 Convergence and complexity

Linear programming, policy iteration and value iteration are all well-known procedures to solve Equation 3.3, respectively. We focus on the **value iteration** algorithm, its convergence and complexity.

Convergence

In accordance with the provided definition of an MDP, the reward function is bounded and real positive. Thus, there exists a maximum reward $0 \leqslant \hat{R} < \infty$ which is given by

$$\hat{R} = \max_{s \in S, a \in A} r(s, a).$$

Knowing $\hat{R}$ we can specify and upper bound on the total discounted reward which could potentially be received by a stochastic process. This upper bound would theoretically be obtained if the maximum reward $\hat{R}$ was received in every transition step. Thereby, we also obtain an upper bound on the valuation of a system state s, $\hat{V}(s)$, given by

$$\begin{aligned} \hat{V}(s) &= \sum_{t=0}^{\infty} \alpha^t \hat{R} \\ &\overset{\substack{\text{geometric} \\ \text{series}}}{=} \frac{1}{1-\alpha} \hat{R}. \end{aligned} \tag{3.6}$$

We introduce the two **update operators** $U_\pi, U : \mathbb{R}^+ \to \mathbb{R}^+$. Given a (preliminary) valuation of system states $V(s),\ s \in S$ which not necessarily agrees with the optimal valuation $V_{\pi^*}(s)$ corresponding to the optimal policy π^*. For each system state $s \in S$, both operators compute $V'(s)$ according to Equations 3.2 or 3.3, respectively, i.e. for all system states $s \in S$, $V'(s)$ is computed by

$$U_\pi : \qquad V'(s) \leftarrow r(s, \pi(s)) + \alpha \sum_{s' \in S} p_{s,s'}(\pi(s)) V_\pi(s')$$

or

$$U : \qquad V'(s) \leftarrow \max_{a \in A} \left\{ r(s, a) + \alpha \sum_{s' \in S} p_{s,s'}(a) V(s') \right\}.$$

Subsequently, after V' has been computed for all system states, both operators update the valuation V, i.e.

$$V(s) \leftarrow V'(s),\ \forall\, s \in S.$$

An iterative application of the operators generates a series of valuations $V^{(n)}(s)$. In the following we show that the operators are *contractive*, i.e. for $n \to \infty$ the series $V^{(n)}(s)$ converges to a unique fixpoint.

Lemma 3.1. *For each two valuations* $V^{(n)}$ *and* $V^{(n+1)}$ *successively gained by applying operator* U*, it holds that*

$$U\, V^{(n+1)}(s) - U\, V^{(n)}(s) \leqslant \alpha \max_{s' \in S} \left\{ V^{(n+1)}(s') - V^{(n)}(s') \right\}.$$

Proof. *See Appendix A.*

From Lemma 3.1 it follows that the operator $\mathfrak{U}$ narrows the maximal divergence between successive valuations of system states. Hence, we can apply the contraction mapping theorem which says that there is a unique fixpoint u^* to which the operator $\mathfrak{U}$ converges. Lemma 3.2 additionally shows that the fixpoint u^* coincides with the system states valuation V_{π^*} corresponding to the optimal policy π^*.

Lemma 3.2. *The series of successive valuations* $\left(V^{(n)}\right)_{n\in\mathbb{N}}$ *gained by iteratively applying operator* $\mathfrak{U}$ *to an initial valuation* $V^{(0)}(s) = 0,\ \forall\ s \in S$ *converges to the system state valuation* V_{π^*} *corresponding to the optimal policy function* π^*.

Proof. *See Appendix A.*

The aforementioned value iteration algorithm is based on Lemma 3.1 and 3.2. Starting with an initial guess $V_0(s) = 0,\ \forall\, s \in S$ the algorithm iteratively generates updated system states valuations and terminates when the maximum deviation of two successively computed valuations falls below a preconfigured threshold. Algorithm 1 summarizes the procedure.

Complexity

Next, we discuss the computational complexity required to achieve convergence in the subsequent application of $\mathfrak{U}$. In each application step, $\mathfrak{U}$ compares the instantaneous reward received if an action is taken plus what is then expected to be obtained in future system states. Since this greedy procedure is carried out for all actions and all system states the resulting complexity is of order of $\mathcal{O}\left(|S|^2|A|\right)$[4]. Consequently, determining V_{π^*} via a subsequent application of operator $\mathfrak{U}$ is only obtained in polynomial time if and only if operator $\mathfrak{U}$ provides a contraction which lets the divergence of successive valuations $V^{(n)}$ and $V^{(n+1)}$ fall below a given threshold, denoted $\epsilon > 0$, i.e. $\max_{s\in S}\left\{V^{(n+1)}(s) - V^{(n)}(s)\right\} \leqslant \epsilon$, in polynomial time. However, by today, no algorithm is known which guarantees polynomial convergence depending on $|S|$ and $|A|$ only, which would be called a *strong polynomial* algorithm. Yet, value iteration is known to stop in *pseudo-polynomial* time according to the following considerations [LDK95].

We consider the worst case for which the maximum divergence between initial guess $V^{(0)}$ and the first application of $\mathfrak{U}$, i.e. $\mathfrak{U}\,V^{(0)}$ can be upper bounded by the maximum valuation $\hat{V}$ given in Equation 3.6, i.e.

$$\mathfrak{U}\,V^{(0)}(s) - V^{(0)}(s) \leqslant \frac{1}{1-\alpha}\hat{R}.$$

According to Lemma 3.1 another application of $\mathfrak{U}$ to $\mathfrak{U}\,V^{(0)} = V^{(1)}$ lets the maximum divergence between $V^{(1)}$ and $\mathfrak{U}\,V^{(1)} = V^{(2)}$ shrinking by at least a factor α.

$$\mathfrak{U}\,V^{(1)}(s) - \mathfrak{U}\,V^{(0)}(s) \leqslant \frac{\alpha}{1-\alpha}\hat{R}$$

[4] $\mathcal{O}$ refers to the O-notation used in the theory of computational complexity.

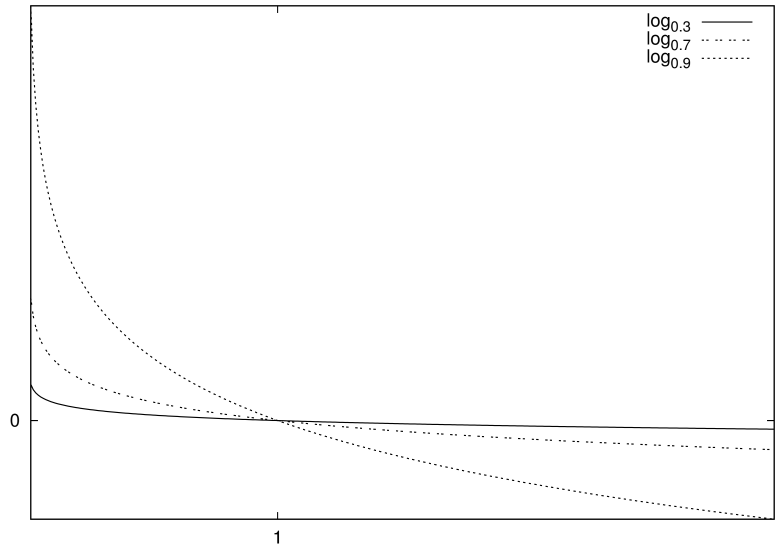


Figure 3.3: Logarithmic functions to selected bases smaller than 1.

After $n+1$ applications of the operator U the divergence of successive valuations can be upper bounded by

$$U\,V^{(n)}(s) - U\,V^{(n-1)}(s) \leqslant \frac{\alpha^n}{1-\alpha}\hat{R}.$$

Hence, an upper bound to the maximum number of required applications of the operator U, denoted $N+1$, can be given by

$$\begin{aligned} \frac{\alpha^N}{1-\alpha}\hat{R} &\leqslant \epsilon \\ N &\leqslant \log_\alpha\left(\frac{(1-\alpha)\epsilon}{\hat{R}}\right) \end{aligned} \tag{3.7}$$

Without loss of generality we assume $\hat{R} > 1$. Equation 3.7 then yields a positive number since the logarithm of a number smaller than 1 to a base smaller than 1 is positive (cf. Figure 3.3).

Now, a *pseudo*-polynomial inspection is considered since we refer to computers by means of which value iteration will be solved. Consequently, and without loss of generality, we assume ϵ and $\hat{R}$ to be representative by an according number of bits, i.e. $\epsilon = 2^{-B_\epsilon}$ and $\hat{R} = 2^{B_{\hat{R}}}$. Hence, we obtain

$$\begin{aligned} N &\leqslant \log_\alpha\left(\frac{(1-\alpha)\epsilon}{\hat{R}}\right) \\ &= \log_\alpha\left(\frac{(1-\alpha)2^{-B_\epsilon}}{2^{B_{\hat{R}}}}\right) \\ &= \log_\alpha\left((1-\alpha)2^{-(B_\epsilon+B_{\hat{R}})}\right) \\ &= \underbrace{\log_\alpha(1-\alpha)}_{>0} - (B_\epsilon + B_{\hat{R}})\underbrace{\log_\alpha(2)}_{<0} \end{aligned}$$

Since both logarithmic terms are constant for given α, the number of iteration steps required before the algorithm stops increases linearly with the number of assumed bits. Consequently, the value iteration algorithm runs with a complexity polynomial in $|S|$, $|A|$ and $|B_\epsilon + B_{\hat{R}}|$.

Algorithm 1 summarizes the value iteration algorithm. An advanced discussion and further properties of the algorithm are given in [Put05].

Algorithm 1 Value iteration

1. Set $n = 0$ and $V^{(0)}(s) = 0$ for all system states $s \in S$.
2. Make an iteration step by updating each state's value based on the most valuable action, yielding $V^{(n+1)}(s)$, $\forall s \in S$.
3. Determine the maximum deviation of $V^{(n+1)}$ to $V^{(n)}$, i.e.
$$\delta_{max} = \max_{s \in S} \left\{ V^{(n+1)}(s) - V^{(n)}(s) \right\}$$
4. If $\delta_{max} \leqslant \epsilon$ holds, then terminate. Otherwise increase n and continue with Step 2.

3.2.3 Absorbing system states

MDPs for which the set of system states presents a particular structure, allows an advanced modeling. We consider a division of the state space $S = S' \cup \{s_0\}$ in which the single system state s_0 is called *absorbing* in the sense that once entered the process will terminate in state s_0. Furthermore, we consider the following Lemma.

Lemma 3.3.
Let P be the transition probability matrix of the transition law. P^n is the n-times ordinary matrix product of P with itself, i.e. $P^n = P^{n-1} \cdot P$. If, for $n < \infty$ being sufficiently large,
$$p^n_{s,s_0} > 0, \textit{ for all system states } s \in S'$$
holds then the process ends up at time τ in system state s_0 with $\tau < \infty$.

Essentially, if Lemma 3.3 is fulfilled then the process will enter system state s_0 after a finite number of transitions independent of the system state taken at time stage 0. This condition allows to set the discount factor $\alpha = 1$ according to the following considerations.

In general, the discount factor α comes with two interpretations: (a) from a mathematical perspective it ensures convergence of the optimality criteria the purpose of which is likewise achieved if Lemma 3.3 is fulfilled; (b) in economics, for instance, the modeled system often requires some discount of the future due to risk of inflation, for instance. However, for many modeling attempts an appropriate design of the discount factor cannot be derived and a modeling of $\alpha < 1$ leads to distorted system values.

In vector notation, let V be the $|S|$-dimensional vector comprising the valuation for each system state. R denotes the $|S|$-dimensional vector containing the maximum reward for each system state according to Equation 3.3. Then, if the discount factor is set to one the value of system states is given by

$$\begin{aligned} V &= R + P \cdot V \\ &= (E - P)^{-1} \cdot R \end{aligned} \tag{3.8}$$

where E denotes the identity matrix. Hence, the answer for a unique solution to a modeling with a discount factor $\alpha = 1$ can be reduced to the existence of the inverse of $(E - P)$. Therefore, we consider the *Neumann series*.

Theorem 3.2. *Neumann series [Put05]*
Let Q *be a* bounded linear transformation[5] *on a* Banach space[5] *V. Further suppose for the* spectral radius[5], λ, *of* Q: $\lambda < 1$. *Then* $(E - Q)^{-1}$ *exists and satisfies*

$$(E - Q)^{-1} = \lim_{N \to \infty} \sum_{n=0}^{N} Q^n$$

Now, in [HW05] (Proposition 2.6) it is shown that if the process enters the absorbing system state in finite time, then the spectral radius of the transition law must be smaller than one. Hence, Lemma 3.3 is fulfilled and Expression 3.8 has a unique solution which then can be computed using value iteration, for instance.

3.3 Proof of concept: a toy example

Before we elaborate how to design a safety application for a vehicular environment, we approach the problem by means of a toy example. We assume a discretization in time and space and consider a square of 5×7 cells. Two players perform simultaneous movements on the cells in horizontal, vertical or diagonal directions. Both players are not allowed to cross borders of the grid, i.e. at the edges of the square the set of actions is constrained. One of the players moves randomly (in the following *player two*) while to the other one a strategy is assigned (*player one*) in order to avoid collisions among the players. We derive such an optimal strategy by modeling the problem by means of a Markov Decision Process. Therefore, we consider the following notation.

1. *Set of system states,* S
   Let $pos_i = (x_i, y_i)$, $i = 1, 2$ denote the cell positions on the grid by player

[5] see *List of Symbols*

one and two, respectively. Each situation on the grid is then captured by a system state $s = (pos_1, pos_2)$. For 35 considered cells, the number of system states thus amounts to $35^2 = 1225$.

Additionally, we introduce an absorbing system state s_0 to which the process moves if an accident has been detected. Once entered, the process will terminate in the absorbing system state since the goal of avoiding an accident actually to happen is then missed.

2. *Set of actions,* A
   The set of actions available to the controlled player one comprises the movement directions to the eight adjacent cells. In case player one resides at the edge or corner of the grid, the action set is accordingly constrained to avoid leaving the square.

3. *Transition law,* P
   Since we assume player one to be controlled by the applied strategy, randomness in the system's transition is only due to the movements of the uncontrolled player two. The actual transitions thus depend on the current cell occupied by player two. We therefore distinguish the following probabilities depending on the position of the uncontrolled player two. For each system state $s \in S$

$$q(s) = \begin{cases} 0.33 & \text{s comprises a corner field in the grid for} \\ & \text{the uncontrolled player two} \\ 0.2 & \text{s comprises an edge field in the grid for} \\ & \text{the uncontrolled player two} \\ 0.125 & \text{otherwise} \end{cases}$$

The transition law lets the process move into the absorbing system state s_0 whenever a collision occurs. We distinguish two possible collisions: (a) both players are in the same cell of the grid and (b) both players exchange their cell positions, i.e. they collide in between. Having determined probability $q(s)$, the transition probability to move from system state s to the adjacent system state s' when player one has chosen action a is then given by

$$p_{s,s'}(a) = \begin{cases} 1, & s = s' = s_0 \\ 1, & s' = s_0, \text{ system state } s \text{ shows both players in the} \\ & \text{same cell} \\ q(s), & s' = s_0, \text{ action } a \text{ leads player one to the cell occu-} \\ & \text{pied by player two in system state } s \\ 0, & s' = s_0, \text{ action } a \text{ does not lead player one to the cell} \\ & \text{occupied by player two in system state } s \\ q(s), & \text{otherwise} \end{cases}$$

4. *Reward function,* $r(s, a)$
   The goal of the process is to maximize the *time to collision* between both players. Hence, we reward each system state which does not show an accident.
   $$r(s, a) = \begin{cases} 0 & s = s_0 \text{ or } s \text{ shows an accident} \\ 1 & \text{otherwise} \end{cases}$$

One can easily see that a collision among the players cannot be ruled out: with player one staying in any corner cell of the square and having player two in the adjacent diagonal cell, all of player one's options are likewise accessible by player two. We conclude that for a sufficient large number of movement steps $n < \infty$ there is a probability greater 0 to observe a collision, i.e. $p^n_{s,s_0} > 0$, $\forall\, s \in S$. Thus, Lemma 3.3 is fulfilled, we can apply the theory of absorbing system states and a discount factor for the MDP is not required.

With this configuration we can now maximize the total discounted reward, i.e. the time to collision, by solving Expression 3.3 (with $\alpha = 1$) via Algorithm 1. Figure 3.4 visualizes the outcome of the computation for system states in which the uncontrolled player resides close to the center of the square at $pos_2 = (3, 3)$. A more valuable system state, w.r.t. the time to collision, is represented by larger bars. Having obtained this ranking of system states, one can immediately deduce an optimal movement strategy for the controlled player. Depending on the position, the controlled player chooses that action which leads him to the most valuable adjacent state. Again, for the second player being close to the center of the grid, Figure 3.5 visualizes the obtained strategy. An arrow from cell c_1 to cell c_2 illustrates the computed movement suggestion when player one stays in cell c_1. A corresponding valuation and derived strategy for the remaining 34 positions of player two have likewise been obtained.

We evaluated the strategy by means of a simulation study. In 1 000 simulation runs each lasting for 1 000 000 movement steps we recorded the observed collisions if both players move randomly on the grid and for the case when player one moves according to the derived strategy. The success of the strategy expresses in a fallen ratio of experienced collisions per movement step from 2.92 % (variance $\sigma^2 = 1.75\text{e-}04$) to 0.025 % ($\sigma^2 = 3.26\text{e-}08$).

3.4 A safety strategy in a vehicular environment

3.4.1 Related work

In Section 3.1.2 we have already outlined the approach by Dolgov and Laberteaux [DL05] which gave rise to the previous discussion on MDPs and the demonstrated feasibility to derive a safety strategy for the toy example. Dolgov and Laberteaux's main contribution, however, is a *factored MDP* modeling in order to cope with the enormous complexity of the problem. Essentially, a factored MDP aims at

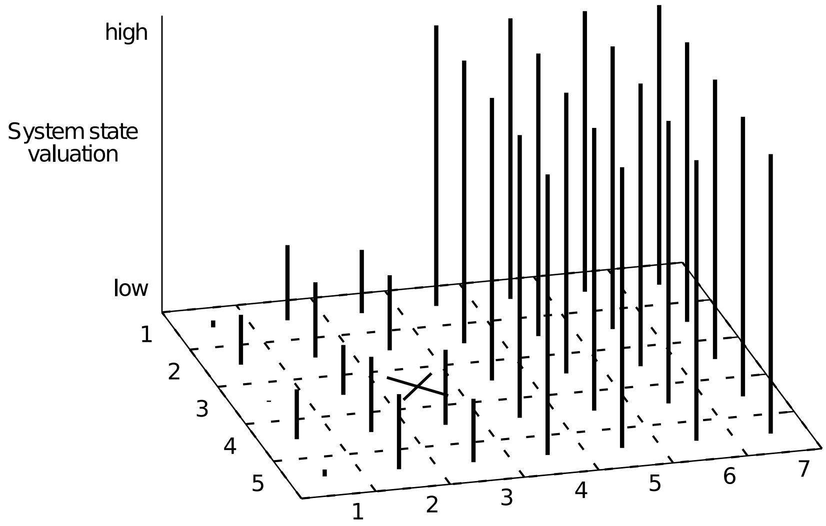


Figure 3.4: Extract of system states' valuation in which the uncontrolled player resides at the cross-labeled cell at $\mathrm{pos}_2 = (3, 3)$. Larger bars represent a safer system state w.r.t. the expected time until a collision occurs.

identifying structures on the state space which then allow for (linear) approximation functions. Thereby, the explicit enumeration of the numerous system states which is typically performed by solving methods can be avoided. Dolgov and Laberteaux suggested to approximate system states given by the exact position of vehicles by means of their distance to a considered reference vehicle. Thereby, the state space is exponentially reduced and a policy could be gained which tendentiously maximizes the distance of surrounding vehicles to the reference vehicle. The policy has shown high-quality results for conducted simulation runs. However, the success of the factored MDP application also results from the assumed highly-structured problem statement. In more realistic traffic scenarios in which each vehicle's motion also depends on surrounding cars the assumed approximation functions might perform less well.

In a former work Geibel describes a system aiming to find a risk-minimal driving policy [Gei01]. Likewise, he used MDPs but with an elaborated formulation containing 'fatal and goal' system states and a discount factor set to one. Following that proposal, the optimal policy would be gained over time by a *reinforcement learning* approach. Reinforcement learning describes methods which let a system learn optimal control decisions over time. Bertsekas and Tsitsiklis synonymously consider reinforcement learning and neuro-dynamic programming methods to allow a system to *learn how to make good decisions by observing their own behavior, and use built-in mechanisms for improving their actions through a reinforcement mechanism* [BT96, Section 1.4]. Geibel used a reinforcement learning mechanism to improve the choice of driving actions which iteratively decrease the risk of entering a fatal system state, i.e. an accident, in the future. He success-

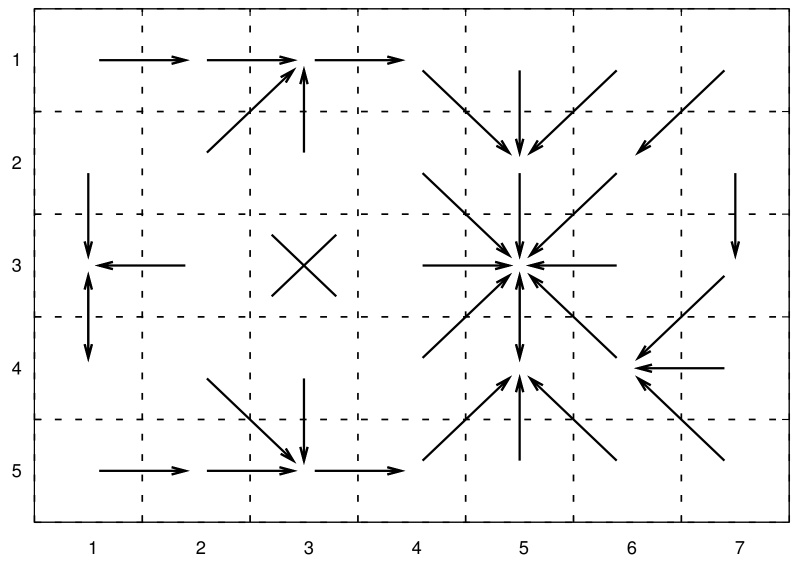


Figure 3.5: Extract of the derived strategy for the controlled player when the second player resides at the cross-labeled cell. An arrow from cell c_1 to cell c_2 illustrates the computed movement suggestion when player one stays in cell c_1.

fully demonstrated the feasibility of the approach by simulation means in principle but likewise pointed to the considered basic scenario setup in his simulation study. Future work is intended to address a more realistic representation of the vehicular traffic system.

In [NS94] Niehaus and Stengel proposed a guidance system without using MDPs. They suggested a stochastic model that uses current measurements in order to predict the worst-case traffic evolvement. On this prediction, actions are suggested by pondering safety vs. the driver's desired behavior. Simulations have shown a proper action selection. Performance measures, particularly on the estimated traffic evolution have not been provided.

Forbes et al. tackled the problem of driving an autonomous vehicle with dynamic probabilistic networks that model their domains as *Partially Observable MDPs (POMDPs)* [FHKR95]. POMDPs take account of decision problems in which the decision maker does not know the current system state with certainty before making a decision. In addition to an MDP model, POMDPs thus consider a probability distribution on the state space representing the assumed system states and a set of observations which allow to update the decision maker's belief of currently supposed states. Lovejoy commented on the difficulty of solving POMDPs: *The major impediment to exact solution is that, even with a finite set of internal system states, the set of possible information states is uncountably infinite. Finite algorithms are theoretically available for exact solution of the finite horizon problem, but these are computationally intractable for even modest-sized problems* [Lov91]. Forbes et al. applied POMDPs to take account for uncertainties resulting from noisy sensors, for instance, which do not allow to exactly determine the position or even presence of neighboring vehicles. They contributed an efficient update procedure on the current belief state and demonstrated the feasibility in five promising simulation studies. However, since the simulation setup has been kept quite simple, we cannot answer whether an application to a more complex domain such as a realistic vehicular traffic scenario is still possible.

All of the presented approaches proposed contributions which successfully demonstrated their feasibility in principle. However, a realistic modeling of the complex vehicular environment has often been neglected so far. We therefore continue by proposing definitions of system states and transition probabilities tailored to a vehicular environment.

3.4.2 Modeling of a traffic safety application

We consider a safety application designed to alert the driver if the current driving behavior is expected to lead into a dangerous traffic situation. We approach such an application basically by the same methodology as been applied to the toy example in Section 3.3: we consider an MDP defined by states of the (vehicular traffic) system, by transition probabilities among the system states and by a reward function representing elapsing time units until an accident is expected to happen. From the total reward criterion, this model then allows to deduce a valuation or ranking, respectively, on the set of system states. The aimed safety application sets up on this ranking and alerts the driver whenever the current driving behavior is expected to lead into a traffic situation the valuation of which falls bellow a predefined safety threshold. A discussion on how to choose the safety threshold at best is not in focus of this thesis; likely, it needs to be adjusted to the individual safety requirements of each driver.

System states

In order to distinguish different snapshots of traffic situations one needs to consider a multitude of details, for example, geographical position or movement vector for each vehicle. Moreover, continuous values as velocity, for instance, causes an uncountable state space of the system 'traffic'. For the sake of manageability, not only a discretization but also a significant reduction of the observation scope is required.

We conceive a safety application to make independently decisions at each car based on the exchanged data. Hence, as a first limitation, we will restrict the considered information on these data belonging to a relevant area, called *neighborhood*, of each vehicle. Furthermore, as proposed by the Cellular Automaton model (cf. Section 4.2.1), we divide the neighborhood into cells of a 7.5 m length that each might be occupied by at most one vehicle. By this means, we restrict the information on the snapshot of the traffic situation to the geographical positions of the vehicles in the surroundings (cf. Figure 3.6). Missing information like

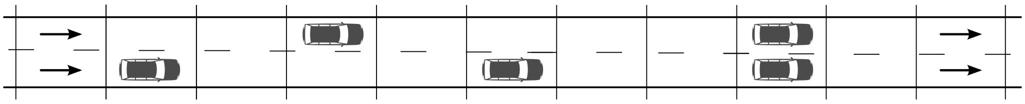


Figure 3.6: Snapshot of a traffic situation

velocity or movement vector are treated accumulated in an expected evolvement of the given snapshot represented in the transition probabilities between system states. By this limitation, a system state can be represented as a binary vector with dimension equal to the number of cells in the neighborhood. Here, we consider the neighborhood to comprise five cells per lane and direction (thus summing up to 20 cells) plus the two centered cells in which the reference vehicle may reside plus the position (left or right lane) of the reference vehicle all accounting for 23 features defining a traffic situation.

For our purpose we additionally consider a division of the state spaces into two classes, i.e.

$$\begin{aligned} & S = S' \cup S_{crash} \\ \text{with} \quad & S' \cap S_{crash} = \emptyset. \end{aligned}$$

Since the aimed safety application is designed to characterize traffic situations in order to avoid accidents actually to happen, the state class S_{crash}, composed of all accident situations, terminates the transition between system states; it thus represents a set of absorbing system state.

Transition law

Previous approaches often applied simple assumptions how traffic situations evolve over time. Given an arbitrary snapshot, we are interested in the *expected* evolvement, i.e. in the expected sequence of succeeding system states under realistic traffic conditions. Certainly, this expectation varies with changing conditions in the observed scenario. For example, in a traffic jam we would expect denser traffic situations to be more likely than on an empty road. Hence, as a simplification we fix a specific scenario[6]: we consider a vehicle going at a fixed speed of 135 km/h on a German motorway, i.e. we consider the speed of the remaining vehicles to range from 80 km/h to 200 km/h. In average, 11.5 vehicles per kilometer drive on the motorway which has two lanes per driving direction. Due to the complexity of advanced mobility models we refrain from an analytical discussion and make use of the traffic simulator VISSIM in order to derive expected traffic evolvement. Throughout the simulation we observe a selected reference car and record the system states as follows: according to our definition of system states, we consider the neighborhood of the reference vehicle to fit into a grid of 22 cells

[6]A safety application designed for different traffic situations can likewise be developed following the same proposed methodology.

Figure 3.7: Extract of conducted simulation in VISSIM

having the reference car in its center (cf. green vehicle in Figure 3.7). The current system state is then derived by mapping each neighboring vehicle to the next adjacent cell of the grid. This procedure clearly serves as an approximation since the continuous space considered in VISSIM is mapped to the discretized space induced by the cells of the grid. From this perspective, a simulation approach which considers a discretization of space might appear more suitable. However, as outlined in the following Section 4.2, mobility models based on a discretization of space in particular show an unrealistic acceleration and deceleration behavior. Yet, for dangerous traffic situations on motorways, we deem a deceleration behavior matching the capabilities of today's vehicles, for example, as crucial to decide whether an accident could have been avoided (e.g. by hard braking) or not. Thus, we made the choice for a simulator which takes account of such details at the expense of inaccuracies introduced by mapping the continuous space to the cells of the grid.

Since the Wiedemann mobility model considered in VISSIM does not allow accidents to happen (see following Section 4.2.3) but a safety application requires to be familiar with these situations, we slightly modify the driving behavior of the reference vehicle. In contrast to the remaining vehicles, the reference vehicle does not react on its surroundings and keeps on driving with its desired travelling velocity. Thereby transitions to some accident situations can be observed. The intention of this modeling explains as follows: the generated sequences of system states provide an expectation what happens if the driver of the reference vehicle does not adapt his driving behavior to the current traffic conditions; for example, due to inattentiveness. Rear-end collisions or accidents when changing lanes constitute prime examples addressed by this modeling. A safety application designed to avoid such accidents relies on expectations on the evolvement of current driving behavior in order to anticipate forthcoming danger.

From the record of system states observed throughout the simulation study, we derive probabilities $q_{s,s'}$ with which traffic situation s' follows on traffic situation s. As an example, for the motivating traffic scenario shown in Figure 3.1, Section 3.1 our simulation study yielded a probability of 78 % and 11 %, respectively, that the traffic situations on the right evolve from the traffic situation on the left (see Figure 3.8). The entire set of derived transitions probabilities then defines the transition law subject to the safety application.

$$p_{s,s'} = \begin{cases} 1, & s = s',\ s \in S_{crash} \\ 0, & s \neq s',\ s \in S_{crash} \\ q_{s,s'} & \text{else} \end{cases}$$

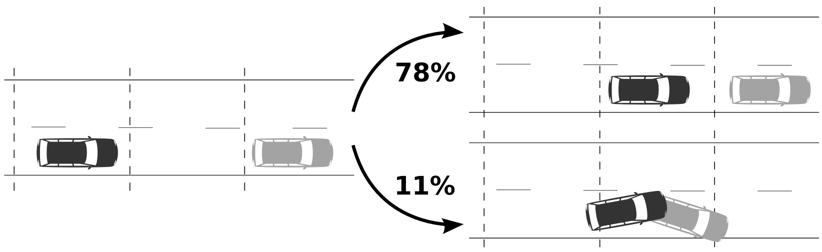


Figure 3.8: The simulation study yielded a probability of 11 % that the traffic situation on the left evolves into an accident.

Since we can confirm that all observed system states evince a probability greater than zero to enter one of the defined absorbing system states in a finite number of time steps, we may apply the theory on MDPs with absorbing system states as presented in the previous Section 3.2.3. Consequently, a discount factor does not need to be considered. From a modeling perspective this achievement is important since economic justifications as addressed by inflation in Section 3.2.3, for instance, cannot be applied. Regarding accidents, the factor time does not mitigate the seriousness of the issue. Thus, accidents occurring in the far future need to be treated as seriously as accidents in the near future which is only ensured if the discount factor is set to one.

Reward function

For the aimed safety application, the value of system states is derived from the likeliness of encountering accidents in the future. Hence, visited system states which do not model an accident are rewarded by a single time step unit at least elapsing more until an accident will occur. Accidents, on the other hand, are naturally not rewarded since an accident has actually happened and no more time can elapse. Hence, we obtain the following reward function.

$$r(s) = \begin{cases} 1, & s \in S' \\ 0, & s \in S_{crash} \end{cases}$$

3.4.3 Implementation of a traffic safety application

By means on the presented modeling, we apply an MDP and solve the total reward criterion to assess traffic situations by means of the expected elapsing time until an accident will occur. Our modeling implies that the action set which is part of the considered MDP only contains a single element[7], namely *do not change current driving behavior*. Such a modeling and the resulting assessment of system states, respectively, may establish the basis for safety applications tailored to the following two situations, for instance.

[7]The literature on MDPs calls such a process a *Markov Reward Process* [Put05].

(a) *Rear-end collisions.* In case the driver of the vehicle equipped with the safety application does not adjust his travelling speed to the front vehicle, the safety application considers increasing danger with a decreasing distance between both cars. When a 'danger threshold' is met, the anticipated danger by the safety application can be displayed to the driver with the intention to increase his attention to the forthcoming danger.

(b) *Overtaking maneuvers.* We consider careless overtaking maneuvers, i.e. overtaking maneuvers in which a driver initiates a lane change without checking if the current traffic situation actually permits such a maneuver. By making use of additional sensor data in the vehicle, the safety application can assume when a driver intends to change lanes, for example, by observing the blinker or the angle of the steering wheel. Then, the valuation of the traffic situations which would be expected to evolve if the vehicle had changed lanes, allows to assess the dangerousness of the intended driving maneuver in advance. In case of danger, again assumed by comparison to a given safety threshold, the safety application could alert the driver of the potentially risky maneuver.

3.4.4 The curse of dimensionality

In theory, the modeling yields an ordering on the set of system states which may serve as a basis for safety applications (cf. Section 3.4.3). Practically, the (intensive) simulation studies to derive transition probabilities among the system states have shown a ratio of 1 to 20 000 of visited to non-visited system states. An application obeying to the definition of an optimal traffic safety application (cf. Definition 3.1), however, needs to ensure that functionality is guaranteed for all traffic situations, no matter whether they have been used in the development or not. Indeed, knowledge on the non-visited situations could be gained by configuring a simulator with according traffic constellations and carrying out an appropriate number of simulation runs to obtain statistical significance. Then, with the derived transition law a valuation of the system states can be gained in polynomial time using value iteration (cf. Section 3.2.2). However, in the light of the few already observed states, the required effort to initially obtain the transition law can be estimated by a complexity of $\mathcal{O}(2^n)$ where 2^n denotes the total number of system states. Hereby, n represents the number of distinguished features of the environment. Regarding our modeling, we considered 22 cells modeling the spatial position of vehicles in the surroundings plus the position of the reference vehicle (left or right lane, respectively); thus the number of features distinguishing system states sums up to $n = 23$. Thereby, the knowledge on the surroundings is constrained on spatial information and other data, like speed information for instance, is only treated implicitly in the expected evolvement of traffic situations. However, a slightly more detailed modeling (by an enlarged number of features n) causes an exponential increase of system states implicating an according effort.

This issue is known as the *curse of dimensionality* as coined by Richard Bellman.

3.4.5 Discussion

In this chapter we studied a fundamental problem of traffic safety applications which is given in the distinction of safe and dangerous traffic situations. This problem has been approached by means of an MDP modeling which allows to derive a valuation of system states (respectively traffic situations) based on the expected elapsing time until an accident will occur. In a toy example, we have successfully demonstrated the feasibility of the approach in principle. The transfer of the concept to a more complex system, as it is for example given by vehicular traffic, showed difficulties mainly due to the following reasons.

- *An appropriate definition of a traffic situation*
  A modeling of the vehicular traffic system by means of an MDP requires the definition of a traffic situation or system state, respectively. If such a definition considers too less details, a single modeled situation represents many (real world) situations. As a consequence thereof, the valuation of a modeled traffic situation obtained by solving the MDP might not correspond to the 'actual dangerousness' of all real world situations represented by the modeled state. If this is the case, the definition of a modeled system state necessitates more details to be considered. Thereby, however, the number of all system states exponentially grows and an MDP becomes increasingly unmanageable.

- *Deriving transition probabilities*
  Independent of the chosen definition of system states, transition probabilities which let the model generate sequences of traffic situations according to real world traffic are hard to obtain. Traffic simulators do exist which have implemented mobility models widely accepted for suitably representing vehicular traffic; hence, these simulators could be of use to derive appropriate transition probabilities. Nevertheless and independent of the actual quality of existing mobility models and traffic simulators, respectively, the multitude of traffic situations requires a huge effort to be taken before statistical significant transition probabilities are obtained. An abundance of simulation runs would be required to take account of rural or urban scenarios, single or multiple lane roads, left- and right-hand traffic, high and low speeds, icy or non-slippery road surface and so forth. At the end, it is even not ensured whether such obtained transition probabilities would fit to the proposed model and its definition of system states.

The mentioned difficulties give reason for safety algorithms operating on relaxed problem definitions. Convergence in the valuation of all system states as computed by an MDP, for instance, might not be of need. Instead a safety application could just look a couple of seconds ahead to estimate whether danger is approaching. Key component for such an algorithm, however, is a suitable expectation on the evolvement of vehicular traffic as been mentioned in above listed difficulties. However, if one thinks of companies like Google, for instance, which already provides photographic data on the globe, then the idea of available data on world wide vehicular traffic evolvement does not seem to be far from reality.

4
State of the Art – Modeling of Communication and Mobility

Any devised safety application necessitates a tool to validate the aimed at functionality. Therefore, computer simulations will likely serve as a primary means. Since the significance of simulation studies, and thus the outcome of the application's evaluation, is also determined by the credibility of the applied simulation models, this chapter surveys modeling approaches for the two remaining building blocks communication and mobility. The goal is to identify appropriate models which then can be incorporated into a simulation tool as been discussed in the following Chapter 5.

4.1 Modeling of communication

For safety reasons, vehicles are expected to frequently transmit status messages, so called *beacon messages*, to their surroundings. Receiving vehicles thereby obtain valuable information of their neighboring cars (e.g., speed and position) and thus become increasingly aware of the current traffic situation. However, more than non-critical applications, beacon messages depend on a robust delivery in time due to their safety nature. Therefore, an evaluation of beacon messages necessitates an accurate representation of the networking behavior which provides information on beacon receptions and the respective points in time.

In this section we firstly discuss models on influencing factors of the communication system which affect the networking performance. We then present

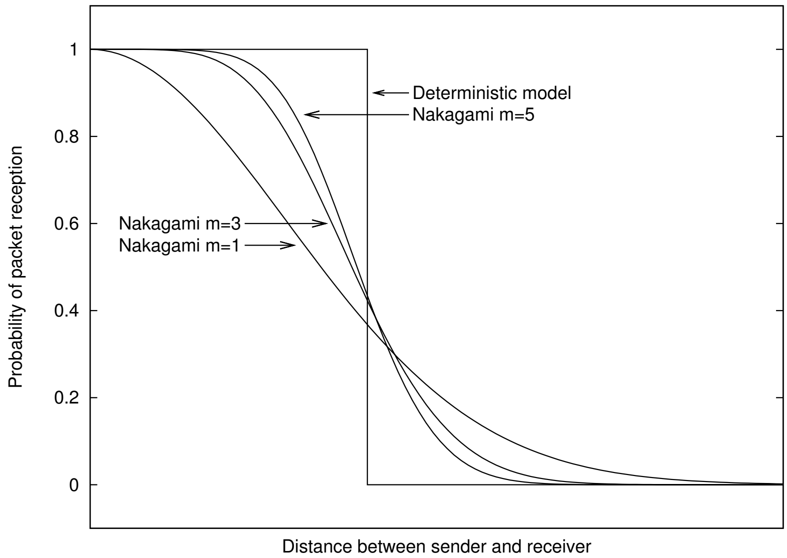


Figure 4.1: Resulting probability of packet reception over distance for four radio wave propagation models. In case of the deterministic model, one can clearly identify the communication distance.

available implementations of the models and explain design decisions taken in this thesis.

4.1.1 Deterministic and probabilistic radio wave propagation

First attempts to consider communication over the wireless channel have been based on rather simple models: packet receptions are conceived successful whenever the distance between sender and receiver does not exceed a given threshold called *communication distance*. The communication distance is derived from the path loss which a radio wave experiences over distance. Depending on the assumed path loss exponent, the power of the signal steadily attenuates until the minimum power value necessary to decode a received signal, called *reception threshold*, is met at the communication distance. Beyond the communication distance packet receptions are ruled out. In the literature, such models are classified as *deterministic* radio wave propagation models and are compared to the *probabilistic* ones. The reason for a probabilistic propagation of the radio wave signal is given by multiple effects taking influence on the radio signal: reflections, diffractions and scattering caused by the environment result in a signal strength varying in time and space. Additionally, the mobility effects of a vehicular network may induce a time-variant distortion of the signal which is known as *fading*. Since the environment can clearly not be captured in a single pattern, an appropriate radio wave propagation model should allow to cover the full spectrum from convenient to adverse communication conditions. A suitable candidate is given by the *Nakagami-m distribution* which allows to model varying channel conditions by means of its fast-fading parameter m, typically chosen from the interval [.5,5] representing bad to good conditions. It has been shown that with suitably configured m parameter the Nakagami model appropriately replicated communication traffic measured in real-world experiments on the road [TJM+04][YHE+06]. For a discussion of the Nakagami-m distribution we refer to Section 9.1.1 in Part II of this thesis. The assumed model of the radio wave propagation significantly influences one key metric in wireless communication networks, the *probability of packet reception*. In case of a single transmitter, Figure 4.1 illustrates the probability of successfully decoded packets over distance for different propagation models. Figure 4.1 also reveals the counterintuitive effect of better communication conditions at farther distances for models considering worse communication channels. Indeed, the illustrated modeling does not incorporate all advices provided by radio modeling experts. Rappaport, for instances, suggested to more precisely consider communication behavior at farther distances by switching assumptions subject to the Nakagami-m model beyond a specific distance, called *crossover distance* [Rap02]. This recommendation, however, leads to a non-analytical behavior of the probability of packet reception at the crossover distance and hence we will retain the Nakagami model as presented throughout this thesis.

4.1.2 Interference and reception

The decision on a successful packet reception is typically determined by comparing the ratio of the received signal power to all disturbances sensed on the communication channel, called *Signal to Interference and Noise Ratio (SINR)*. Disturbances, in this sense, are composed of the noise on the communication channel and of interfering simultaneous transmissions by other nodes. The discussion on the probability of successful packet reception, so far, has only considered a single transmitter; for those scenarios interferences are excluded and the SINR reduces to the SNR. The decentralized access mechanism to the communication medium in IEEE 802.11 ad hoc networks, however, cannot prevent simultaneous and, thus, potentially interfering transmissions. An accurate modeling of the reception behavior therefore requires to keep track of all ongoing transmissions and to jointly consider them when channel sensing is required. This concept of a joint treatment of interferers, called *cumulative noise*, has often been neglected in previous communication modeling attempts. However, it has been shown that without cumulative noise modeling channel conditions tends to be underestimated and a too optimistic communication behavior is inferred (see e.g. [SETMT+06, SETMMH07, SEK08]). Figure 4.2 reflects this issue and illustrates the probability of packet reception over distance in a sample scenario with and without considering cumulative noise. The scenario considers congested conditions in which 600 communicating nodes transmit 10 times per second 500 byte packets with a transmission power corresponding to a communication distance of 500 m in deterministic radio propagation models.

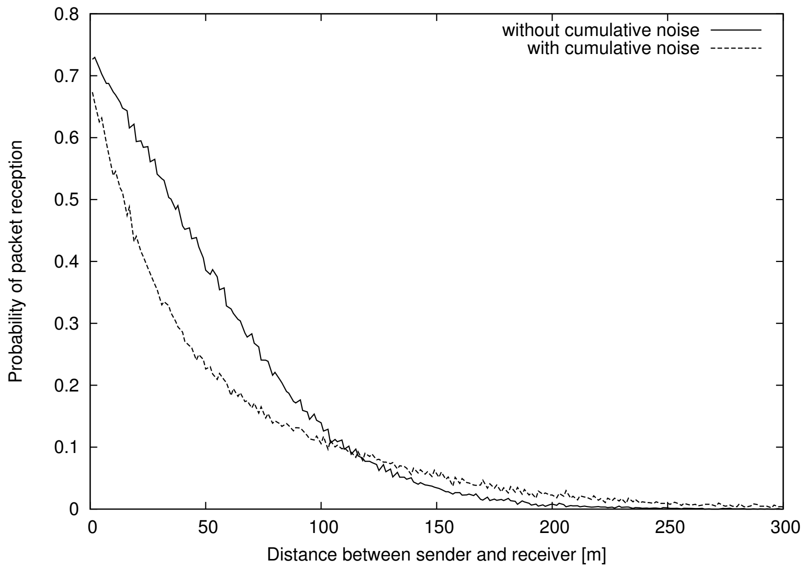


Figure 4.2: Impact of cumulative noise on the probability of packet reception over distance in a sample scenario (600 nodes transmitting 500 byte packets at a rate of 10 Hz with a transmission power corresponding to a communication distance of 500 m).

Noticeably, Figure 4.2 depicts reception probabilities far off 100 % even at very close distances. In fact, real world behavior differs since latest network cards support the *capturing effect* which advantages more powerful sensed radio signals. In principle, when network cards are in progress to decode a sensed signal, they are still capable to switch to another, later arriving, signal if its strength is sufficiently high. Thereby, the later arriving transmission could be saved which would have destroyed both transmissions without the capturing effect. Since the strength of radio signals attenuates with the distance, the capturing effect supports close-by triggered transmissions and almost ensures packet receptions in the very close surroundings. Network cards supporting the capturing effect differ in their capabilities when signal switching is possible. Some cards only support signal switching while decoding a packet's preamble while more advanced cards also allow to lock on a new signal during reception of the packet's payload. The consequences for the probability of packet reception in the close surroundings are significant as been exemplarily depicted in Figure 4.3 for a sample scenario (see also [TMCSEH06]).

The above discussed models deal with physical and technological representations of the addressed communication system. Major blocks completing the communication stack are thereby neglected like communication strategies to disseminate information [TM07] or to control conditions on the communication channel [TMSH06**?**], for example, all playing an important role in vehicular ad hoc networks. Regarding our aim in this part of the thesis to study the impact of awareness induced by beacon messages, however, the focus primarily becomes

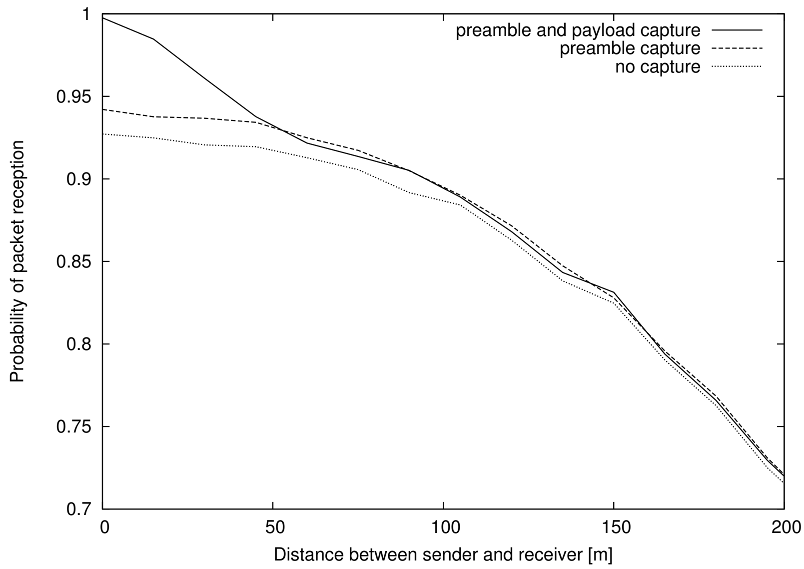


Figure 4.3: The capture effect significantly influences the probability of packet reception at close distances (source: [SEK08]).

one-hop broadcast communication. Access to the communication medium is thereby granted by the IEEE 802.11p draft of standard which aims to avoid simultaneous transmissions among the nodes in a distributed manner. Roughly speaking, IEEE 802.11p is derived from the well known IEEE 802.11a standard and adjusted to the peculiar conditions found in VANETs in terms of delay spread or coherence time, to name a few. The interested reader is referred for details to the current version of the draft of standard [IEE08].

4.1.3 Available implementations

Since many attempts to capture all addressed models in a single analytical expression have not been successful so far (see Section 8 in Part II), researchers have often made use of simulators for a joint impact consideration. Plenty of network simulators are available and have been used in studies on vehicular ad hoc networks. Regarding our discussion above, the latest release of the publicly available network simulator NS-2.33 is the only simulator which has implemented all models, namely probabilistic radio wave propagation, cumulative noise, capturing effect and IEEE 802.11p [CSEJ+07]. NS-2 has often been criticized in comparison to other simulators because of its runtime performance [SFKW08]. On the other hand and despite of potential amendments possible to the software architecture of NS-2, computational effort is also owed to the high level of accuracy which, in particular, holds for the probabilistic radio wave propagation and the cumulative noise models. In this thesis, we decided to put weight on an accurate modeling and have therefore chosen to apply NS-2.33 in simulation studies when a network simulator is concerned. Our decision is made in the light of traffic safety applications the impact assessments of which may respond sensitively to discrepancies in the (timely) availability of information at a vehicle. Nevertheless, our claim for accuracy is only valid within the boundaries of certain restrictions as being outlined in the subsequent Section 4.1.4.

4.1.4 Design decisions in this thesis

For all simulation studies carried out in this thesis we will assume environmental conditions as being found in highway scenarios. This restriction is due to hardly explored communication behavior in urban environments. Knowledge on whether reflection, diffraction and scattering effects at buildings in the surrounding will in general contribute or impair to establish communication links, and to which extent, has not yet been derived. Therefore, our aim is to minimize the influence of obstacles in the environment, yet, we are aware that vehicles themselves may be the reason for impeded line of sight communications. Our used simulation framework has not considered obstacle models since the maturity of proposed models is still in its infancy [NE08]. On the one hand, the impact of the environment on the signal propagation could be properly considered if previously discussed probabilistic propagation models were exchanged by ray tracing simulations. However, on the one hand ray tracing simulations come with strong requirements on computational resources and, on the other hand, an integration can likely not be achieved without considering modulation schemes, channel coding theory and error correction codes, for instance. In order to keep the scope of this thesis in limits, we will refrain from a detailed discussion of these topics.

4.2 Modeling of mobility

One key building block of Mobile Ad Hoc Networks (MANETs) describes the movement behavior of communicating nodes. The motion determines the nodes' spatial distribution and thereby, from a communication point of view, strongly influences the likeliness for any two nodes to establish a communication link. A very popular and often applied model in MANETs is the *Random Waypoint (RWP)* mobility model. According to this model, each node randomly chooses a destination point within a rectangular area and selects its individual travelling speed from a predefined speed interval $[v_{min}, v_{max}]$. On arrival, a node waits a randomly chosen idle time before heading to a next destination following the same procedure. Its wide application also gives reasons for many analytical and empirical proposed evaluations revealing peculiarities of the RWP model. For example, although initialized with a uniform spatial distribution of the nodes, the RWP model exhibits a non-uniform distribution having its maximum at the center of the rectangular as time goes on (see, e.g. [BHPC04]). Researchers studied the evolving spatial distribution of many proposed mobility models and demonstrated their influence on the performance of communication protocols. Conclusions from a vehicular traffic point of view can hardly be drawn since the gained mobility patterns, i.e. random paths in an open area, do not hold for vehicular traces. Researchers responded on this shortcoming by suggesting to restrict the open area assumed in RWP to a street map like shape. First attempts were proposed for freeway and urban scenarios [BSH03] but criticism was commented because of an unrealistic movement behavior of the vehicles. Later proposals considered an advanced vehicle behavior especially at crossroads and additionally based their models on real world street maps [CB05, PM06]. Most of the proposed approaches claimed a more realistic modeling due to their contributions since simulation results have shown that the performance of communication protocols significantly changes compared to previous mobility models. However, an actual comparison of thereby generated mobility traces to real world traces has not been provided. On the other hand, apart from the MANET research community, vehicular traffic engineers have been working for decades on traffic models and cross-checked their results to real world traces. We will present some of their insights in the following.

Traffic engineers distinguish three classes of mobility models: macroscopic, mesoscopic and microscopic. The distinction is based on the level of detail considered in the model. Macroscopic models describe vehicular traffic at a high level of aggregation as a traffic flow. The behavior of the flow mostly depends on statistical numbers like the average speed in dependency of the traffic density, for instance. Contrarily, microscopic models take the perspective of a single vehicle and determine its movement behavior depending on other entities in the surroundings. Mesoscopic models are in between of both previously mentioned. According to Hoogendoorn and Bovy, a mesoscopic models *does not distinguish nor trace individual vehicles, but specifies the behavior of individuals* [HB01]. Such a modeling, for instance, causes a vehicle to do a lane change but the reason for the lane change is based on statistical numbers such as the current traffic density and speed, for instance. According to this classification, we decided to deal with microscopic models since an impact assessment of traffic safety concerns the individual driving behavior of each single vehicle.

Microscopic models again differ in the considered level of detail: *high-fidelity* models aim at precisely representing a vehicle's motions. Environmental studies, for instance, which analyze the emission of vehicular traffic likely depends on high-fidelity models which accurately represent the acceleration and braking behavior of vehicles. Contrarily, *low-fidelity* models consider a reduced set of details and thus allow for a more computational-efficient modeling. Low-fidelity models exemplarily apply in microscopic simulations of a highway street network. Among the plenty of proposed models since the 1950s, we will discuss two models in details belonging to the low- and high-fidelity category, respectively, to the results of which we will refer in the remainder of this thesis.

4.2.1 Cellular Automaton model (Nagel, Schreckenberg)

In the early 90s, Nagel and Schreckenberg proposed a low-fidelity traffic model based on discretization in time and space [NS92]. They suggested to divide the road in segments of $\Delta x = 7.5$ m length which corresponds to the average length a vehicle occupies in a traffic jam. Each of the segments, called cells, may either be occupied by a single vehicle or by none. Additionally, possible taken speed values by the vehicles are discretized on the cell size, i.e. velocity, v, is expressed in number of cells, $\hat{v}$, taken per time slot, Δt, i.e. $v = \hat{v}\frac{\Delta x}{\Delta t}$, $\hat{v} \in \{0, 1, \ldots, \hat{v}_{\max}\}$. Typically, $\hat{v}_{\max}$ is set to five which corresponds to a maximum velocity of 135 km/h when time steps of one second are assumed. In every time step, each vehicle i updates its position by successively obeying rule one through four:

1. *Acceleration*
   If the maximum speed $\hat{v}_{\max}$ has not been attained, the vehicle accelerates by one velocity step
   $$\hat{v}_i \to \min\{\hat{v}_i + 1, \hat{v}_{\max}\}$$
2. *Deceleration*
   If the distance in cells, d, to the preceding vehicle is smaller than the current speed, velocity is reduced in order to keep a safety distance
   $$\hat{v}_i \to \min\{\hat{v}_i, d - 1\}$$
3. *Randomization*
   Taking into account that drivers do not constantly stick to a once chosen velocity, speed is decremented with probability $\hat{p}$
   $$\hat{v}_i \to \hat{v}_i - 1$$
4. *Vehicle movement*
   Within the next timestep Δt the vehicle moves $\hat{v}_i$ cells ahead

The cellular automaton model obviously comes with a coarse-grained modeling which is, for example, expressed in an unrealistic acceleration behavior of 27 km/h. Indeed, traffic engineers are aware that essential features of vehicular traffic are not captured by the model (for an extended discussion we refer the interested reader to [CSS00]). Nevertheless, the simplicity of the model allows to simulate a large number of vehicles in real-time and key symptoms of vehicular traffic like shock waves can still be replicated in given limits. A more detailed but, at the same time, computational more expensive modeling has been pursued by *follow-the-leader* models of which the *Wiedemann* model is a prominent representative.

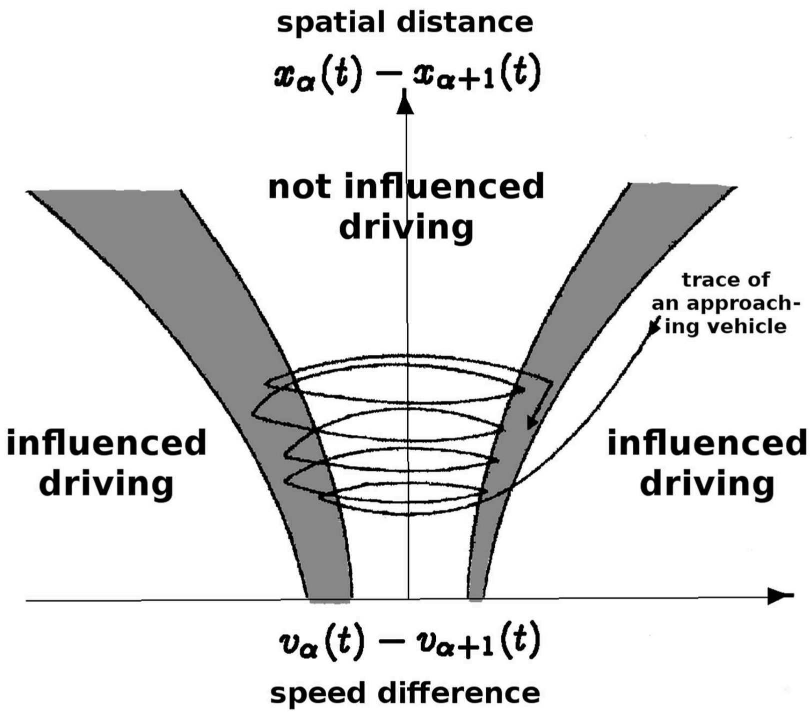


Figure 4.4: Driving behavior of an approaching vehicle according to Wiedemann 74. The transition from influenced to not influenced driving depends on perception thresholds. The thresholds vary over time which is indicated by the gray shaded areas (source [Hel97]).

4.2.2 Wiedemann model

Follow-the-leader models presume that the behavior of a driver-vehicle-entity mainly depends on the behavior of its front vehicle. If no front vehicle exists a vehicle moves on with its individual desired speed. An advanced follow-the-leader model which is based on different cognition levels of a driver has been presented in 1974 by Wiedemann [Wie74]. Wiedemann focused on modeling a single lane road in a rural area and thus did not consider overtaking maneuvers in the first instance. Wiedemann assumed that reactions taken by a driver depend on spatial and speed differences to the front vehicle. Essentially, he distinguished influenced and not influenced driving behavior. Since the perception of a driver varies over time an approaching vehicle tends to switch between both states as sketched in Figure 4.4. While vehicle α is approaching vehicle $\alpha + 1$ with notable speed surplus (depicted on x-axis) the driver is influenced and reduces speed. The driver might have overreacted and the speed surplus turns into a deficiency causing an increasing distance between both vehicles (depicted on y-axis). If driver α realizes the grown gap he accelerates and reenters the not influenced driving state expressed in a 'follow the leader' behavior. The perception threshold which let the driver realize to take an action are not fixed but vary over time as illustrated

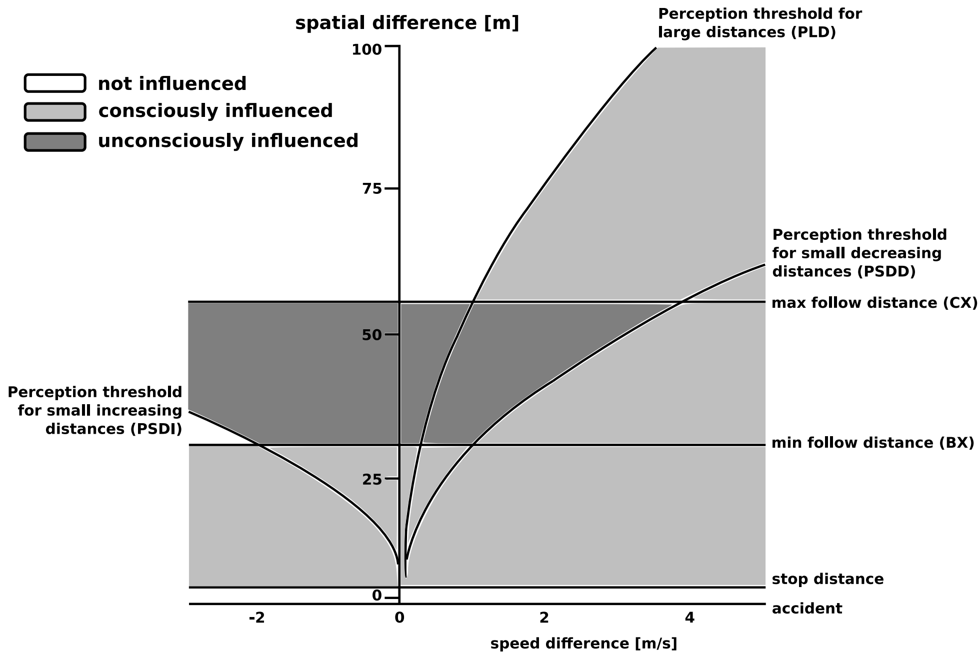


Figure 4.5: Perception states and thresholds according to Wiedemann 74 (source [Wie74])

by the gray shaded areas in Figure 4.4.

We will elaborate on Wiedemann's model since we will refer to its details later on in this thesis. Wiedemann distinguished three cognition states: (a) *not influenced driving*, (b) *consciously influenced driving* and (c) *unconsciously influenced driving*. The current state of a driver depends on the spatial distance and the speed difference to its front vehicle as illustrated in Figures 4.5 and 4.6. Regarding the spatial distance, Wiedemann basically took the following distinction.

1. If the distance to the front vehicle is below a threshold called *minimum follow distance (BX)* (cf. Figure 4.5), the vehicle needs to brake to avoid a rear-end collision. From an implementation point of view, the braking behavior is specified in the *BRAKEAX* procedure (cf. Figure 4.6).

2. If the distance to the front vehicle is larger than the BX distance but smaller than the *maximum follow distance (CX)*, the vehicle is endeavored to keep the speed of its front vehicle which is implemented in the *FOLLOW* procedure.

3. If the CX distance is exceeded, then it depends on the speed difference between both vehicles to determine whether the driving behavior of the succeeding vehicle depends on the front vehicle or whether it can go at its desired velocity. If the succeeding vehicle is considerably faster, it brakes to get into follow distance to its front vehicle (implemented in the procedure

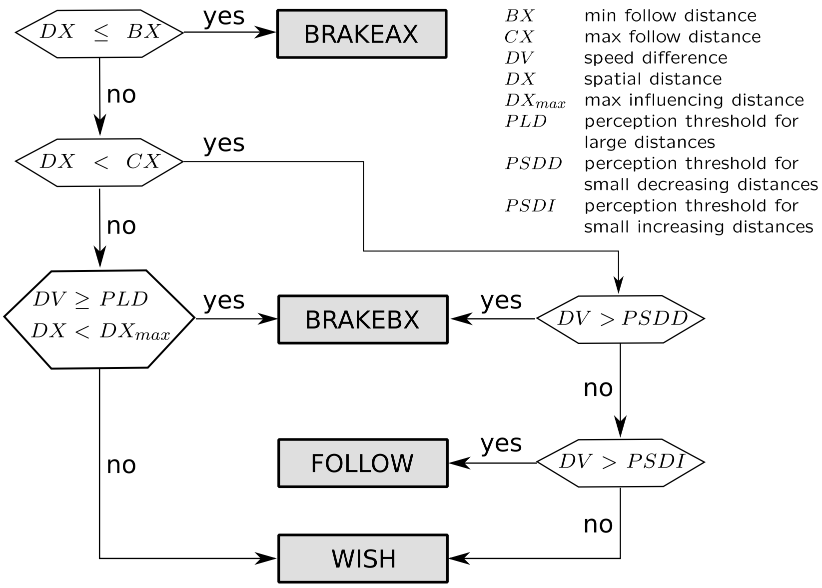


Figure 4.6: Structure diagram of reaction procedures in Wiedemann '74 (source [Wie74])

BRAKEBX). Otherwise, the vehicle is freely driving which is implemented in the procedure *WISH*.

4. Wiedemann also considered a maximum distance DX_{max} beyond which vehicles are assumed to not perceive their front vehicles. This distance is configurable and typically set to 250 m.

The introduced procedures are correlated to the aforementioned perception states. The procedure WISH represents the not influenced cognition state, the procedure FOLLOW is covered by the unconsciously influenced driving state and remaining two procedures BRAKEAX and BRAKEBX belong to the consciously influenced driving perception state. The transitions among the cognition states again depend on the speed and spatial differences between two successive cars and are modeled by three perception thresholds. For their explanation, we consider the example of a notably faster approaching vehicle.

1. While approaching the slower front vehicle, the decreasing distance causes the driver's perception to cross the *perception threshold for large distances (PLD)* (cf. Figure 4.5). Thereby, the driver becomes aware of the front vehicle and enters the consciously influenced driving perception state. As aforementioned, he starts braking to get into follow distance and, when speed has been sufficiently reduced, becomes unconsciously influenced by the front vehicle.

2. If the braking behavior even leads to a notable speed deficiency compared to the front vehicle, the perception of the driver crosses the *perception thresh-*

old for small increasing distances (PSDI) and the driver becomes uninfluenced by the preceding car.

3. On the other hand, if the braking maneuver and the subsequent follow behavior even cause a continuously shrinking distance between both vehicles, the driver's perception crosses the *perception threshold for small decreasing distances (PSDD)*, is thus consciously influenced and starts braking to avoid an accident.

The joint influence of speed and spatial changes to the perception states of a driver and the resulting driving behavior is illustrated in Figure 4.5 and 4.6. Details on the implementation of the BRAKEAX, BRAKEBX, FOLLOW and WISH procedure are provided in [Wie74] or [Gau07, Section 2.3.2], respectively.

In order to take account for varying driver characteristics in terms of aggressiveness or reaction capabilities, for instance, Wiedemann modeled perception and distance thresholds based on four random variables individual to each driver. The random variables are Gaussian distributed with mean and variance chosen to fit empirical measured driving behavior in 1974. Many succeeding modeling approaches have made use of Wiedemann's proposal of 1974 to take account for an extended traffic modeling like overtaking maneuvers, for instance (see, e.g. [WR91]).

4.2.3 Model selection

Hoogendoorn and Bovy [HB01] distinguished three types of follow-the-leader models: (a) safe-distance models, (b) stimulus-response models and (c) psycho-spacing models. Models belonging to the first mentioned type consider a succeeding vehicle to adapt its speed to keep a specific distance to its front vehicle. The safe-distance models distinguish in the computation of the aimed at distance; Pipes, for example, considered a linearly increasing distance with the speed of the succeeding vehicle [Pip53]. Pipes' model has been compared to field measurements and showed slight divergences to taken headways of the vehicles. However, Hoogendoorn and Bovy commented that *considering the model's simplicity, agreement with real-life observations is astonishing.*

Stimulus-response models differ in that they determine the behavior of a succeeding vehicle to conform to the behavior of the preceding vehicle. In this respect, the response of the succeeding vehicle, mostly acceleration or braking, deduces from a received stimulus and a sensitivity factor (a delay time) of the driver. Stimulus is thereby an input from the traffic situation like a detected change of the speed difference or spatial distance between succeeding vehicles. Prominent representatives of this model type are, for example, the Gipps model [Gip81], the IDM model [THH00] or the Krauß model [Kra98].

The latter mentioned type of models, the psycho-spacing models, presume that the vehicle/driver entity reacts differently on its preceding vehicle depending on the actual distance between both. At larger distances the succeeding vehicle is assumed to be less sensitive (or even not influenced at all) to speed or spatial changes compared to its front vehicle than for a small spacings. The Wiedemann model presented in the previous Section 4.2.2 falls into this category, for instance.

Treiber et al. proposed the Human Driver Model (HDM) extension which can be applied to many representatives of the stimulus-response class [TKH06]. They introduced a refined behavior of humans comprising false estimation and anticipation of traffic situations which is often not considered in stimulus-response models. Surprisingly, the interplay of impairing (e.g., false estimations) and assisting (e.g., anticipation) effects seem to cancel out each other which also explains why many macroscopic (vehicular traffic) effects (such as the propagation of stop-and-go traffic) are modeled that well by many stimulus-response models. On the other hand, Treiber et al. noticed that the stimulus-response models *produce unrealistic dynamics and crashes when simulating these models with realistic reaction times*. Regarding the psycho-spacing models, Treiber et al. adjudged that *human driving behavior can be modeled by so-called action-point models, where the response changes discontinuously whenever certain boundaries in the space spanned by the input stimuli are crossed*. The addressed 'action-points' thereby correspond to the perception thresholds defined in the Wiedemann model (cf. Section 4.2.2). We conclude that the Wiedemann model is assumed to suitably represent the behavior of human drivers.

Many of the presented car-following models have been implemented in simulators like VISSIM (Wiedemann) [ptv], Aimsun (Gipps) [aim], SUMO (Krauß) [sum] or VanetMobiSim (IDM) [HFBF06], for instance. However, since traffic engineers which have implemented these simulators are primarily interested in analyzing traffic flows, human misbehavior like accidents has not been considered in the simulation tools. Nevertheless, we have decided to make use of the traffic simulator VISSIM whenever vehicular traffic needs to be simulated due to the implemented Wiedemann model and the acceptance among traffic engineers. We will return to the open problem of non occurring accidents in traffic safety simulation studies later in Chapter 5.

5
Traffic Safety Assessment via Simulation

Previous simulation studies which aimed at evaluating safety aspects in VANETs often focused on communication performances. These approaches analyzed key figures of merit which then served as a measure to estimate whether assumed safety requirements are fulfilled. The delay of disseminating messages to a certain area and the achieved coverage, for instance, constitute prime examples of often addressed 'safety metrics'. Actually, however, such metrics only assess the conditions on which applications designed to improve traffic safety operate. The true effect on traffic safety requires a joint consideration of communication and application performances then expressed in a vehicular safety metric; for example, in terms of a decreasing number of accidents. Such an assessment by simulation means requires an appropriate replication of the domain traffic comprising safety concerning occurrences. However, the discussion in the previous Section 4.2 has shown that available traffic simulators have mobility models implemented which do not allow such situations to happen. We conclude, available simulation tools will not allow for simulation studies which assess inter-vehicle communication in terms of a decreasing number of accidents.

In this chapter we address the problem of assessing the impact of VANETs on traffic safety by simulation means. In a nutshell, we make the following contributions.

- In Section 5.1 we propose a modeling of vehicular mobility which allows traffic accidents to happen.

- Section 5.2 discusses available simulation approaches for VANETs. We adapt one of the presented proposals and incorporate the proposed mobility model into the simulation framework. The resulting tool comprises the fundamental building blocks application, mobility and communication (cf. Section 1.2).

- In the concluding Section 5.3 we assess a basic traffic safety application designed to prevent accidents in overtaking maneuvers by simulation means. The simulation study evaluates how a changing amount of information on the traffic situation effects the performance of the safety application reflected in the number of occurring traffic accidents.

5.1 Mobility model considering accidents

5.1.1 Overtaking maneuvers

The wide acceptance of the traffic simulator VISSIM among traffic engineers and, accordingly, the acceptance of the Wiedemann mobility model underlying VISSIM encouraged us to take it as a basis for considering accidents. We follow Wiedemann's proposition as been outlined in Section 4.2.2 but extend the model to consider two lane roads and thus overtaking maneuvers. Precisely, when the driver leaves the 'unconsciously influenced driving' state and is, thus, not able to achieve the desired travelling speed anymore, an overtaking maneuver is started. An overtaking maneuver basically distinguishes the *wish* to overtake from the *ability* to do so. The wish is expressed when the desired travelling velocity of a reference vehicle V_R cannot be reached due to a preceding vehicle V_P and a driving lane on the left side exists (cf. Figure 5.1). The ability to overtake depends on the driver's assessment whether a lane change is assumed to be safe. Therefore, a driver considers two criteria: *i)* the distance to and speed of the new front vehicle on the left lane $V_{P_{left}}$ complies with the safety requirements of V_R's driver and *ii)* the new succeeding vehicle on the left lane $V_{S_{left}}$ is not forced to brake hard because of the lane change of V_R. While the evaluation of the former criterion may be based on similar mechanisms as used for approaching a vehicle on the same lane, the latter requires to consider individual parameters of other vehicles, namely, $V_{S_{left}}$. In our implementation the reference vehicle V_R assumes that its own safety requirements are valid for other vehicles and thus may determine whether the second criterion is satisfied. When both criterions are fulfilled the vehicle changes lanes. After having overtaken V_P, V_R again checks for a safe lane change and continues driving on the right driving lane.

A more elaborated description of the considered driving behavior is given [Gau07]. An extract of the documented C++ implementation of the mobility model describing the overtaking procedure is provided in Appendix B.

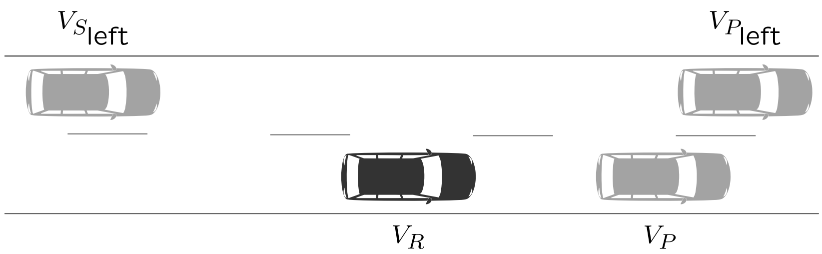


Figure 5.1: Key vehicles in overtaking decision taken by vehicle V_R.

5.1.2 Evaluation

The quality of a driver model is reflected in its capability to represent measurements taken on roads in reality. Due to missing data traces of road networks, we evaluate the derived driver model by comparison to the traffic simulator VISSIM. VISSIM itself has based the vehicles moving behavior on the Wiedemann model but applied publicly non available extensions to take account for lane changes, for instance. Since VISSIM, however, offers interfaces to let users take control on the vehicles' driving behavior, we are able to interlink our own driving model to the traffic simulator. Thereby, simulation runs with and without an external driver behavior model enable a comparison of both mobility models. Appendix C elaborates on VISSIM's *DriverModel*-interface which we utilized to interlink our model.

At first, our evaluation addresses the Wiedemann model without considering extensions like overtaking maneuvers. Therefore, we simulate a scenario having only a single lane per driving direction. We consider two vehicles of which the succeeding faster vehicle approaches the preceding one and thus passes the three perception states (cf. Section 4.2.2). We take a microscopic perspective and compare the driving behavior of the succeeding vehicle for both mobility models, our own and VISSIM's model. Figure 5.2 illustrates the speed taken by the reference vehicle over time in both models. We can distinguish three phases.

(a) During the first 250 s, the vehicle is not influenced by its front vehicle and drives with its desired travelling speed. Both models show divergences around the aimed travelling speed of approximately 39.5 m/s (procedure *WISH* in Section 4.2.2).

(b) From 250 s to 300 s the vehicle is forced to decrease speed since it approaches the slower front vehicle. The driving behavior of both models mostly coincides (procedure *BRAKEBX* in Section 4.2.2).

(c) From 300 s to 500 s the vehicle follows the front vehicle and is hampered to continue driving with its desired travelling speed. Again, for both models we observe divergences around a travelling speed of approximately 32.5 m/s (procedure *FOLLOW* in Section 4.2.2).

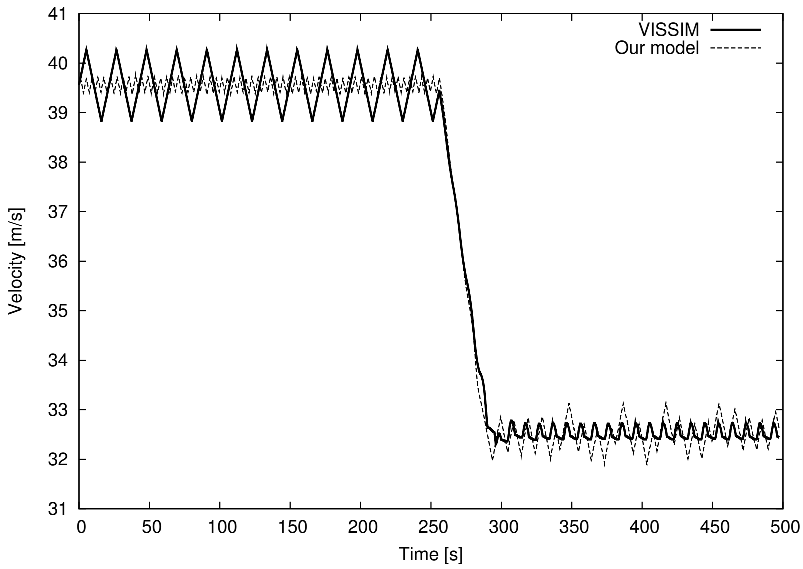


Figure 5.2: Microscopic comparison of our and VISSIM's driver model: velocity over time of a reference vehicle.

The oscillations of the travelling speed in phase (a) and (c), respectively, show varying intensities. In phase (a), Wiedemann thereby intended to model that drivers cannot constantly keep the same speed due to the sensitiveness of the throttle control, for instance. Phase (c) represents Wiedemann's modeling of perception thresholds: the attention of the driver of the approaching vehicle thereby changes with the speed difference and spatial distance to the front vehicle (this behavior is visualized in Figure 4.4). For example, assume a speed surplus of the succeeding vehicle and thus a decreasing distance between both cars. The driver of the succeeding vehicle is assumed to become increasingly attentive with decreasing distance, then perceives the situation and reacts by decelerating. Thereby, the distance decreases and the driver will later notice that he may accelerate again. This continuous repetition of acceleration and deceleration behavior is expected to cause more oscillations of the travelling speed than what we observe in phase (a). Indeed, this behavior reflects in our model which strictly adheres to Wiedemann's original proposal. The differing behavior of VISSIM's model is due to modifications which, as aforementioned, are not publicly available.

The simulation of a second scenario serves to compare the lane change extension implemented in both models. Therefore, we consider a motorway having two lanes per driving direction and observe the vehicles' mobility behavior by taking a macroscopic perspective; precisely, we evaluate the mileage of the vehicles over simulation time. Figure 5.3 depicts the mileage for 16 vehicles over 100 simulation seconds showing strong conformance between both models (average deviation $\mu = 0.68\,\%$, variance $\sigma^2 = 4.22e\text{-}05$).

Clearly, with increasing simulation time the minor deviations that may be ascribed to effects as addressed in Figure 5.2, sum up. Still, since a comparison of

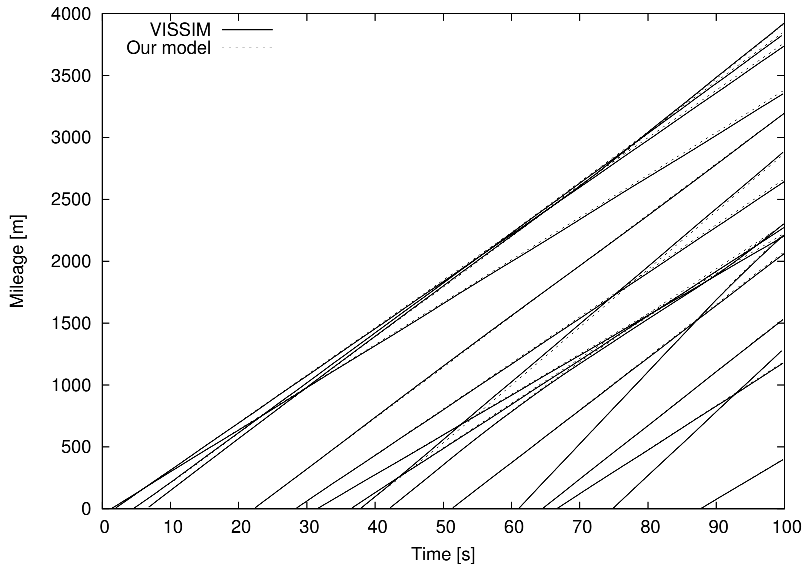


Figure 5.3: Macroscopic comparison of own and VISSIM's driver model: mileage of 16 vehicles over time.

the mileage traveled by almost 150 vehicles after 1 000 simulation seconds yielded a divergence of only $\mu = 1.76\,\%$ ($\sigma^2 = 7.25e\text{-}04$) between both models in average, we infer the validity of our model against the traffic simulator VISSIM.

5.1.3 Modeling accidents

The advantage of the implemented model is given in the control on knowledge which is used to determine the driving behavior of the driver/vehicle entities. In Section 4.2.3 we pointed out that the Wiedemann model does not allow accidents to happen since each driver perfectly considers all information in his surroundings and thus avoids running into a dangerous traffic situation. Now, with the model at hand we obtain the possibility to take influence on the amount of knowledge processed by a driver. Specifically, with our extension on overtaking maneuvers, we are able to model an inattentive driver who always changes lanes whenever the *wish* to overtake is expressed without checking for the *ability*, i.e. a safe traffic situation (cf. Section 5.1.1). Thereby, we address one particular class of accidents, namely accidents in overtaking maneuvers, which can benefit from inter-vehicle communication since neglected knowledge might still be incorporated via vehicle-to-vehicle communication and an according notification to the driver.

The traffic simulator VISSIM prevents accidents to happen but does not exclude them, i.e. one can construct a situation of two touching vehicles but, according to VISSIM's mobility models, it will not happen. An integration of the above presented model into VISSIM, however, facilitates simulations which allow accidents to happen.

5.2 Simulation framework

5.2.1 Related work

A couple of approaches have been proposed to combine vehicular traffic and communication simulations. Conceptually, the previous works can be divided into proposals combining both concepts in a single simulator and into approaches interlinking autonomous mobility and communication simulators. On the one hand, a single simulator jointly considering both research disciplines appears comfortable but on the other hand, and in particular in the light of an accurate representation of both issues as required for traffic safety studies, a joint treatment may likely overlook the specifics of each discipline. Gorgorin et al., for instance, proposed a combined implementation of the Wiedemann model, the IEEE 802.11 standard and a deterministic radio wave propagation [GGD$^+$06]. At least from a communication expert's point of view, various effects as discussed in the previous Section 4.1 have not been addressed and, thus, casting doubts on a realistic replication of the communication behavior. A different approach has been pursued by Choffnes and Bustamante who incorporated the STRAW mobility model into the wireless extension SWANS (Scalable Wireless Ad Hoc Network Simulator) to the JiST (Java in Simulation Time) discrete-event simulation engine [CB05]. Roughly speaking, the STRAW model builds the bridge between the Random Waypoint Model (cf. Section 4.2) and the characteristic shape of the network coined by the street map. STRAW is not restricted to, but currently uses the TIGER database which freely provides street plans in North America [tig]. Their results have shown that communication protocol performances are sensitive to the applied mobility model but a validation of their proposed model, the STRAW model, has not been provided. Conclusions on real vehicular traffic, in particular when having the scope of traffic safety assessment, can hardly be drawn.

Other approaches build on the expertise of the respective disciplines and interlink the latest results. Various combinations [EOSK05, LCS$^+$05, ARM09] and even frameworks [PRL$^+$08] have been proposed to connect existing traffic simulators (e.g., VISSIM, SUMO, VanetMobiSim, CARISMA) with network simulators (e.g. NS-2, QualNet, JiST/SWANS, OMNeT++). The distinct approaches do not only differ in the used simulators and, naturally in the maturity of the underlying models, but also in the extent of the coupling itself. For impact studies on vehicular traffic a functionality to support mutual influences among the coupled simulators is likely required since message reception significantly depends on the mobility and mobility may change on reception of certain information. Such an advanced approach has been exemplarily proposed by Lochert et al. who interlinked VISSIM with NS-2 [LCS$^+$05]. Figure 5.4 sketches the proposed components and their connectivity. Since both simulators typically run under different operating systems, information exchange is provided by means of a socket connection. The use of VISSIM and NS-2 and the possibility of a loop-back functionality, i.e. the exchange and incorporation of simulation results in the respective

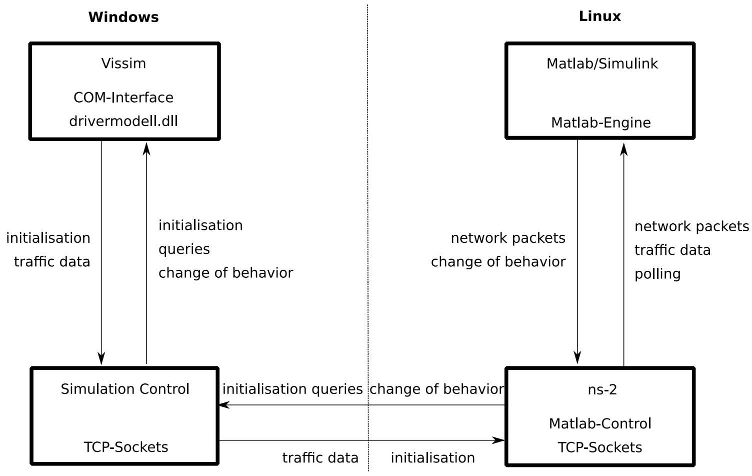


Figure 5.4: Approach to couple the simulators VISSIM and NS-2 (source: [LCS+05]).

other simulator, made us to follow this approach.

5.2.2 Joint simulation of NS-2 and VISSIM

Software coupling

In principle, we follow Lochert et al.'s approach and interlink VISSIM and NS-2 via a TCP socket connection. On NS-2 side, we therefore utilize the scripting language TCL which serves as the controlling interface to the C++ code of the simulator. TCL also provides libraries to establish TCP connections of which we make use to connect to a TCP server running in a proxy component interlinked to VISSIM's DriverModel interface (cf. Appendix C). On startup, NS-2 connects to VISSIM and uses the connection throughout the simulation process to inquire updated positions or to notify on packet receptions. On VISSIM side, the proxy component implementing the TCP server likewise takes care of the application logic. On reception of (communication) messages it decides whether a vehicle adjusts its driving behavior. If this is the case, the proxy component implements the changes by using the DriverModel interface.

Synchronization

The different operating systems providing the platform for the simulators VISSIM and NS-2 suggest two parallel simulations for which synchronization is required. In fact, however, the different time scales and time-advance mechanisms applied in both simulators give reason for a sequential coupling of the two simulators. VISSIM implements a *fixed increment* time-advance mechanism, typically chosen from 100 ms to 1 s, which supports a visualization of steadily moving vehicles. In contrast, the network simulator NS-2 advances in time using a *next* *event* mechanism based on a time scale in nanoseconds. Thereby, the simulation process jumps to successive events which are typically not arranged in a fixed time-increment manner. Figure 5.5 illustrates both time-advance mechanisms.

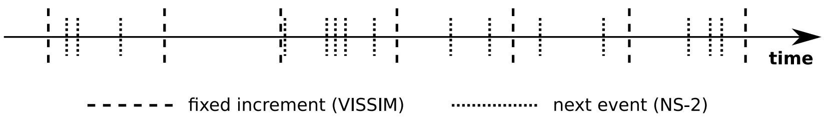


Figure 5.5: Illustration of the *fixed increment* and the *next event* time advance mechanisms used in the simulators VISSIM and NS-2, respectively.

The much more coarse-grained time resolution considered in VISSIM suggests that the two simulators exchange mutually influencing events when VISSIM updates the vehicles' positions. In detail, VISSIM computes new positions for all vehicles, performs the according movements and informs NS-2 on the updated positions of the communicating nodes. In between of VISSIM's next time step, NS-2 processes communication protocols among the vehicles. Received information may thereby get passed to the application (proxy component) responsible to evaluate information and to trigger new transmissions. Right before VISSIM becomes active again to compute the next simulation step, relevant information which may cause adjustments to the driving behavior are conveyed via NS-2 and the application to VISSIM. VISSIM considers the received information while computing new positions, updates the graphical user interface and passes control again to NS-2. Figure 5.6 illustrates the interaction of the components.

Indeed, one can argue that the application needs to operate on the time scales of both simulators depending on how the application's functionality is encapsulated. For example, on detection of danger in a specific vehicular traffic situation the application might trigger an alert message to warn vehicles in the surroundings. The actual information dissemination is performed via communication protocols which may again keep parts of the application's intelligence. A clear distinction which functionality belongs to the application and what is assumed as a basic feature provided by the communication system may depend on the perspective of the simulation framework's user.

In the succeeding simulation experiment we consider the application to be tightly coupled to VISSIM as suggested in Figure 5.6. Thereby, the application is conceived to evaluate received information only; in which manner information is disseminated belongs to responsibility of the communication block.

5.3 Sample scenario

In this section we make use of the proposed simulation tool to evaluate a basic traffic safety application. The application is designed to alert drivers whenever they intend to overtake a vehicle but the traffic situation does not allow for the necessary lane change. We assume that those accidents occur because of an inattentive

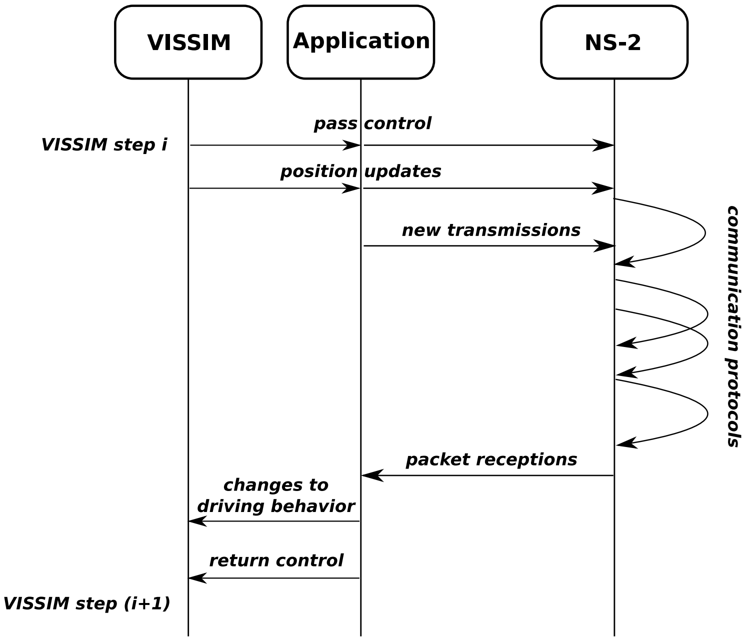


Figure 5.6: Interaction of the simulation components

driver, i.e. the information that the traffic situation is too dangerous for a lane change is available but the driver does not use it. A VANET application, however, which receives such information via inter-vehicle communication could correct the false estimation of the driver.

5.3.1 Scenario setup and simulation goal

We assume a highway in Germany having two lanes per driving direction (no opposite lane) and a traffic density of approximately six vehicles per lane and kilometer. The vehicles' speed ranges from 80 km/h for trucks up to 200 km/h for fast cars. We consider a single reference vehicle the driver of which is modeled to be inattentive throughout the simulation experiment. In that sense, the driver of the reference vehicle is modeled accident-prone as outlined in the previous Section 5.1.3, i.e. he always overtakes other vehicles whenever the wish is expressed without checking for safe traffic conditions. Since the reference vehicle is going by 135 km/h it is quite often involved in overtaking maneuvers.

The goal of the simulation study is to assess the impact of the *information system* on the performance of the considered application. In this context, 'information system' refers to the communication system and, specifically, to the information provided via communication. A lack of provided information can then be attributed to the following two reasons: (a) the quality of the communication system prevents the provision of all information where needed; (b) Not all of the required information is available. From a communication perspective, the latter may exemplarily be concerned if only a fraction of vehicles is equipped with radio technology and thus can at all provide and disseminate information. In this simulation study, we do not distinguish between both mentioned reasons. We evaluate the performance of the considered safety application in dependency of varying qualities of the information system. The performance of the application is evaluated by means of occurring traffic accidents.

5.3.2 Simulation building blocks

For the simulation experiment we consider the following implementations of the building blocks application, mobility and communication.

1. Application
   We assume that the driver's intention to change lanes can be recognized by the safety application, e.g. by observing the blinker. When a lane change is initiated, the safety application checks, based on the provided information, whether the traffic situation is assumed to be safe. If the situation is supposed to be dangerous, the lane change is suppressed and will not take place.

   The safety application assumes danger whenever it has information on the presence of a single vehicle within the spatial area, the neighborhood (cf. Section 3.4.2), surrounding the reference vehicle. We iteratively determine the minimum size of the neighborhood in simulation experiments, i.e. we successively increment the size until the safety application is able to avoid all accidents when full information on the traffic situation is given. The application does not use information which has been provided in the past, i.e. whenever the safety of a traffic situation needs to be evaluated, only the most recently provided information is used.

2. Mobility
   In the traffic simulator VISSIM we use the mobility model proposed in the previous Section 5.1. Except for the reference vehicle, all vehicles obey to the car following behavior proposed by Wiedemann and consider all relevant information on the traffic situation. In contrast, the reference vehicle changes driving lanes without checking for safe traffic conditions and thereby provokes accidents to happen. An accident is recorded whenever two vehicles touch.

3. Communication
   As aforementioned, our goal in this experiment is to assess the impact of the information system. For this goal, a detailed representation of the networking behavior as provided by NS-2 does not seem to be required. Instead, we evaluate the number of occurring accidents if the full spectrum from no information to full information is provided to the safety application. We therefore apply a simple methodology which allows to imitate differing qualities of the information system: we represent the quality of the

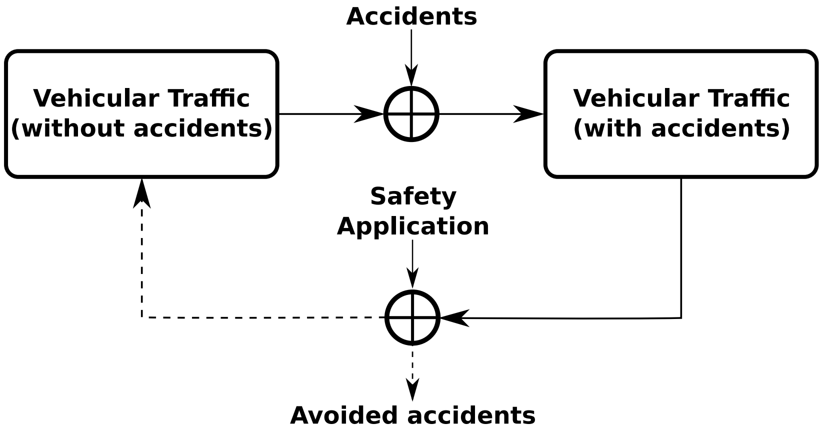


Figure 5.7: The process of simulating a VANET safety application. Accidents are introduced to an a priori safe model on vehicular traffic. Safety application are intended to balance the introduced accidents. Dashed lines represent intended effects.

> information system by a fraction of knowledge on the traffic situation which is available to the safety application. A fraction of x % thereby denotes that the application knows about the presence of each single vehicle in the neighborhood of the reference vehicle with a probability of x %. The *amount of information* or the *knowledge on the traffic situation*, respectively, thereby provided to the safety application simply results from rolling the dices for each vehicle in the neighborhood of the reference vehicle.
>
> For our goal of evaluating the information system, the presented methodology does not depend on the coupling to the network simulator NS-2. Indeed, we could save the synchronization overhead between VISSIM and NS-2 and 'simulate' the provided knowledge in a module efficiently interlinked with the mobility model. Other simulation goals, however, which aim at evaluating communication protocols in VANETs, for instance, rely on detailed simulations of communication as provided by afore presented coupling to NS-2.

Figure 5.7 visualizes the idea of simulating VANETs in principle and explains the functionality of the respective building blocks: in the first instance, we look at the vehicular traffic system the model of which does not consider the concept of accidents. Hence, we extend the model and introduce an imperfect driving behavior which provokes accidents to happen. Then, applications operating by means of the provided communication capabilities are envisaged to balance the introduced imperfection. In the most optimal case, the applications facilitate to return to a system which then truthfully does not allow accidents to happen.

Figure 5.8 illustrates the impact on the number of observed accidents.

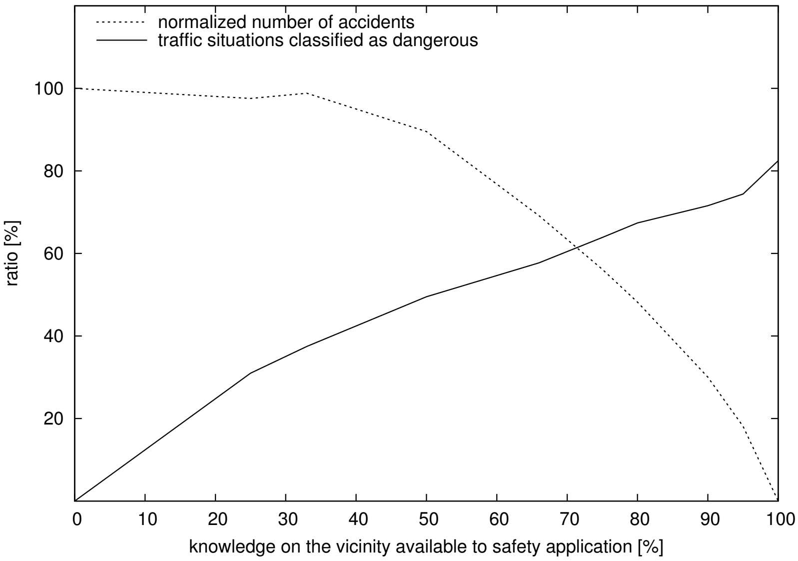


Figure 5.8: Evaluation of the simulation experiment on the number of occurring accidents.

5.3.3 Evaluation

Each of the conducted simulation runs has lasted for 1 000 driven kilometers by the reference vehicle. The runs differ in the amount of provided information to the safety application as been outlined before. We divide the evaluation of the experiment into two parts: (a) the impact of knowledge on traffic safety and (b) the performance of the heuristic and its proximity to an optimal safety application.

The x-axis denotes the amount of knowledge on the surroundings that is available to the safety application installed in the reference vehicle. The dashed curve depicts the normalized number of accidents that were detected in the simulation runs in dependency of the amount of provided knowledge. The 'normalized' number reflects the ratio compared to the maximum number of accidents that occur when no information is provided. Intuitively, this curve decreases with increasing knowledge, i.e. more knowledge on surrounding vehicles results in less accidents. However, a notable impact on the decay of accidents can be observed when more than 50 % of knowledge on the surroundings is provided to the safety application. Furthermore, even an increase from 90 % to 100 % of knowledge on surrounding vehicles prevents 25 % of accidents which would happen if no information was provided.

The solid curve in Figure 5.8 concerns the activity of the safety application. Illustrated is the ratio of assessed dangerous traffic situations to all evaluated traffic situations, expressing the application's capabilities in dependency of the awareness of the vicinity. For any level of provided knowledge, the relationship gives the ratio of traffic situations that the application classified as dangerous. For the remaining, unclassified traffic situations, no statement is issued, i.e. the situation

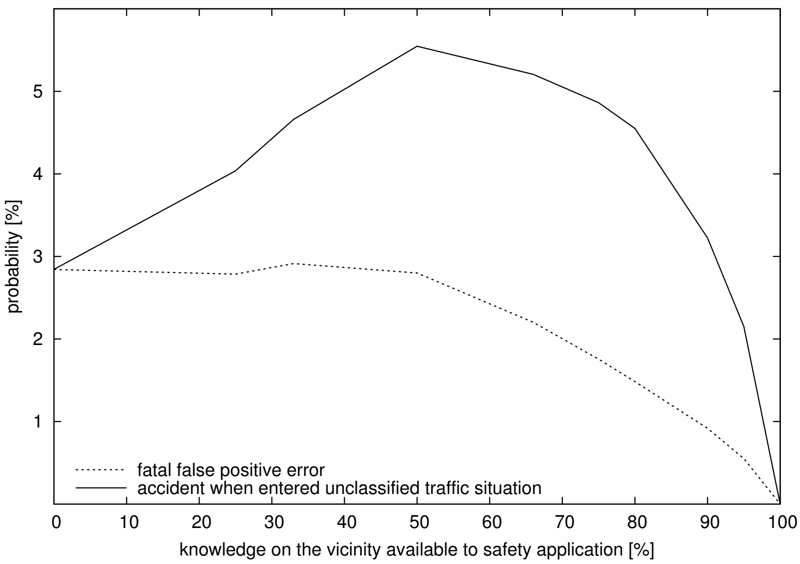


Figure 5.9: Evaluation of the performance of the heuristic applied in the simulation experiment.

could either be safe or dangerous. Again we observe a monotone behavior: more knowledge on the surroundings of the reference vehicle enables identifying more dangerous situations.

Regarding the performance of the application, we firstly introduce an evaluation from a more abstract point of view. The application basically carries out an hypothesis test whereas herein the hypothesis states: *The current traffic situation is dangerous*. In statistics, we distinguish two kinds of errors which come with a hypothesis test: *false positive* and *false negative* errors. The false positive error is defined by a true hypothesis and a rejected test result at the same time. Transferred to our vehicular traffic scenario, a false positive error is reflected in an actual dangerous traffic situation which has not been detected by the safety application. If we take these situations to the extreme, we deal with a dangerous traffic situation which has not been identified by the application and which leads into an accident; we call this a *fatal false positive* error. Figure 5.9 visualizes the probability of observed fatal false positive errors in the conducted experiment showing a decreasing trend with increasing knowledge (dashed curve).

The second category of error, the false negative error, is essentially harder to study. A false negative error comprises the concurrence of an actually wrong hypothesis and a positive, i.e. contrary, test result at the same time. The difficulty of investigating this error becomes obvious when looking at the conducted simulation experiment. In a false negative error the application wrongly assumes a dangerous traffic situation and thus prevents an intended overtaking maneuver to be carried out. The intervention of the application, however, interrupts the evolvement of the current traffic situation and thus avoids to eventually decide whether the application was right or wrong. On the one hand, it is possible to configure a simulator with each decision situation taken by the application and to simulate the consequences of both decisions (to intervene or not). Yet, on the other hand, attaining statistically significant statements following this procedure bears no proportion to the required effort. An indicator for an increasing false negative error, however, may partly be found when taking a look at the effectiveness of the application. The solid curve in Figure 5.9 illustrates the credibility of the application, i.e. the probability of running into an accident after the heuristic did not find evidences for danger. In the interval from 0 % to 50 % of provided knowledge the curve illustrates a decreasing credibility since the probability of accidents increases although the overall number of accidents keeps approximately constant (see Figure 5.8). In fact, at the same time, the application classifies more traffic situations as dangerous (Figure 5.8) which thus must have been superfluous. In other words, the application commits an increasing number of false negative errors. For the remaining part of the solid curve in Figure 5.9 no statement on false negative errors can be issued since the steadily increasing number of interventions then comes along with a falling number of accidents at the same time.

The discussion of the simulation results has revealed two evaluation criteria: one focusing on the goal of avoiding accidents and the other one pointing to the effectiveness of the underlying algorithm. Indeed, both issues need to be considered when comparing the studied safety algorithm to an optimal application as been defined by Definition 3.1: intervention is only required *if and only if the current driving behavior leads into an accident*. Without the equivalence condition a safety application which refuses to drive would likewise meet the definition of an optimal traffic safety application.

5.4 Conclusions

This chapter has addressed an impact assessment of VANETs on vehicular traffic safety by simulation means. Therefore, we firstly took care of an extended modeling of the mobility behavior of vehicles to take account of traffic accidents. We integrated the proposed model into a simulation framework comprising the fundamental building blocks application, mobility and communication. In a concluding simulation experiment we then investigated the performance of a safety application designed to prevent accidents in lane change maneuvers for different qualities of the information system. The results of the simulation study indicate that a notably decreasing number of accidents can be observed when the application is provided with information on the presence of more than 50 % of surrounding vehicles. In particular, the result of 25 % saved accidents[1] if the provided knowledge on the surroundings is increased from 90 % to 100 % provides a valuable message since it suggests that it is worth to optimize the quality of the

[1]Compared to the situation when no information is provided.

information system.

Regarding our applied methodology, we particularly point to the following two insights gained from the conducted experiment.

- *The methodology of a VANET simulation on traffic safety*
  From an abstract point of view, the procedure of evaluating a vehicular traffic safety application by simulation means presents as follows: we firstly consider the model of a system which shows a desired behavior (i.e. vehicular traffic without accidents). This model, however, does not truthfully represent the system, i.e. the observed behavior does not reflect the actual properties of the system (accidents do occur in reality). Hence, we introduce modifications to the system behavior which results in an undesired behavior (accidents are introduced). The goal of the evaluation study is then to analyze to which extent an application can balance the introduced undesired behavior (how many accidents can be avoided). At best, we thereby return to the initial model of the system which has shown the desired behavior.

- *Evaluating a traffic safety application*
  The assessment of a safety application needs to consider at least two evaluation criteria: (a) its success to improve traffic safety and (b) its effectiveness to interfere the driving behavior only when necessary. The former criterion seems obvious and can be easily measured by means of a decreasing number of accidents, for instance. The second criterion, however, is difficult since it needs to take account of the 'human factor'. For the application considered in this chapter, for instance, a general prohibition of lane changes would comply with the first criterion but cause a disbelief of the driver in such an application. As a consequence, a driver would likely ignore the application. Obviously, an optimal traffic safety application needs to meet the demands of both criteria.

6
Résumé

In this part of the thesis we have addressed an impact assessment of inter-vehicle communication on vehicular traffic safety. In particular, we focused on assessing how an increased awareness of the traffic situation is reflected in a reduced number of accidents. 'Awareness', thereby, is assumed to be created via continuous communication messages mutually informing the vehicles of their presence.

We firstly aimed at revealing the potential of the communication facilities w.r.t. traffic safety and assumed the communication system being capable to provide all information to every traffic participant. Under this assumption, the potential of the VANET system is expressed in the number of avoided accidents leveraged by utilizing the provided information. The thesis contributed a formal description of how to assess and utilize traffic information information w.r.t. traffic safety.

1. *Formal description of a traffic safety application*
   We adapted a previous approach by Dolgov and Laberteaux to model the vehicular traffic system by means of a Markov Decision Process. The fundamental problem was to derive a valuation of traffic situations regarding their expected duration time until an accident occurs given that current system parameters remain unchanged. The thesis proposed a more accurate problem statement which manages a valuation of system states without being dependent on a distorting discount factor. Having obtained such a valuation, a traffic safety application avoids driving actions which are expected to lead into dangerous traffic situations. In a toy example, we successfully demonstrated the feasibility of this approach. The transfer of this concept to the vehicular traffic system required an adapted definition of system states

and transition probabilities: we utilized available traffic models and simulators to derive empirically established figures on the expected evolvement of the vehicular traffic system. As a result, we were able to compute a valuation for system states with the highest probability of occurrence. For the remaining system states, however, a valuation could not be obtained due to the complexity of the vehicular traffic system.

In particular, our discussion rendered the following insights.

- The problem of assessing traffic situations according to the probability of forthcoming danger can be modeled and solved by application of an MDP.
- The definition of system states, an essential part of an MDP, underlies conflicting goals. In case of too few system states, many traffic situations in reality need to be mapped to a single traffic situation in the model. Thereby, potentially crucial distinctions of the situations get lost and the modeled evolvement of the system represents a generalization with a potentially huge variance, naturally impairing the application's performance. In case of too many system states, however, the time and resource consumption required by solving algorithms do not allow to determine a valuation of system states. Obviously, one needs to find the tradeoff between the fidelity of the model on the one side, and the resulting complexity on the other side.
- In future, safety applications may profit from the steadily increasing amount of available information. In the light of companies like Google, for instance, which already provide manifold terrestrial information, a database on the vehicular movement traces world wide does not seem to be far from reality. Having such information, a safety application could efficiently estimate forthcoming danger by considering the expected evolvement from the current traffic situation over a limited time horizon.

Any type of algorithm to be devised for accident avoidance necessitates a tool to validate the aimed at functionality. The thesis therefore reviewed simulation means which, however, so far often struggle with an accident-aware modeling of the mobility behavior of vehicles: available traffic simulators typically do not allow accidents to happen which impedes the envisaged simulation studies on traffic safety. The thesis therefore developed the following contribution.

2. *An accident-aware simulation tool allowing for traffic safety studies in VANETs*
   We developed a mobility model which took the car following model by Wiedemann as a base and additionally incorporated an overtaking behavior. We successfully validated our model against the traffic simulator VISSIM which also bases the driving behavior on the Wiedemann model. Our proposed implementation enables the modeling of inattentive drivers who

do not check for safe traffic conditions when changing driving lanes. An integration of our mobility model into the traffic simulator VISSIM facilitates simulation studies in which accidents in overtaking maneuvers can be provoked. Additionally, a coupling to the network simulator NS-2 and the provision of a module hosting the application logic, like our lane change assistant, enables impact studies of VANETS on vehicular traffic safety.

The implemented simulation framework essentially provides a tool set to support the fundamental idea of simulating the impact of inter-vehicle communication on vehicular traffic safety: we introduce a disturbance (a misbehavior) to an initially ideal system and measure the consequence with and without countermeasures. The deployment of a communication system allows for distributed safety applications which are intended to compensate the introduced malfunction, i.e. to avoid accidents. At best, we seemingly return to the initial model of an ideal driver who never causes accidents.

In a concluding simulation experiment the thesis has corroborated this claim and demonstrated the feasibility to assess safety applications by means of the proposed simulation tool.

3. *Assessing traffic safety applications by simulation means*
   We considered a highway scenario in which a single driver has been modeled to be inattentive whenever he intended to overtake a slower front vehicle. A safety application installed in the vehicle of the driver assessed the danger of lane changes based on information provided on surrounding vehicles and suppressed the maneuver when danger was assumed. The simulation experiment confirmed the intuition of a decreasing number of occurring accidents when an increasing amount of information is provided.

   As far as the application is concerned the thesis has stressed two main issues to be fulfilled by a well designed safety application:

   (a) its impact on traffic safety, e.g. reflected in the number of avoided accidents and
   (b) the capabilities of the application to distinguish properly dangerous situations from non-critical ones. This is particularly important to achieve acceptance by the drivers who do not like to be overly kept in tutelage. In addition, the safety concern must not jeopardize the efficiency of road traffic.

   Hence, an evaluation of a safety application needs to take account of both mentioned criteria.

   Our investigated safety application has shown an effective accident avoidance only if the information system provided knowledge on the presence of at least 50 % of surrounding vehicles. Furthermore, 25 % of the accidents which happen when no information is provided can be avoided if instantaneous information on the vicinity can be increased from 90 % to 100 %. This result indicates that for crash avoidance a *complete* information system has to be the goal. This conclusion is different from the results of the traffic efficiency study obtained in the following Section 10.2.

Part II

Impact on Vehicular Traffic Efficiency

7
Introduction

7.1 Forecasted growth of vehicular traffic

Passenger and freight transport are forecasted to rise and pose huge challenges for today's transport systems. Regarding the increase just for vehicular traffic, considerable impact on the road network itself, traffic safety, and on the environment can be expected. On the one hand, alternative transport carriers like railways, aircrafts, and inland waterways do exist, but the vast majority of the expected increase will be taken up by road transport. Taking Germany as an example, statistics indicate an increasing transport demand without a change in the load balance among the transport carriers. Regarding the transport of goods, Figure 7.1 illustrates the growth in Germany over the past 10 years. The bottom picture in Figure 7.1 shows an increasing volume of freight transport relative to the gross domestic product (GDP) and a simultaneously growth in the GDP itself. The vast majority of the rising freight transport demand has been served by road transport and, as indicated by the top picture in Figure 7.1, the relative load taken by the respective transport carriers has been kept nearly constant over the years. Following this suggestion, the road network is supposed to be additionally stressed and traffic congestions, accidents, and economic and environmental damage results.

Countermeasures are particularly expected from advancements in technology: smart vehicles supported by radio communication facilities are supposed to mitigate congested roads by more efficiently using the existing infrastructure. For example, today's *Intelligent Transportation Systems (ITS)* adaptively react to changing traffic conditions and influence the traffic flow through speed regula-

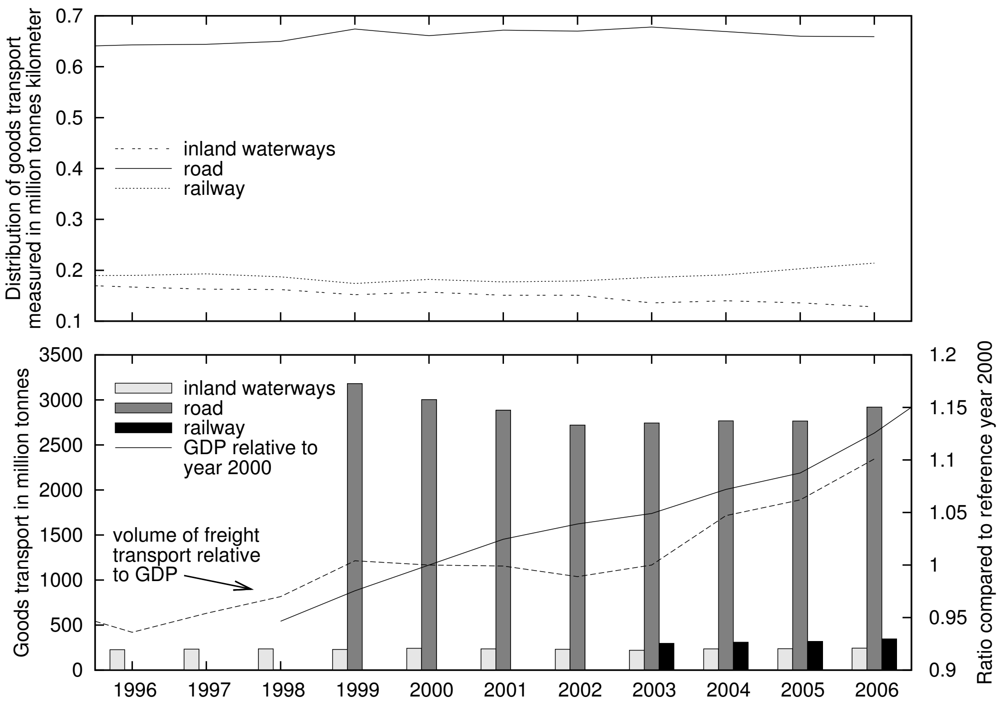


Figure 7.1: Freight transport evolution in Germany (source: [Com08]).

tions. The required information on the traffic flow is collected via fixed installations, such as mounted cameras or inductive loops installed in the road, that geographically limits the concerned area. Vehicle-to-x communications could clearly be deployed as a means to provide more accurate data about the traffic. A communication network spanned over multiple radio-equipped vehicles allows for the relay of traffic information over long distances to a traffic control center without being dependent on huge investments in communication infrastructure. By utilizing the contrary communication direction, traffic management authorities will be enabled to influence traffic flows in areas that are not well-equipped with today's control facilities, such as adaptively changing traffic signs. Furthermore, the processed information set can be enriched through additional data generated by trams, traffic lights, ferries, or (draw-)bridges, for example, which leads to the vision of a comprehensive, cooperative traffic telematics system.

7.2 Traffic efficiency simulations

The increasing interaction of many individual and complex components within the traffic telematic system considerably complicates the estimation of the effect that a single control action might induce. Already in simpler, non-communicating systems, at first glance rational actions produced contrary effects. In Stuttgart, Germany, for instance, the construction of an additional road caused the counter-

Süddeutsche Zeitung WISSEN Dienstag, 24. Januar 2006

Deutschland Seite 9, Bayern Seite 9, München Seite 9

Ewig lockt die Schnellstraße

Psychologen bestätigen ein mathematisches Paradoxon: Manchmal lösen zusätzliche Strecken den Stau erst aus

Von Wolfgang Blum

Verkehrsminister haben es nicht leicht. Wenn sie in Zeiten leerer Kassen mal den Bau einer neuen Straße durchsetzen, kann es passieren, dass ihnen die Mathematik einen Strich durch die Rechnung macht. Denn neue

⋮

Verkehrsaufkommen in jeweils 55 Minuten zu bewältigen. Anders die schmalen Landstraßen. Auf ihnen hängen die Fahrtzeiten von der Verkehrsdichte ab. Pro 1000 Autos steigt sie um zehn Minuten. Rollen 1000 Vehikel auf einer der Straßen,

⋮

Verkehrsaufkommen auf der Landstraße nach X-Dorf sinken. Wer dort entlang führe, wäre 30 plus 10 plus 40 Minuten unterwegs, also 80, während sich für die 1000 Verkehrsverbesserer an den 95 Minuten nichts ändert.

⋮

Figure 7.2: *Süddeutsche Zeitung*, January 24th, 2006 (in German, [Blu06])

effect and slowed down the traffic in 1969 (see Figure 7.2). Mathematicians explained that phenomenon with *Braess' paradox*, but still in more complicated scenarios an analytical approach fails because of complexity reasons. In fact, to minimize the possibility of undesirable effects, nowadays road planners intensively study construction projects by means of computer simulations. As with road planners, a traffic management authority who is confronted with an intensified traffic situation likewise depends on a tool that allows impact assessment of potential measures to be taken.

The autonomous behavior of the numerous entities in a vehicle-to-x communication-enabled traffic system places requirements on an assessment tool based on computer simulations. In contrast to the simulation challenges discussed in Part I, however, the focus of the conceived tool primarily is scalability. The targeted impact study basically assesses changes to the traffic flow in the investigated road network when certain measures have been taken. Hence, a reasonable evaluation requires a sufficiently large number of reacting entities for an appropriate representation of the modeled traffic flow.

A traffic management authority may likely demand the simulation tool to provide simulation results in time in order to estimate the effect of traffic control measures and then to react appropriately. In this thesis we conceive 'in time' simulation constraints as *real time* requirements, i.e., the simulation of a single second in the scenario must not take more than one second of computation time. This boundary is meant to serve as a first guideline and does not claim to meet all requirements posed by a traffic management authority.

7.2.1 Scalability of the building blocks

The scalability of a vehicular ad hoc network simulation depends on the scalability of its components. According to our identification of the required building blocks in Chapter 1, we review the runtime performances of the application, mobility, and communication integrants when more than 1 000 communicating vehicles are considered.

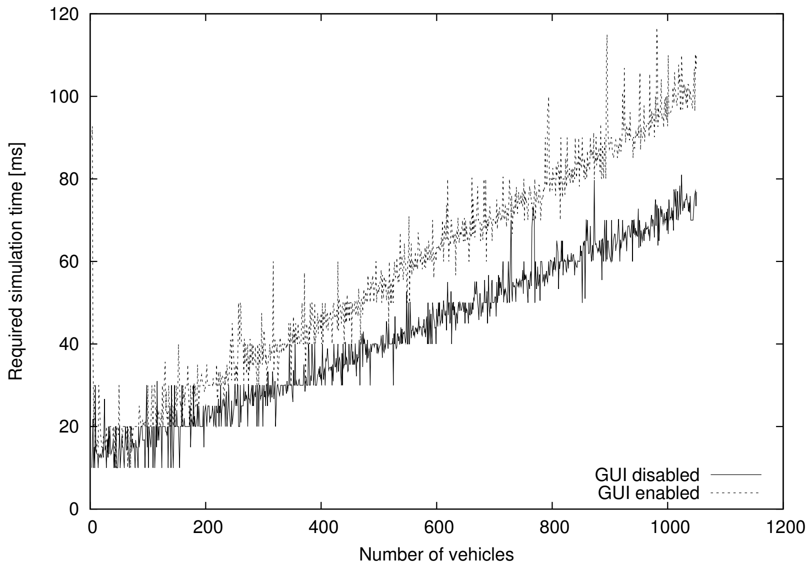


Figure 7.3: Runtime performance of the traffic simulator VISSIM to compute 100 ms simulation steps based on the number of vehicles.

Application

Scalability statements on traffic efficiency applications can hardly be given in general terms. Regarding the aforementioned scenario related to Braess' paradox, the phenomenon was locally bounded to the very inner-city center of Stuttgart; for such a scope, scalability problems do not necessarily occur. Yet, a different conclusion is likely drawn when optimized routing decisions for thousands of vehicles distributed in a metropolitan area need to be determined at the same time. In the scope of this thesis, we consider traffic-efficiency applications addressing locally bounded traffic optimizations and thus are not concerned by scalability problems. A representative candidate of application is exemplarily given in the dissemination of speed recommendations at bottlenecks in the street network to improve traffic throughput.

Mobility

An evaluation of VISSIM's performance yielded runtime requirements that linearly increase with the number of simulated vehicles. Figure 7.3 visualizes our simulation experiment computing 100 ms simulation steps carried out on an Intel Core 2 Duo T5800 at 2 GHz computer equipped with 1.5 GByte main memory running in a virtual machine hosted by a Linux operating system. The unfavorable simulation setup suggests that a more suitable simulation environment will likely result in an accelerated performance of the simulator. However, even under the given environmental conditions, the performed experiment evinces real-time conditions for approximately 1 000 vehicles, slightly differing depending on whether the graphical visualization of the vehicles has been switched on or off.

Furthermore, traffic engineers even suppose simulation steps of 1 s to be appropriate for highway scenarios, thus enabling the simulation of 10 000 vehicles under real-time conditions. According to these considerations, we conclude the scalability of the mobility block for our considered scope using the traffic simulator VISSIM.

Communication

In the same way that the mobility block demanded accuracy for each entity in traffic safety studies in Part I of the thesis, the communication block required a detailed modeling of the multiple factors involved in the communication system. For this purpose the advanced models implemented in the network simulator NS-2 turned out to be a suitable choice. In traffic efficiency studies, however, in which the number of communicating nodes notably grows, the discrete-event fashion of the simulation and the details of the implemented models causes a computational effort which cannot be executed in real time anymore. A back of the envelope calculation will support this statement: each transmitted packet in the wireless communicating network generates two events indicating the start and the end of the packet's preamble, and also a third event denoting the completed transmission of the packet's payload for each recipient. Where accurate simulations are concerned, the three transmission events are registered at every node in the network, since the packet contributes to interferences no matter whether it can be decoded or not. Thus, a single packet transmission produces $3(n-1)$ simulation events, where n denotes the number of receiving nodes. Now, let f denote the rate at which each node triggers transmissions, then the number of events to be processed per simulation second increases non-linearly with the number of nodes by $3fn(n-1) = 3f(n^2-n)$. If we consider $n = 1\,000$ nodes transmitting at a relaxed rate of $f = 3$ Hz, we almost generate 9 000 000 simulation events per simulation second. In 2003 Fujimoto et al. analyzed the performance of NS-2 on a 550 MHz Intel computer and measured 48 real-time seconds required to process 9 117 070 simulation events [FPP+03]. We repeated a similar experiment using the latest NS-2 release presented in Part I, Section 4.1, and required 33 real-time seconds to compute approximately 9 100 000 simulation events on an Intel Core 2 Duo T5800 running at 2 GHz each. Obviously, even the relaxed large-scale scenario of 1 000 nodes sending at a rate of 3 Hz fails to meet real-time conditions by far.

At first sight, it might appear counterintuitive why transmissions of all, vehicles in the network need to be considered at all if the evaluation goal is on a locally bounded application and its transmissions. On the other hand, network traffic that is not related to the application itself, so-called background data traffic, impairs the conditions of the communication system and thus influences the evaluation of the application in focus. Figure 7.4 exemplarily depicts how an increased amount of background data traffic (here induced by an increasing number of transmitters) affects the probability of packet reception over distance. Regarding VANETs, researchers suppose the vehicles to frequently broadcast beacon

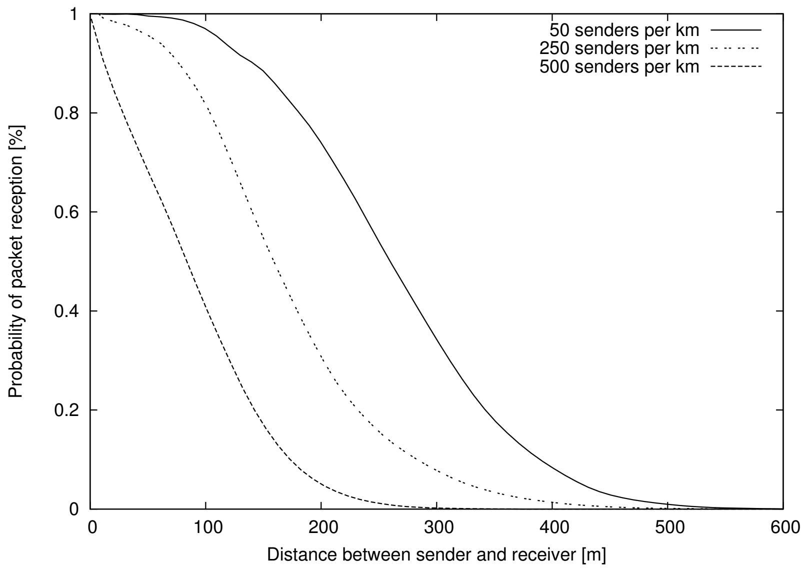


Figure 7.4: The probability of packet reception over distance based on three node densities: in all scenarios, the nodes transmit packets at the same rate with the same transmission power.

messages for safety reasons, which report on their current status with regard to speed, movement direction, etc. From the perspective of a particular traffic efficiency application, these beacon messages contribute to the background data traffic. Hence, an evaluation of such an application cannot be thoroughly carried out if the background data traffic is not considered in the evaluation study.

We conclude that accurate discrete-event network simulations based on NS-2 or a similar simulator do not meet the posed requirements for the communication block in large-scale inter-vehicle communication simulations.

A solution to the scalability problems discovered for the communication block may be found by making use of the fact that traffic-efficiency evaluations demand accuracy on the level of the system behavior. In contrast to traffic safety evaluations discussed in Part I, an incorrect representation of a particular situation is accepted if the overall behavior of the communicating nodes, i.e., of the vehicular traffic flows, proves correct. Hence, the goal is to find an efficient replication of the communication system that does not neglect its details and thus ensures statistical validity. Such an approach is covered by the concept of hybrid simulations.

7.3 Hybrid simulation

In the literature, the term *hybrid simulation* is ambiguously used. In the context of this thesis, a hybrid simulation describes a simulation process, of which one part is processed in a discrete-event manner while the remaining part is encapsulated in a mathematical model in order to save computation time. The underlying concept of accelerating the runtime of simulation studies has been well-known since the 1970s. In 1978 Schwetman noticed [Sch78]:

> "By combining, in a hybrid model, discrete-event simulation and mathematical modeling, we are able to achieve a high level of agreement with the results of an equivalent simulation-only model, at a significant reduction in computational costs."

Regarding the simulation of large-scale vehicular ad hoc networks, Schwetman's conception of a hybrid model could serve as a remedy to deal with the huge computational costs for inter-vehicle communications. The simulation of vehicular traffic and of the application logic, on the other hand, would still be simulated in a detailed manner, since they do not suffer from scalability problems as outlined before. The key difficulty with a hybrid simulation approach to VANETs constitutes the need for a model that accurately represents communication behavior. With respect to the appropriateness of hybrid models, Schwetman commented:

> "…the results of a hybrid model should be in as close an agreement as possible with the equivalent simulation model."

However, a pure analytical approach that describes the communication behavior in IEEE 802.11 networks and that could be used as a hybrid model has often been targeted but never has been comprehensively proposed. From today's perspective, the joint consideration of the entire problem space spanned by the environment, technological equipment, and concurrent transmissions seems too difficult to capture in a single analytical expression. The succeeding Chapter 8 provides a detailed overview of proposed approaches on analytical communication models in IEEE 802.11 networks.

7.4 Objective and structure

We propose empirical model-building as means to facilitate accurate hybrid simulations of large-scale vehicular ad hoc networks. We make use of advanced simulators to obtain a large set of performance data about the communication system. Subsequently, we apply analytical derivations and curve-fitting techniques in order to derive a mathematical expression that gives a key figure of merit in wireless communication networks, namely the probability of packet reception. The model will be designed so as to be flexible to changing conditions in the scenario layout and thus constitutes a building block for the targeted hybrid simulation architecture. Finally, we present an integration of the communication model to the traffic simulator VISSIM and demonstrate the suitability of the resulting software architecture to study the impact of inter-vehicle communication on traffic efficiency.

The remainder of this part is structured as follows: Chapter 8 discusses previous approaches tailored to enable large-scale simulations of wireless communication networks. Since in the following we pursue a hybrid simulation approach, this chapter also provides an overview on proposed analytical approaches of how to model communication behavior in wireless ad hoc networks. This survey concludes that not all of our requirements are met and thus we put forward empirical model-building in Chapter 9. In Chapter 10 the resulting model is incorporated into a simulation architecture, which thus provides a tool for the simulation of large-scale vehicular ad hoc networks. The appropriateness of the tool is demonstrated by means of simulation studies. Finally, we highlight our main conclusions in Chapter 11.

8 Related Work

Following the insights from the previous Chapter 7, a large-scale simulation approach on vehicular ad hoc networks primarily struggles with an accurate representation of the performance of the communication system. This chapter therefore provides an overview on existing attempts to represent the communication building block in large-scale scenarios. Firstly, we turn towards discrete-event simulators which have been designed to cope with scalability issues. Afterwards, we address analytical models on wireless communication according to the IEEE 802.11 standard which may serve as candidates to be used in a hybrid simulation approach.

8.1 Scalable simulation of wireless communication

Regarding the runtime requirements of a discrete-event simulation of wireless communication networks the primary source of performance loss has been identified in the propagation of radio signals. When accuracy is a goal of the simulation study, the transmission of a packet needs to be considered at each affected node along the propagation path of the radio signal; a notably huge area which an electro-magnetic wave may cover in free space. A registration of start and end of the transmission is even required for receiving nodes which experience a radio strength below a reception thresholds, since radio strength aggregations influence simultaneous ongoing transmissions (see Section 4.1). Intuitively, discrete-event simulation approaches attempting for scalability crop the radio signal when it falls below a given threshold and thus save transmission registrations at farther nodes at the expense of a diminishing accuracy. Ji et al. followed this procedure, took simplified assumptions and derived by analytical and empirical means an upper bound to which neighboring nodes still need to be considered [JZTB04]. In a sample scenario they have shown that their suggestions allow a speed-up factor of 55 compared to a non-improved simulator without notably changing the outcome experienced at higher layers of the protocol stack. Facilities to support the capturing effect, for instance, and performance evaluations covering the full spectrum from relaxed to heavy stressed scenarios have not been taken into consideration.

Performance accelerations have also often been the motivation for parallel simulations distributed to multiple processing units. The difficulty of parallel simulations is given by the challenge of optimally balancing the computational load to the processing units while considering the synchronization costs to maintain time integrity among the nodes. The synchronization effort especially matters for simulations of wireless communication since typically many simulation events are generated which influence multiple simulation units. In a recent work Bracuto and D'Angelo [BD07] exemplarily addressed the parallel simulations of wireless networks aiming at a large scale. They proposed a simulation framework which has shown a speed-up of 2.5 compared to a monolithic simulation architecture for 200 000 simulated nodes. However, details on their implementation of the wireless communication stack are missing (especially how radio wave propagation is considered) and thus insights on the accuracy of the simulation results can hardly be drawn. Nevertheless, their results have likewise shown that the speed-up does not increase monotone with the number of processing units but an optimal number is determined by the required synchronization effort. In the referred work four units have proven to yield the best performance which does not meet our demands even if the theoretical speed-up of 4 would be achieved.

The abundance of events generated in discrete-event simulations of wireless communication let researchers think of hybrid simulation approaches. In principle, the idea exploits that communication protocols are based on the OSI reference architecture and the layer of interest often allows to take abstractions on the behavior of lower layers. In [HBE$^+$01] Heidemann et al. therefore noted: "…*when the application is insensitive to detail, abstract simulations can be effectively applied*". In two sample studies Heidemann et al. demonstrated the dependency on the evaluation goal, i.e. the application, and showed the feasibility of the approach in principle but also pointed to distorted simulation results caused by too simplistic abstractions. The possible effectiveness of this approach has led to many applications such as the evaluation of multi-cast applications [HEH98] or routing protocols [GDK06]. Regarding an abstraction of the communication behavior on lower layers, however, previous proposals suggested simplistic models which serve the needs required in the respective scenario. Yet, in general, applications the performance of which is sensitive to (one hop) transmission failures, ranges or delays, respectively, may likely need an advanced modeling; in our opinion, many applications in vehicular ad hoc networks fall into this category. Therefore, we survey existing models on the communication behavior in IEEE 802.11 networks in the following.

8.2 Analytical communication models

Many suggested proposals to model communication behavior in wireless networks are limited to the scenario and evaluation goal for which they were used. Prominent candidates are for example given by models which decide on possible packet receptions only on basis of the deterministic communication range. These approaches are not suitable in the evaluation of applications the performance of which is sensitive to present transmission conditions.

In VANETs, vehicles are assumed to communicate in wireless ad hoc networks which are based on the IEEE 802.11 standard. Therefore, we put our focus on advanced analytical modeling approaches on the networking behavior in IEEE 802.11 networks. In particular, we orientate our discussion on the communication effects which have been presented in Part I, Section 4.1 and their consideration in the presented models.

8.2.1 IEEE 802.11

The majority of proposed analytical models refer to a paper by Bianchi that studies the maximum throughput in IEEE 802.11 networks. Bianchi assumed saturated conditions, i.e. all nodes in the network always have packets ready for transmission. Due to this assumption, a node in the network is either transmitting a message or has chosen a backoff slot in its contention window. Bianchi applied two dimensional Markov Chains to model the contention window of a single node: one dimension considers the backoff slots and the second dimension takes account of differing backoff stages in which the number of backoff slots varies. The transitions between the system states are taken by a node according to the following transition law: (a) whenever the medium is sensed idle for a DIFS period and the backoff counter is larger than zero, the node decrements its backoff slot. When the backoff counter equals zero the node starts a transmission. In case (b) when the transmission is successful the node resets the contention window and starts processing the next packet to be transmitted. If (c) the transmission collides since any other node in the network has chosen the same slot in its contention window, the node increases its backoff stage and reenters the contention phase by choosing a new backoff slot. For this Markovian process Bianchi determines the steady-state probability distribution over system states and, thus, derives the probability that a node starts a transmission in a generic time slot. The expansion of this transmission probability to all nodes in the network eventually leads to the probability of a successful transmission and, thus, to the system's throughput. For a detailed discussion on this approach we refer the reader to Bianchi's paper [Bia00].

Bianchi has validated his results by comparison to a simulation study. The conformance of both approaches, however, also results from implemented models in the simulator that comply with the assumptions taken by Bianchi. His models do not attain the same accuracy as those presented in Part I, Section 4.1 and, thus, differing outcomes of a comparison via simulation with advanced models would likely to be obtained. Likewise, many follow-up papers have proposed extensions that relax some (strong) assumptions taken in Bianchi's approach. In the following we give a short but non-exhaustive overview of papers proposing refinements of the above mentioned model.

Bianchi's model does not precisely replicate the modeling of the backoff stages. In conformance with the IEEE 802.11 standard Bianchi considers a finite number of backoff stages, i.e. the size of the contention window is at most doubled a finite number of times. In contrast to the standard, however, Bianchi does not consider packet drops due to a failed transmission in the last backoff stage. He assumes a node to stay in the last backoff stage and to retry unsuccessful transmissions (potentially) infinite times. Chatzimisios et al. [CBV04] addressed this issue and proposed a modeling in line with the standard. Furthermore, as a second contribution, the authors digressed from the assumption of inevitably successful transmissions in presence of only a single sender and, thus, introduced transmission errors modeled by a *bit error rate (BER)*. In their evaluation the authors compare analytical with simulation results, infer the suitability of their considerations and highlight the impact of an increasing bit error rate on traffic throughput and delay. Both of their evaluation approaches, analysis and simulation, however, consider an ideal channel in the sense that a node is able to detect any ongoing transmission regardless of its (geographical) distance to the sender. This inaccuracy has often been discussed in papers that address the problem of hidden terminals.

8.2.2 Hidden terminal problem

Papers on the hidden terminal problem commonly identified the chosen time steps in Bianchi's Markov model as key difficulty. From the perspective of a single node's contention window succeeding system states are taken when the communication channel has been (sufficiently long) sensed idle or when the node transmits a message. During a transmission, however, system conditions are assumed to be immutable, i.e. we either observe a successful transmission or a collision for all transmitted bits. In case of the hidden terminal problem some nodes are not able to detect an ongoing transmission and thus might turn an initially assumed successful transmission into a failed one. A revised modeling that assumes finer-granular time steps has been exemplarily proposed by Hou et al. [HTL03], Tsertou and Laurenson [TL06] and by Ekici and Yongacoglu [EY08] whereas the former two primarily focused on the RTS/CTS and the latter, more generally, also on the basic IEEE 802.11 access mechanism. All three papers additionally cluster neighboring nodes according to their distance into 'contending' and 'hidden' nodes with the latter covering all potential hidden terminals. This enhanced modeling requires modifications to Bianchi's analysis: while the probability of transmission in a generic slot remains unaffected by hidden nodes the probability of collision is indeed impaired. The analysis in all papers is suitably backed by according comparisons to simulation studies but, again, lacks in some details to be discussed in the following. In contrast to the two firstly mentioned papers, however, Ekici and Yongacoglu [EY08] consider a former work that relaxes Bianchi's assumption of saturated load conditions.

8.2.3 Configurable load on the communication channel

Duffy et al. digressed from the assumption of saturated conditions by introducing a (constant) probability reflecting the likeliness of packet arrival per time slot and node [DML05]. The exploitation of the configuration interval of the introduced probability from 0 to 1, hence, allows to model the entire spectrum from lightly loaded to saturated conditions on the communication channel. Since under this modeling a node is not necessarily throughout contending for access to the communication channel, the introduction of additional system states to Bianchi's model were required. Almost at the same time Engelstad and Osterbo [EO05] published a paper that analyzes performance measures of the priority scheme in the EDCA mechanism of IEEE 802.11e networks. In the special case of only a single priority class, however, the analysis complies with afore addressed models. Engelstad and Osterbo proposed a comprehensive Markov chain model that enhances Bianchi's model by the consideration of non-saturated conditions, packet drops due to finite retransmissions and post-backoff timer. Again, both mentioned papers validate their analysis via NS-2 simulations assuming packets to arrive in non-saturated conditions according to a Poisson distribution.

8.2.4 Probabilistic radio wave propagation

All previously mentioned papers only focused on the IEEE 802.11 MAC mechanism but neglected effects resulting from the underlying PHY layer. Indeed, performance metrics as the system throughput certainly depend on the environment that influences, for instance, the radio wave propagation. Pham, for instance, addressed this issue and studied the performance of IEEE 802.11 under idealistic radio conditions and under the probabilistic Rayleigh channel [Pha05]. Thereby fading effects of the radio signal are introduced that Pham modeled by means of a second Markov chain representing the 'up' and 'down' time of the communication channel. His analysis also comprises an advanced Markov chain for the IEEE 802.11 standard and covers its basic and RTS/CTS access mechanism. Although his concluding comparison to NS-2 simulations mostly agree with the analytically derived results, the paper excludes, e.g. a discussion on the hidden terminal problem or on the rarely addressed capturing effect.

8.2.5 Capturing effect

The capturing effect results from advanced network cards that may allow to lock on the most powerful packet in case of multiple simultaneous receptions. Thereby the system's throughput can be significantly increased since not all simultaneously arriving packets are automatically discarded. Li and Zeng [LZ06] proposed a mathematical analysis that considers the capturing effect, Rayleigh fading and log-normal shadowing of the wireless channel. The paper assumes all nodes to be uniformly distributed in a circular area and determines, depending on the number of simultaneously transmitting nodes, the probability distribution of the radio strength of the joint signals. Thereby, a comparison to the strength of a single signal allows to determine whether one out of all simultaneously transmitted messages could have been captured. Li and Zeng incorporated the determined capturing probability to an IEEE 802.11 mechanism description by Tay and Chua [TC01]. Tay and Chua carried out a similar analysis of the wireless standard as Bianchi without modeling the problem by means of Markov chains. The assumptions of saturated conditions, for instance, are likewise taken and thus influence Li and Zeng's results when including the capturing effect. Key inaccuracy in their approach results from the assumption of ideal carrier sensing and the concluding fact of strictly synchronized communicating nodes. On the other hand, however, fading effects or the hidden terminal problem give reason for asynchronously started transmissions (and so collisions) that have not been considered in the paper. Even the incorporation of the contribution made in above mentioned 'hidden terminal' papers does not solve the problem since a thoroughly modeled carrier sensing needs to consider the joint signal strengths of surrounding transmissions that is known as *cumulative noise*.

8.2.6 Conclusions

Many papers more have been published that discuss analytical approaches to describe the behavior of IEEE 802.11 networks. This short and certainly non-exhaustive overview is meant to give an impression on the various efforts researchers have spent on the hard problem of analytically describing the communication behavior in distributed wireless networks. In line with the discussion in Part I, Section 4.1 the survey concludes with summarizing the key influencing factors which have mostly been separately addressed but never jointly considered. These are: IEEE 802.11 MAC mechanism, configurable load on the communication channel, bit errors during transmission, the hidden terminal problem, a probabilistic radio wave propagation, the capturing effect and cumulative noise. Table 8.1 lists the contributions of the discussed papers above according to the identified key challenges.

We conclude that there is no model yet available which accurately represents the communication conditions in vehicular networks and which could be used in an hybrid simulation approach. The following Chapter 9 therefore suggests empirical model building which uses analytical and simulation means to obtain an appropriate analytical description of communication performances.

Table 8.1: Discussed issues in the referred papers.

Paper	IEEE 802.11 MAC mechanism	Configurable load	Bit errors	Hidden terminal	Prob. radio wave propagation	Capturing effect	Cumulative noise
Bianchi [Bia00]	√	–	–	–	–	–	–
Chatzimisios et al. [CBV04]	√	–	√	–	–	–	–
Duffy et al. [DML05]	√	√	–	–	–	–	–
Ekici and Yongacoglu [EY08]	√	√	–	√	–	–	–
Engelstad and Osterbo [EO05]	√	√	–	–	–	–	–
Hou et al. [HTL03]	√	–	–	√	–	–	–
Li and Zeng [LZ06]	√	–	√	–	√	√	–
Pham [Pha05]	√	√	√	–	√	–	–
Tay and Chua [TC01]	√	–	–	–	–	–	–
Tsertou and Laurenson [TL06]	√	–	–	√	–	–	–

9
Empirical Model

Key building block of a hybrid simulation approach is an accurate mathematical model that saves computation effort without distorting the outcome of the simulation. As been outlined in the previous Chapter 8 communication behavior depends on numerous factors that all amount to the complexity of the communication system. Since pure analytical approaches to understand communication specifics are mostly constrained to some chosen effects, computer simulations have often been applied for a joint impact study. Meanwhile network simulators have advanced (communication) models available which facilitate, from today's perspective, accurate simulation studies. Nevertheless, the variety of influencing factors gives reason for an extraordinarily large number of differing simulation studies before the problem space might appropriately be sampled. Therefore, we pursue an approach that reduces the complexity by fixing certain configuration parameters. Afterwards, we conduct extensive simulation studies on the resulting (reduced) problem space to obtain a lookup table on key figures of merit under changing sample conditions. In case of a sufficiently large and uniform sampling of the problem space, approximations among known data points might allow to derive suitable estimations for non-simulated scenarios, i.e. unknown data points in the problem space. If the approximations can even be given in a closed-form analytical expression the captured metrics may also be exploited to solve numerical problems as for example demonstrated in Section 9.3.2.

Primary intention of the targeted empirical model is the application in car-to-x simulators. Clearly, the implied simulation of communication may comprise advanced communication protocols among the vehicles that can hardly be represented in general forms. Hence, in the scope of this work we will focus on communication primitives which provide a base for more advanced communication protocols: we will study key figures of merit of *one hop broadcast communication*. The reader may also conceive the aimed broadcast communication as beacon messages which are periodically transmitted by the vehicles (cf. Chapter 1).

Among the plenty influencing factors all determining the performance of the broadcast communication, we identify four key inputs which span our considered problem space: assuming a traffic density of δ vehicles per kilometer that all periodically broadcast messages with a certain transmission power ψ at a rate f and denoting the distance to the sender by d, the model $\mathcal{M}$ provides the corresponding probability of one hop packet reception $\Pr_R(d, \delta, \psi, f)$. While the distance as input factor can naturally be explained by an attenuated radio signal over distance, we consider the remaining three input dimensions for the following reason. First of all, because all vehicles communicate over a shared medium, communicating nodes in close proximity need to cooperatively agree on adequately time-separated transmissions if packet collisions are to be avoided. As the number of neighboring nodes and quantity of packets to be served increase, the coordination of transmissions becomes more stressed. Hence, the frequency of transmissions (and thus the amount of packets) and the product of traffic density and communication distance (and thus the number of nodes) become major indicators for the challenge of collision-free distributed channel allocation. Concededly, the thereby defined problem space does not cover the entireness of possible scenarios but still the presented methodology likewise holds and can be repeated under varying preconditions.

Before delineating the model building process, its evaluation and validation, we start by outlining invariable parameters which we assumed in our simulation study.

9.1 Assumptions

The scenarios subject to the model building process will assume all vehicles to communicate according to the IEEE 802.11p draft standard [IEE08]. The draft standard offers a range of transmission rates from 3 Mbit/s to 27 Mbit/s. In [MFW05] Maurer et al. argued that lower data rates facilitate a robust message exchange by offering better opportunities for countering noise and interferences. Indeed, a recently conducted simulation study has empirically shown best communication performances w.r.t. to the probability of reception when a bandwidth of 6 Mbit/s is considered [JCD08]. In consideration of safety applications that in particular rely on a robust message exchange we suppose that the ongoing draft standard will agree on a similar configuration and we therefore apply henceforth a bandwidth of 6 Mbit/s.

All of the nodes are supposed to frequently broadcast packets to their one-hop neighborhood as it is, for example, envisioned by beacon messages which inform the vicinity on the current status. At first sight, this assumption might appear tight, even more if a unique frequency and transmission power is assumed for all nodes. Let us assume for the moment that vehicles are uniformly distributed over a straight road according to a given vehicular density. Then, the product of (uniformly) chosen transmission power, transmission rate and vehicular density gives an estimator of sensible transmissions at any geographical position on the road. This relationship has been defined by Jiang et al. as *communication density*, the number of carrier sensible events per unit of time and road [JCD07]. Jiang et al. have shown that differing scenario set-ups with a common communication density experience very similar communication performances. Moreover, the communication density is additive in nature: when two groups of vehicles with differing communication densities G_1 and G_2, $G_1 \neq G_2$ mix then the resulting communication density of the joint group amounts to $G_1 + G_2$. Now, returning to the strict assumptions at first sight, one could conceive the communication density on a road with n vehicles as an additive compound of n distinct communication densities belonging to n 'single vehicle groups'. Then, the communication density of the considered road section is given by $\sum_{i=1}^{n} G_i$ and provides an indicator of the communication activity in the geographical area. Thereby, we obtain an instrument to consider varying communication conditions in the respective road segment.

Regarding sizes of the transmitted packet, we will consider a fixed size of 400 bytes. Since an agreement of format and content of beacon messages has not yet been obtained, our decision for 400 bytes is based on an estimation of the upper bound of required payload. Roughly speaking, we assume half of the packet size to be used for the indispensably required security protection and only 200 bytes for identifiers, positioning information, timestamps, incident information and so forth. For the development of the sought empirical model, however, a constant size is required since the additive property of the aforementioned communication density does not hold for the packet size. Again, we emphasize that the subsequent methodology for the model building can likewise be applied to various preconditions as the packet size, for instance.

For the PHY layer we assume a probabilistic radio wave propagation according to the Nakagami-m distribution. We will consider moderate channel conditions expressed in the Nakagami fast fading parameter $m = 3$. An analytical derivation of the Nakagami $m = 3$ model is given in the subsequent Section 9.1.1 and will be used in the model building process discussed in Section 9.2. However, when transmission power values are declared we will make use of deterministic radio wave propagation models. Deterministic models assume an attenuation of the radio signal according to a fixed loss exponent over distance. In absence of interferences this modeling leads to a continuous decay of the radio strength that complies with the reception threshold at the 'intended communication range', i.e. the farthest distance at which packets can potentially be received. In case of the Nakagami model, the declaration of a communication distance fails because of the probabilistic distribution of the radio strength covering any power value.

Henceforth, we will give transmission powers by means of the 'intended communication range' in meter that would be achieved if the transmission power is chosen under a deterministic model.

With respect to interferences on the communication channel we consider the cumulative noise modeling that assumes a node to sense an energy level composed of the additive strength of simultaneous, surrounding transmissions (see Section 4.1).

Table 9.1 provides an enhanced overview of our assumptions subject to the subsequent simulation study.

Table 9.1: Simulation configuration parameters.

Parameter	Value
Antenna gain	4 dB
Antenna height	1.5 m
Carrier sense threshold	-94 dBm
Frequency	5.9 GHz
IEEE 802.11p data rate	6 Mbps
Minimum contention window	31 slots
Noise floor	-99 dBm
Packet size	400 bytes
PLCP header length	8 µs
Preamble length	40 µs
Radio propagation model	Nakagami m=3
SIFS time	32 µs
SINR for frame body capture	10 dB
SINR for preamble capture	5 dB
Slot time	13 µs

9.1.1 Probability of reception according to Nakagami-m

A successful transmission of a packet over the wireless communication channel is determined by comparing the strength of the radio signal to the noise level on the medium. Only if the *Signal-to-Noise-Ratio (SNR)* is sufficiently large the arriving packet can successfully be decoded. The instantaneous SNR per bit, denoted as γ, is a time-invariant random variable with a *probability density function (pdf)*, $h(\gamma)$, which, in the following, we assume to be given by the *Nakagami-m* distribution, i.e.

$$h(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Gamma(m)} e^{-\frac{m\gamma}{\bar{\gamma}}}, \qquad \gamma \geqslant 0 \tag{9.1}$$

where $\bar{\gamma}$ denotes the average SNR per bit and m is the fast fading parameter, the configurable input to the Nakagami-m distribution [Rap02].

It is known that the pdf of a *gamma distribution* $\Gamma(p, b)$ is given by

$$g(x) = \frac{b^p}{\Gamma(p)} x^{p-1} e^{-bx}$$

that agrees with Expression (9.1) when setting $b := \frac{m}{\bar{\gamma}}$ and $p := m$. Moreover, for $p \in \mathbb{N}$ the gamma distribution coincide with an *Erlang distribution Erl(b,p)* for which the *cumulative density function (cdf)*

$$G(x) = \int_0^x g(x)dx = 1 - e^{-bx} \sum_{i=1}^{p} \frac{(bx)^{i-1}}{(i-1)!}$$

is well known. For the Nakagami-m distribution with a positive integer value for the fast fading parameter m we thus obtain the cdf, $H(\gamma)$,

$$H(\gamma) = 1 - e^{-\frac{m\gamma}{\bar{\gamma}}} \sum_{i=1}^{m} \frac{\left(\frac{m\gamma}{\bar{\gamma}}\right)^{i-1}}{(i-1)!}. \tag{9.2}$$

As aforementioned, a packet is successfully received if the SNR is sufficiently large, meaning greater or equal to a defined threshold γ_R. This threshold value is typically given in dBm, the ratio of the measured power referenced to one milliwatt in decibels

$$\begin{aligned} \gamma_R &= 10 \cdot \lg\left(\frac{R_x\,[\text{mW}]}{1\,[\text{mW}]}\right) \\ R_x &= 10^{\gamma_R/10} \end{aligned} \tag{9.3}$$

where R_x is the corresponding power value in milliwatt. For an investigated transmission the corresponding SNR, γ, is determined by the received strength of the signal, S_x, and the power of the noise, N_x, on the medium

$$\gamma = \frac{S_x}{N_x}.$$

If we rule out simultaneous transmissions on the communication medium, noise on the channel results only from atmospheric disturbances denoted by an assumed constant $\bar{N}_x$. Under this assumption, the minimum transmission power required to successfully decode a bit equals the assumed power for the reception threshold given in Expression (9.3) (referenced to the constant noise level $\bar{N}_x$). In other words, with only a single sender failed transmissions are due to a too small SNR which only depends on the strength of the received signal. On the contrary, the probability of a successful bit reception is given by

$$Pr_R = 1 - \int_0^{R_x} f(\gamma(x))\ dx = 1 - H(\gamma_R). \tag{9.4}$$

A convenient way to declare the strength of a radio signal is given in the largest distance at which the message could potentially be decoded. At this distance the power of the radio signal attenuates to the reception threshold, the minimum required radio strength. While neglecting external circumstances as, for example, fast-fading and shadowing, radio propagation models assume an attenuation of the radio signal according to a loss-exponent, typically, in $\{2,3,4\}$. From the *Friis*-model which assumes a quadratic radio attenuation we can thus infer the maximum distance ψ at which receptions are still possible when a specific transmission power T_x is chosen, i.e.

$$R_x = \frac{T_x}{\psi^2} K \tag{9.5}$$

where K depends on antenna and frequency specifics. Likewise, we infer the radio strength for a specific distance d according to the Friis-model via

$$D_x = \frac{T_x}{d^2} K. \tag{9.6}$$

Using Expressions (9.5) and (9.6) as reception threshold strength and average power, respectively, we infer from Expression (9.4)

$$\begin{aligned} \Pr_R(d) &= 1 - H_d(\gamma_R) \\ &= e^{-m \frac{\frac{R_x}{N_x}}{\frac{D_x}{N_x}}} \sum_{i=1}^{m} \frac{\left(m \frac{\frac{R_x}{N_x}}{\frac{D_x}{N_x}}\right)^{i-1}}{(i-1)!} \\ &= e^{-m\left(\frac{d}{\psi}\right)^2} \sum_{i=1}^{m} \frac{\left(m\left(\frac{d}{\psi}\right)^2\right)^{i-1}}{(i-1)!}. \end{aligned} \tag{9.7}$$

For moderate radio channel conditions expressed in a relaxed fast-fading parameter $m = 3$ we thus obtain the probability of reception at distance d when a transmission power ψ according to Expression (9.5) has been chosen:

$$\Pr_R(d, \psi) = e^{-3\left(\frac{d}{\psi}\right)^2} \left(1 + 3\left(\frac{d}{\psi}\right)^2 + 4.5\left(\frac{d}{\psi}\right)^4\right) \tag{9.8}$$

9.2 Model building

In the introduction of this chapter we defined the problem space to be given by the dimensions distance between sender and receiver d, vehicular traffic density δ and transmission rate f and power ψ chosen by the vehicles. Communication performance or, in particular, the probability of one-hop packet reception impairs if communication conditions become more stressed due to increasing values in

d, δ, f or ψ, respectively. In case of a scenario involving only a single transmitter, however, the relevant factors reduce to the distance d and the transmission power ψ. Then, the probability of successful packet reception is derived from the assumed Nakagami $m = 3$ radio propagation which is given by Expression (9.8).

In general, however, many frequently transmitting nodes need to be considered which may cause interferences to the transmission in focus. Since one cannot make use of a pure-analytical representation as given by Expression (9.8) (cf. Chapter 8) we pursue a hybrid approach: by applying linear least squares curve fitting techniques to an abundance of simulation traces, we obtain an analytical term for the probability of reception. Additionally, we reveal that dependencies exist between the varying input variables, which will allow us to infer non-simulated parameter setting later on.

All of the simulations were conducted according to the following scenario setup. In order to mimic varying highway conditions, we pseudo-uniformly placed nodes on a straight line to reflect the simulated traffic density δ. In order to circumvent the 'border effects' at the two ends of the road, we based distance calculations on the arc length of a circle. This approach essentially 'eliminates' the two ends of the road by creating a torus. All of the nodes broadcast packets at the configured rate f with an equivalent transmission power of ψ meters (cf. Section 9.1).

In each simulation, the receptions of packets sent out by one specific node were recorded. To avoid correlations of subsequent transmissions triggered by the node of interest, we applied a relaxed transmission interval of one second to the selected node. With a scenario duration of 100 seconds and 30 seeds for each scenario, we thus captured up to 6000 packet receptions at each distance in every scenario (note that each distance exists on both sides of the sender). The number of simulated scenarios is determined by all combinations in the three dimensions

traffic density [veh/km],	δ:	25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500
transmission power [m],	ψ:	100, 200, 300, 400, 500, 600
transmission rate [Hz],	f:	1, 2, 3, 4, 5, 6, 7, 8, 9, 10

that do not exceed a communication density of 900 packet transmissions per second. This limit is based on the work of Jiang et al., who defined communication density as the product of transmission power, transmission rate and traffic density [JCD07], which correspond to the number of packets per second. Assuming our default packet size of 400 bytes, a communication density of 900 corresponds to approximately 2.88 Mbit/s, or, when considering the entire neighborhood of a vehicle, to 5.76 Mbit/s that almost corresponds to the available bandwidth of 6 Mbit/s. Larger communication densities would even stress the congested communication channel once more, exceed the channel's capacity what might lead to irregularities that can hardly be captured by dependencies across the problem space's dimensions.

All simulations were run on the advanced discrete-event simulator presented in Part I, Section 4.1. The results of the numerous simulation runs agree with the intuitive expectation that slight changes in the scenario set-up lead to only minor deviations in the probability of reception. In more detail, when a single *configuration parameter* (transmission power, transmission rate, vehicular density) varies little, then we expect no abrupt deviation in the probability of one-hop broadcast packet reception. Mathematically speaking, we suppose the probability of reception to be partially differentiable on the three-dimensional interval that agrees with aforementioned restrictions on the configuration parameters (e.g. communication density not larger than 900). Figure 9.1 backs this supposition and exemplarily depicts how the probability of reception varies when configuration parameters change.

In order to obtain an empirical model from the simulation runs, we applied the technique of linear least squares curve fitting to each scenario trace. We use Expression (9.8) as a starting point which is then extended to the fourth polynomial by introducing linear and cubic terms. In addition, we consider fitting parameters a_1 through a_4 to the introduced terms to take account for changing communication conditions.

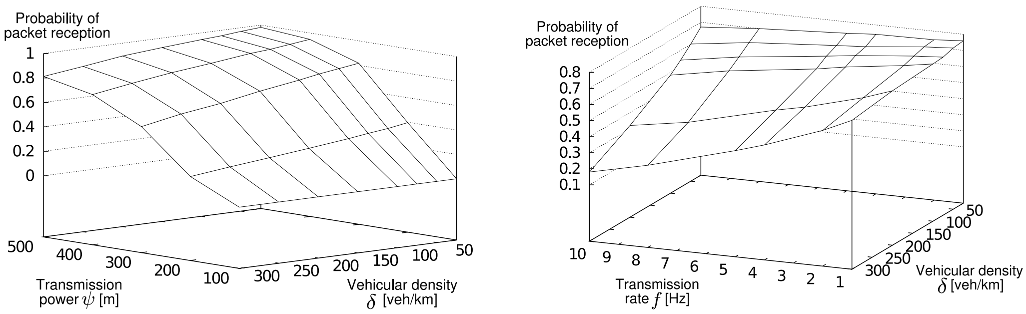
$$\widetilde{\Pr}_R(d,\psi) = e^{-3\left(\frac{d}{\psi}\right)^2}\left(1 + a_1\left(\frac{d}{\psi}\right) + a_2\left(\frac{d}{\psi}\right)^2 + a_3\left(\frac{d}{\psi}\right)^3 + a_4\left(\frac{d}{\psi}\right)^4\right) \tag{9.9}$$

Following the curve fitting process, Expression (9.9) proved to be an almost perfect match to the simulation traces for all (≈ 610) simulated scenarios. As a result of the curve fits, we obtained a set of data points consisting of the determined fitting parameters a_1 through a_4 for all scenarios. Hence, we translated the dependencies pertinent to our objective (probability of reception) from the tuple (transmission power, transmission rate, vehicular density) to the tuple (a_1, a_2, a_3, a_4) and obtained the closed-form analytical Expressions (9.9).

Now, knowing that the fitting parameters $a_i,\ i = 1..4$ only depend on the configuration parameters and assuming the differentiability of the probability of reception in the configuration parameters, we infer the differentiability of the fitting parameters in the configuration parameters. Again, this conclusion is supported by Figure 9.2, which illustrates the fitting parameters according to varying configuration parameters. At this point, our concern is to find a functional dependency that would allows us to choose the appropriate fitting parameters for a given scenario configuration. The assumed differentiability of the fitting parameters in the configuration parameters allows to apply *Taylor series* expansions to approximate the sought functional dependency by means of a polynomial. In mathematical terms, we consider polynomial functions h_i, which provide the corresponding fitting parameter a_i, respectively, for any configuration parameter tuple, i.e.

$$h_i(\delta,\psi,f) = \sum_{j,k,l\geqslant 0} h_i^{(j,k,l)}\delta^j\psi^k f^l \approx a_i, \qquad i = 1..4$$

where $h_i^{(j,k,l)}$ are the coefficients. We obtain h_i by approximating each a_i as closely as desired using a polynomial of appropriate degree N and a linear least



(a) Probability of reception at a distance of 200 m. Transmission rate fixed at $f = 2$ Hz.

(b) Probability of reception at a distance of 75 m. Transmission power fixed at $\psi = 100$ m.

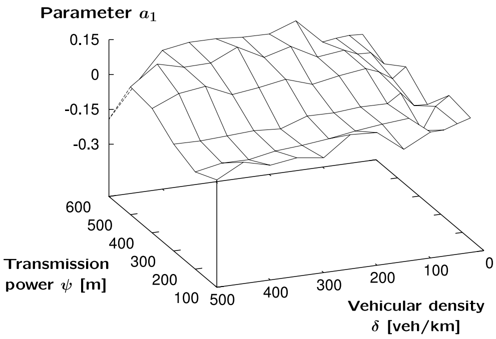
Figure 9.1: Probability of packet reception according to various configuration parameters.

squares approximation algorithm. However, due to the three-dimensional polynomial, the number of the coefficients $h_i^{(j,k,l)}$ for each a_i rapidly increases even for small N values because the number of coefficients $h_i^{(j,k,l)}$ is given by $\sum_{n=0}^{N} \binom{3+n-1}{3-1} = \frac{1}{6}(N+1)(N+2)(N+3)$. Hence, instead of achieving accuracy at the expense of complexity, in the resulting empirical model, we reduce complexity by applying generalizations, such as communication density.

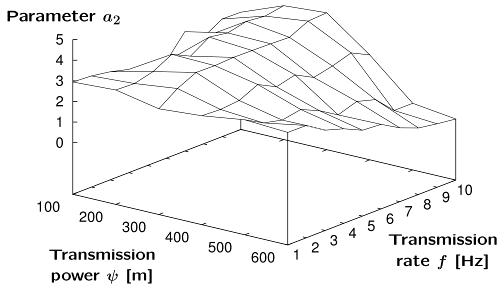
Indeed, the communication density used in the sense of abstraction seems to be appropriate since the outcomes of scenarios with the same communication density widely coincide. Figure 9.3 backs this statement and depicts matching curves of the probability of reception in various scenarios. Inspired by this relationship we downgrade the three-dimensional polynomial h_i to a one-dimensional polynomial depending only on the communication density $\xi = \delta \cdot \psi \cdot f$. However, Figure 9.4 shows significant deviations of the fitting parameters a_i from polynomials Φ_i of fourth degree based on the communication density. Obviously, there exists another relationship of the fitting parameters apart from the communication density. In order to reveal this parameter, we study the deviations of the fitting parameters a_1 through a_4 from the polynomials Φ_1 through Φ_4 applied in Figure 9.4. Table 9.2 lists the correlation coefficients of the residuals $\rho_i = a_i - \Phi_i$ to various input combinations. In particular residual ρ_2 and residual ρ_3 show

Table 9.2: Correlation coefficients of residuals ρ_1 through ρ_4 to various input combinations.

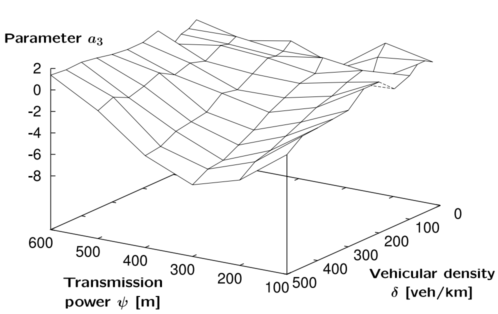
	ψ	δ	f	$\psi \cdot \delta$	$\psi \cdot f$	$\delta \cdot f$	ξ
ρ_1	**0.5910**	-0.2645	-0.2506	0.2748	0.3111	-0.5779	0.0000
ρ_2	**-0.7310**	0.2989	0.2562	-0.2938	-0.3857	0.5747	0.0000
ρ_3	**0.7055**	-0.2879	-0.2386	0.2844	0.3786	-0.5487	0.0000
ρ_4	0.1263	-0.0435	0.0208	-0.0800	0.0176	**0.1549**	0.0001



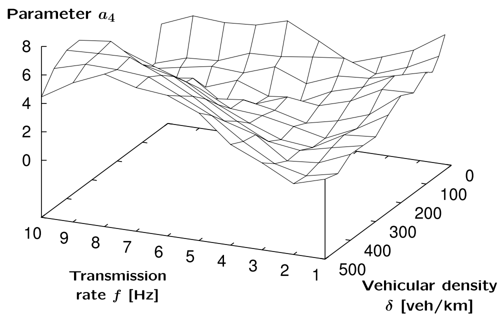
(a) Parameter a_1, tx rate fixed at $f = 2$ Hz



(b) Parameter a_2, vehicular density fixed at $\delta = 100$ veh/km

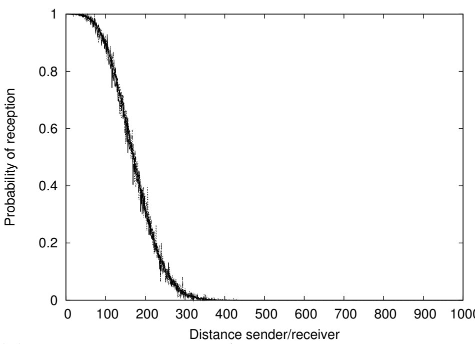


(c) Parameter a_3, tx rate fixed at $f = 2$ Hz

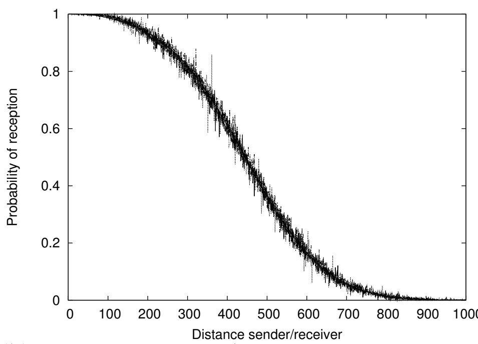


(d) Parameter a_4, tx power fixed at $\psi = 100$ m

Figure 9.2: Fitting parameters a_1 through a_4 based on configuration parameters.



(a) 5 scenarios with transmission power $\psi = 200$ m and communication density $\xi = 60000$.



(b) 5 scenarios with transmission power $\psi = 500$ m and communication density $\xi = 150000$.

Figure 9.3: Similar communication behavior (probability of reception) in differing scenarios with identical communication densities.

a noticeable correlation to the transmission power. Therefore, we choose a two-dimensional polynomial on the communication density ξ and the transmission

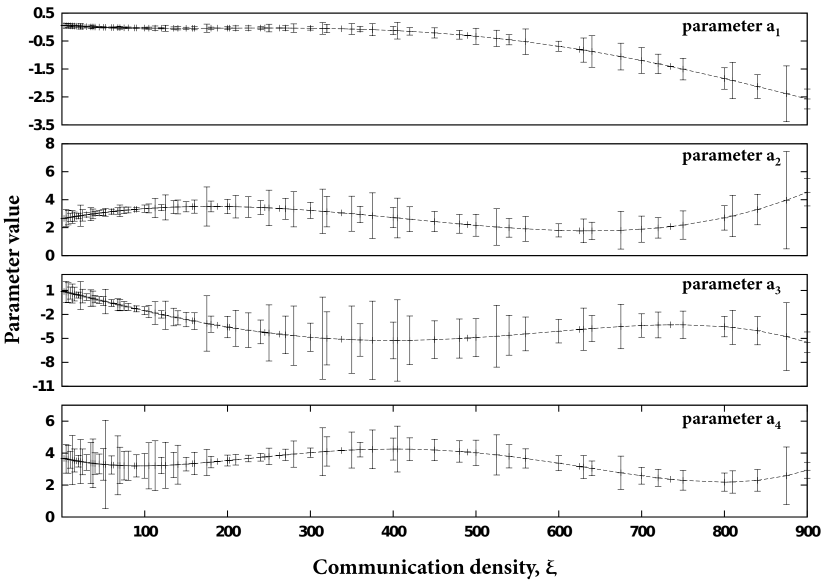


Figure 9.4: Curve fit of a polynomial (fourth degree) to fitting parameters a_1 through a_4 based on the communication density ξ.

power ψ as fitting function to the parameters a_1 through a_4.

$$a_i \approx h_i(\xi, \psi) = \sum_{j,k \geqslant 0} h_i^{(j,k)} \xi^j \psi^k, \qquad i = 1, 2 \tag{9.10}$$
$$\text{with } \xi = \delta \cdot \psi \cdot f$$

Regarding the degree of the two-dimensional polynomial we analyzed the impact of an increasing degree on the accuracy of the fitting parameter a_i. Figure 9.5 illustrates the coefficient of determination R^2 of the fitting process using the *Levenberg-Marquardt*[1] algorithm for various degrees. Based on Figure 9.5 we have chosen a two-dimensional polynomial of fourth degree for all fitting parameters in Expression 9.10, i.e. $j + k \leqslant 4$. We thus state the sought empirical model

$$\mathcal{M}: \quad \widetilde{\Pr}_R(d, \delta, \psi, f) = e^{-3\left(\frac{d}{\psi}\right)^2} \left(1 + \sum_{i=1}^{4} h_i(\xi, \psi) \left(\frac{d}{\psi}\right)^i\right) \tag{9.11}$$

and list the coefficients obtained from the polynomial functions h_i (cf. Expression 9.10) in Table 9.3. Note, although some values in Table 9.3 seem to be negligible a sensitivity analysis has shown that if a single of the $h_i^{(j,k)}$ parameter is omitted deviations in the probability of reception from 8 % to 100 % can be observed.

[1]For the curve fitting process we utilized the open source software *GRETL (Gnu Regression, Econometric, and Time-series Library)* version 1.7.1.

Table 9.3: Coefficients $h_i^{(j,k)}$ subjected to the polynomials h_1 through h_4. Although some values seem to be negligible all values significantly influence the resulting probability of reception.

	(j, k)			
	(0,0)	(1,0)	(2,0)	(3,0)
$h_1^{(j,k)}$	0.0123679	-2.25450e-06	6.36982e-12	-2.09306e-17
$h_2^{(j,k)}$	2.99714	2.53145e-05	-5.63148e-11	9.81719e-18
$h_3^{(j,k)}$	-0.610698	-6.96673e-05	1.95332e-11	1.80545e-16
$h_4^{(j,k)}$	4.15044	-9.01791e-06	1.49252e-10	-2.44958e-16
	(4,0)	(3,1)	(2,1)	(2,2)
$h_1^{(j,k)}$	1.05684e-23	-7.55774e-21	1.07606e-14	4.35680e-18
$h_2^{(j,k)}$	3.06358e-23	-8.01474e-20	1.36395e-13	-1.66585e-17
$h_3^{(j,k)}$	-1.39711e-22	1.06503e-19	-3.27537e-13	8.08115e-17
$h_4^{(j,k)}$	1.09573e-22	1.12769e-19	-4.38097e-14	-9.45343e-17
	(1,1)	(1,2)	(1,3)	(0,1)
$h_1^{(j,k)}$	4.18407e-09	-2.95060e-12	-7.17582e-15	0.00109906
$h_2^{(j,k)}$	-4.08656e-08	-7.91283e-11	8.52923e-14	-0.0152642
$h_3^{(j,k)}$	1.96554e-07	-4.45038e-11	1.49057e-14	0.0604508
$h_4^{(j,k)}$	-1.18915e-07	2.42917e-10	-1.22398e-13	-0.0389028
	(0,2)	(0,3)	(0,4)	
$h_1^{(j,k)}$	-8.53786e-06	2.19213e-08	-1.70152e-11	
$h_2^{(j,k)}$	0.000105275	-2.42757e-07	1.86228e-10	
$h_3^{(j,k)}$	-0.000411583	9.25967e-07	-6.90747e-10	
$h_4^{(j,k)}$	0.000307395	-7.01965e-07	5.05531e-10	

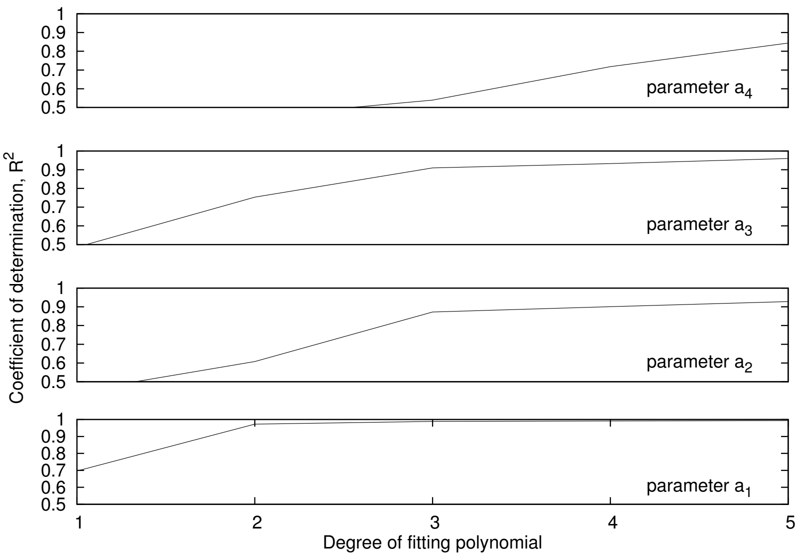


Figure 9.5: Accuracy of the fitting polynomial with varying degree to the configuration parameter a_1 through a_4.

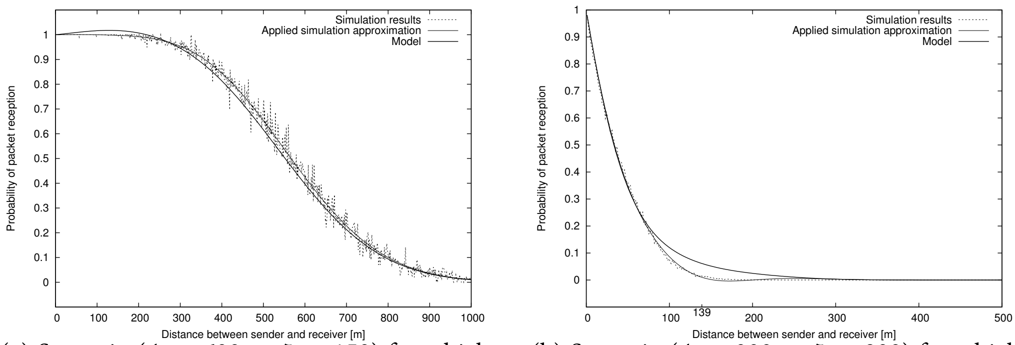
9.3 Evaluation of the model

The derived empirical model $\mathcal{M}$ is meant to be an analytical representation of the outcome of the numerous simulated scenarios generated in the previous Section 9.2. Assuming the model's validity, we can infer at least the following two benefits from the model: *i)* the model replaces an according lookup table gained from the numerous simulation results and thus saves storage and lookup efforts. *ii)* the model may allow to give suitable approximations to non-simulated scenarios, i.e. unknown data points in the problem space, later on. A third strong advantage addresses the numerical skills obtained by the analytical representation. Parameter configuration problems as for example the difficulty of optimally choose transmission power can often be given by means of an optimization problem. Solutions to such formulated problems could easily be found by numerical means if all terms of the problem are analytically available.

In the following we give in Section 9.3.1 statistical numbers to compare the model with a lookup table deduced from the simulation results and then jointly consider the second and third mentioned advantage in the following Section 9.3.2 by looking to a transmission power control problem.

9.3.1 Statistical evaluation

For each scenario, we determined the average probability of reception at each distance over all 30 seed values and computed the squared error between model and simulation results, respectively, in each distance. Instead of the simulation trace files, the comparison considers the curve fits which have been used in the model building process (see Section 9.2, Expression 9.9) in order to circumvent distorted results caused by noisy trace files. Then, taking into consideration all of the distances in the investigated scenario, we summed up the squared errors (SSEs). Across all scenarios, the average value of these sums turned out to be $\mu_{sse} = 0.037$ (variance $\sigma^2_{sse} = 0.0023$). The largest SSE of $\mu^{max}_{sse} = 0.393$ resulted from a scenario with a vehicular density of $\delta = 25$ all sending at a transmission rate of $f = 10$ Hz with a configured transmission power of $\psi = 600$ m and is illustrated in Figure 9.6(a). The figure shows the actual simulation traces, their curve fit according to Expression 9.9 and the estimation of the empirical model.



(a) Scenario ($\psi = 600$ m, $\xi = 150$) for which the maximum sum of squared errors (SSE) has been determined.

(b) Scenario ($\psi = 200$ m, $\xi = 900$) for which the maximum deviation has been determined.

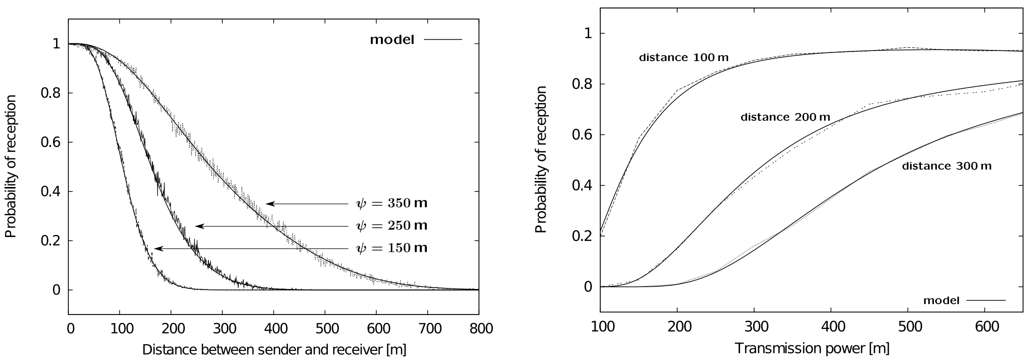
Figure 9.6: Comparison between model and simulation results

Regarding a comparison of the probability of reception determined in each distance and scenario by the model and simulation, respectively, we observed an average maximum deviation of μ_{dev} =1.4 % (σ^2_{dev} =4.92e-05) across all scenarios. The maximum deviation of 5.1 % was encountered at a distance of 139 m in a scenario with a traffic density of $\delta = 450$ vehicles at a transmission rate of $f = 10$ Hz and a transmission power of $\psi = 200$ m (cf. Figure 9.6(b)).

9.3.2 Solving optimization problems

A key problem in vehicular ad hoc networks concerns the optimal transmission power to be chosen by the vehicles. The single communication medium shared by all nodes requires a joint consideration of advantages from individual power increases, which induce interferences for surrounding nodes. An uncooperative choice of transmission power by each single vehicle, however, leads to 'uncontrolled' load on the communication channel, thus, impairing the functionality of the communication system. For MAC fairness reasons, in general neighboring nodes should cooperatively decide on a common transmission power. From the perspective of a single application, an optimal power configuration is obtained when the application's constraints are fulfilled with a minimum amount of occupied resources in order to minimize the impact on surrounding vehicles. In the following we assume an application $\mathcal{A}$ to run on all vehicles; the application periodically broadcasts packets as, e.g. envisioned by beacon messages providing information on each vehicle's status. Let us assume that for a proper functionality $\mathcal{A}$ is constrained to certain probabilities of reception, q_i, at given distances, d_i. For the sake of simplicity, we treat transmission power adjustment as the only means of changing communication conditions.

Indeed, by utilizing the model, one can infer the minimum transmission power that satisfies $\mathcal{A}$'s constraints. Assuming the application is provided with enough knowledge on the current traffic conditions, the model allows one to assess the suitability of various transmission power configurations. The assessment could focus on either the *overall* influence or on the *selective* influence of the chosen transmission power. The former evaluates the impact on any potential recipient, i.e. the probability of reception over all distances. Figure 9.7(a) exemplarily compares one simulated scenario under three various power configurations with the model $\mathcal{M}$. All of the scenario's trace files were not used in the model-building



(a) Varying distance between sender/receiver for three differing transmission powers ψ.

(b) Varying transmission powers for three differing distances between sender/receiver.

Figure 9.7: Validation of the model. The scenario involves a traffic density of $\delta = 150\,\text{km/h}$ all transmitting at a rate of $f = 6\,\text{Hz}$. The simulation traces have not been used in the model building process.

process presented in Section 9.2.

In contrast, a selective influence evaluation focuses on a specific distance for which the communication quality is studied. For the scenario underlying Figure 9.7(a), Figure 9.7(b) compares the probability of one-hop packet reception at distances of 100 m, 200 m and 300 m for the simulation results and empirical model, respectively. Obviously, the divergence between the two approaches is kept within a small limit.

We use the selective influence evaluation for determining the minimum transmission power that will meet the application's constraints. Typically, one of the constraints dominates the others, i.e. the dominant constraint requires a certain (dominant) transmission power; however other constraints would likewise be satisfied under different power configurations. By utilizing the model $\mathcal{M}$, $\mathcal{A}$'s dominant transmission power is determined by numerically solving the optimization problem:

$$\begin{array}{ll} \min & \psi \\ \text{subject to} & q_i - Pr_R(d_i, \delta, \psi, f) \leqslant 0, \qquad \forall i \end{array}$$

where q_i represents the aforementioned target probability of reception at distance d_i.

In the following, we compare the computed dominant transmission powers for the scenarios outlined in Table 9.4 with the simulation results. The simulations were not used in the model-building process and differ in that the reference vehicle also adapts to the commonly chosen transmission rate.

The three curves in Figure 9.8 represent the probability of reception at distances of 100 m, 200 m and 300 m in scenario A gained by simulations means. Obviously, the analytical solutions to meet constraint 1 (ψ_1 = 245 m), constraint 2 (ψ_2 = 364 m) and constraint 3 (ψ_3 = 444 m) diverge only slightly from the simulative results. The computed solution to meet all constraints agrees with the dominant constraint 3 and corresponds to a communication density of 444.

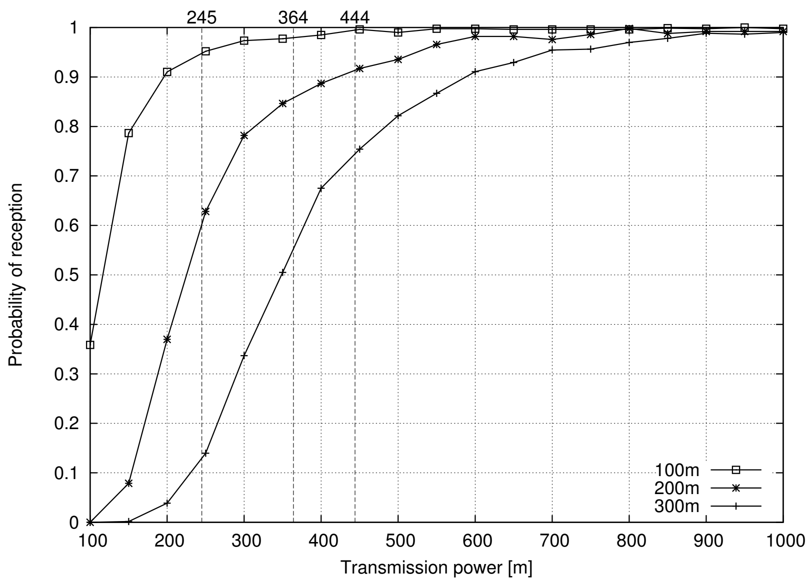


Figure 9.8: Scenario A (cf. Table 9.4) – Probability of packet reception w.r.t. chosen power value: analytical computation (numbers) and simulative results (curves).

Table 9.4: Scenario set-ups

Scenario	δ [veh/km]	f [Hz]	q_1 at 100 m	q_2 at 200 m	q_3 at 300 m
A	125	2	95%	85%	75%
B	250	1	90%	90%	90%
C	200	5	85%	65%	50%

Figure 9.9 illustrates the results for scenario B with relaxed traffic conditions but tightened constraints. Again, only a small divergence between the analytical and simulative solutions is noticeable.

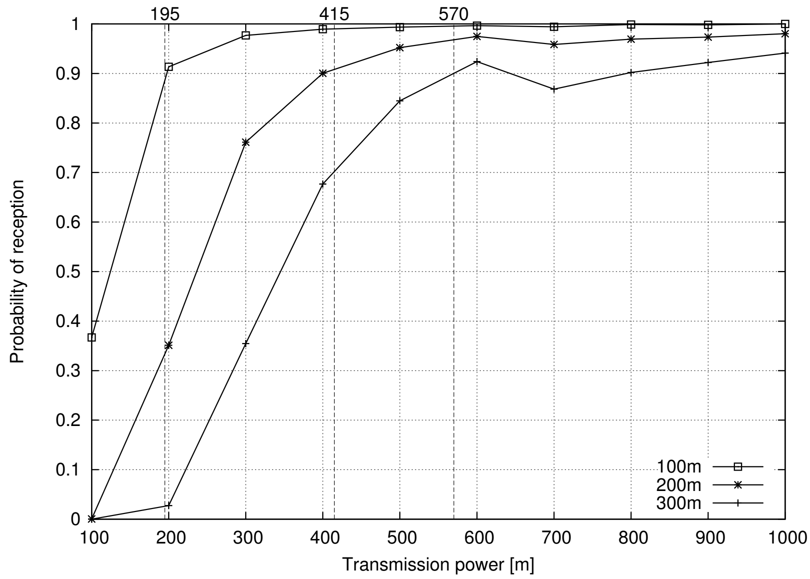


Figure 9.9: Scenario B (cf. Table 9.4) – Probability of packet reception w.r.t. chosen power value: analytical computation (numbers) and simulative results (curves).

Finally, Figure 9.10 depicts the results for scenario C. Again, the deviations of results gained from simulation studies and model, respectively, are kept within a small limit. Additionally, the numerically computed solution to constraint 3 is dominant since it agrees with the solution to the optimization problem which demands all constraints to be fulfilled at the same time.

Although the three discussed scenarios have demonstrated the usefulness of the empirical model for dealing with the transmission power control problem, for best results, we highly recommend obtaining knowledge about the current traffic situation in advance. In reality, additional (communication) effort is required to provide vehicles with information in order to allow a precise estimation of the current communication density. If this condition is fulfilled, the presented approach may prove useful for choosing a suitable transmission power or other parameter optimization problems.

Summarizing, the discussion on the transmission power control problem has shown the model's suitability to be used in numeric operations in oder to solve optimization problems tailored to parameter configurations. Secondly, the model evidently allows to approximate non-simulated data points in the defined problem space spanned by the dimensions distance, transmission power, transmission frequency and vehicular density.

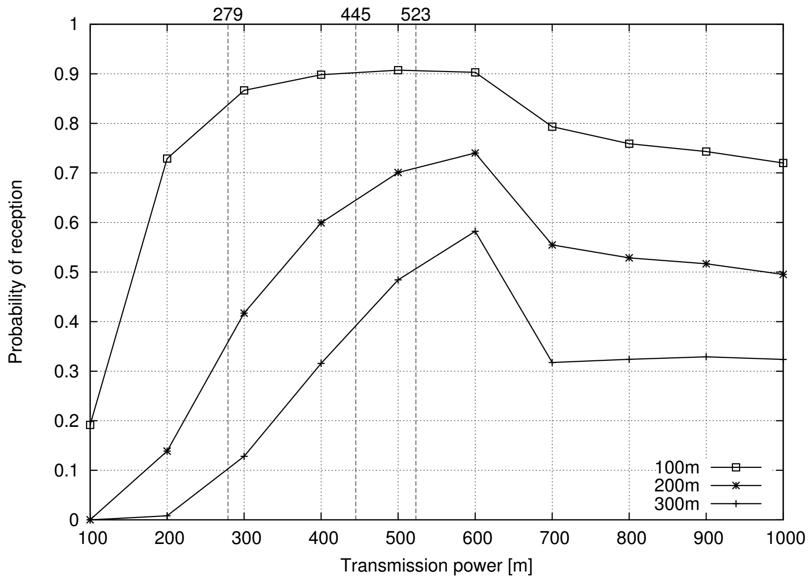


Figure 9.10: Scenario C (cf. Table 9.4) – Probability of packet reception w.r.t. chosen power value: analytical computation (numbers) and simulative results (curves).

10 Hybrid Simulation

This chapter discusses our implementation of a hybrid simulation architecture in order to simulate inter-vehicular communication scenarios for traffic efficiency applications. In the subsequent Section 10.1 we will describe the components of the simulation framework and the procedure of interaction among the building blocks. In Section 10.2 we demonstrate in first sample scenarios the performance of the hybrid simulation architecture and show the results of preliminary impact studies.

10.1 System architecture

As depicted in Figure 10.1 the simulation framework consists of three building blocks responsible for the vehicular traffic, the communication among vehicles and for the behavior of traffic efficiency applications. In particular, we consider *i)* the traffic simulator VISSIM to take care of the vehicular traffic flows, *ii)* a module called *VCOM* responsible to determine successful packet transmissions and *iii)* an *Application* module triggering and processing wireless messages and, in case, inducing an adjusted driving behavior. The distinct modules are connected among each other by well defined interfaces. The type of interface is chosen considering the following constraints: software systems already available (VISSIM), degree of interaction between the modules, and usability for future users of the simulator. In the following the design of the different modules and interfaces will be described in more detail.

The traffic simulator VISSIM has been chosen as the controlling instance in

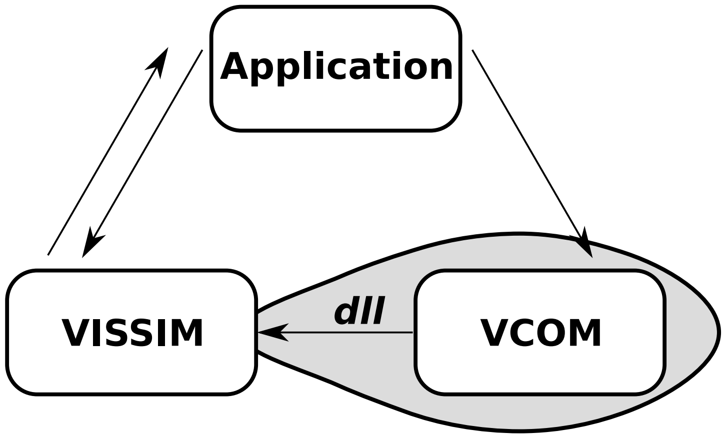


Figure 10.1: Proposed architecture consisting of the vehicular traffic simulator VISSIM, the VCOM module responsible for simulating inter-vehicle communications and the application module specifying the driver's behavior on reception of messages. Arrows represent method invocation calls among the modules.

this architecture for the following reasons. In contrast to the simulation of communication which operates on a time scale in nanoseconds, VISSIM assumes 100 ms as finest grained simulation resolution. Yet, one second timesteps are typically considered for large-scale scenarios. Consequently, communication events which fall into a VISSIM step and which may invoke a changed driving behavior, cannot be considered before the next VISSIM step, anyhow. Additionally, VISSIM operates in a *fixed-increment time advanced* manner. Thereby a continuous movement of the vehicles is guaranteed. Contrarily, communication simulators typically advance in a *next-event time-advance* manner where the sequence of (communication) events determine the process of simulation. In particular for the simulation of vehicular traffic this procedure leads to the undesired effect of 'jumping' vehicles.

VISSIM provides two newly implemented interfaces to the other two modules and coordinates/triggers them. The interface to the Application module is used between every two successive movement steps when VISSIM passes the control to the Application module and waits until the control is returned. The second interface of VISSIM is provided to the VCOM module in order to allow VCOM to efficiently obtain information on the scenario's environment. Since this information exchange is triggered by VCOM only, a detailed discussion is postponed to the presentation of VCOM.

After having obtained the control of the simulation process, the Application module checks for inter-vehicle communication events waiting to be processed. Events in this sense may count as received messages which still need to be evaluated or as observations of the environment which may cause the transmission of wireless messages. In order to gather contextual information on the environment the Application module makes use of a dedicated interface to the traffic simulator

VISSIM. The queried information itself, its actual processing along with possible consequences to the communication and driving behavior are left to each specific application. Therefore an application frame is provided which needs to be filled by every application designer. A further discussion is given in the subsequent Section 10.1.1.

For transmissions and receptions of wireless messages the Application module contacts the VCOM module. Since the reception of a message may again induce the transmission of an additional message (and, vice versa, a transmitted message may cause additional receptions) the Application and the VCOM module need to play a 'ping-pong' game which is captured in Figure 10.2. In this game the Ap-

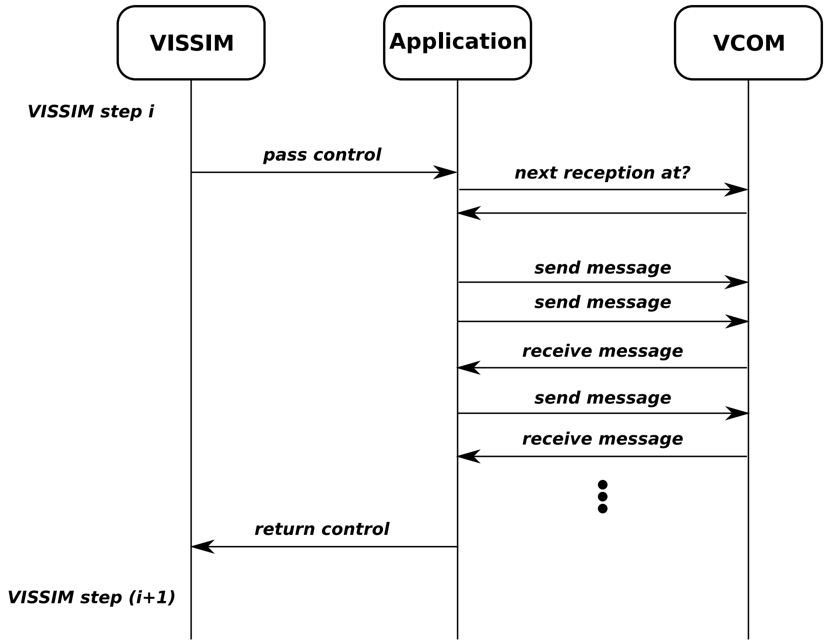


Figure 10.2: The flow chart sketches the interaction of the three components VISSIM, Application and VCOM.

plication module takes control and warrants time synchronization between both modules. When interaction with the VCOM module has taken place, the Application module is informed on state changes in the VCOM module in terms of next receptions to come. Having this knowledge, the Application module can schedule new transmissions and upcoming receptions in a synchronized manner. When this ping-pong game has advanced to VISSIM's next time step, the Application module returns control to VISSIM. At this point the presented implementation assumes the Application module to additionally pass information on an adjusted driving behavior for certain vehicles to VISSIM. VISSIM incorporates the modifications, performs a movement step for all vehicles and starts the repetition of the delineated procedure.

The reason for the hybrid characteristic of the presented architecture is given in the VCOM module. VCOM facilitates an instantaneous processing of the messages generated by the Application module without neglecting the impact of communication traffic apart from the considered application. In vehicular ad hoc networks, communication resulting from beacon messages, for instance, can typically be conceived as such remaining or 'background' communication traffic. Clearly, an increasing amount of background traffic impairs the conditions for the messages of interest and thus the performance of the application to be evaluated. For this reason, VCOM makes use of the empirical model presented in Chapter 9 to determine packet receptions of the application based on the impact of background communication. Information on the required input parameters to the model are obtained via an interface to VISSIM. Since the amount of information queried over this interface easily increases with frequent transmissions and potentially many recipients, an efficient coupling using shared memory is considered. Hence, VISSIM incorporates VCOM as a *dynamic link library (dll)* which allows direct method invocation. This approach facilitates runtime performances significantly outperforming previously available interfaces to VISSIM. Regarding advancements in time, VCOM implements priority queues to keep track of upcoming packet receptions. A statistical correct distribution of reception times may likewise be determined as demonstrated for the probability of packet reception. For the sake of simplicity this implementation considers a Gaussian distribution with configurable mean and variance added to the propagation delay of the message.

10.1.1 Application programming interface

As described in the previous Section 10.1 VISSIM passes simulation control to the Application module after having performed a movement step for all vehicles. After all application events that happen within the current VISSIM step have been processed the Application module returns control back to VISSIM and the next movement step is computed. Within a timestep the application iterates through a generic framework sketched in Listing 10.1.

```
<ENTRY POINT OF VISSIM>
WHILE (time < next vissim step) DO
  IF (event exists that triggers a transmission) THEN
    send $message
  ELIF (next reception time < next vissim step) THEN
    receive $message
    process $message
  FI
DONE
<RETURN TO VISSIM>
```

Listing 10.1: Generic framework of application code

The 'intelligence' of the application consists in deciding under which conditions a message should be generated and sent and in processing the received messages properly, i.e. modeling the 'behavior'.

The application proceeds as long as operation do not surpass the point in time at which VISSIM computes the next movement. Firstly, the application checks whether any incidents cause a node to send out messages. Secondly, all messages received in the current VISSIM step are fetched from the VCOM module. The processing of the fetched message may invoke an interaction of the Application module with VISSIM but likewise the transmission of additional messages. Consequently, the set of messages to be received within a VISSIM step may vary over time. Finally, when either the point in time of the next VISSIM step is reached or no further operations of the application are left to process, the control is given back to VISSIM. This return may also include final instructions to VISSIM how to adjust the driving behavior of certain vehicles. VISSIM now considers the data exchanged with the application and computes the vehicles' next position before the control is again passed to the application.

In order to evaluate and to take influence on the current traffic simulation the application may request and modify several information in VISSIM. The present implementation provides interfaces to obtain and alter information on the position, speed, acceleration and movement vector of all vehicles. Furthermore, communication primitives to send and receive messages are provided to interact with the communication module VCOM. All interfaces are supported for the programming languages *Python* and *C++*. Note, that comfort in the development gained with the programming language Python contrarily causes a lower simulation performance.

10.2 Simulation study

In this section we make use of the presented hybrid simulation architecture and analyze a traffic efficiency problem in two scenarios. The first scenario considers a bottleneck situation on a two lane highway caused by a reduction of lanes to only a single one. The second scenario deals with a well-calibrated 33 km piece of motorway in the state of Hessian in Germany. In both scenarios we take the perspective of a traffic management authority who is interested in an optimized traffic throughput and can take influence on the traffic behavior by means of vehicle-to-x communication. We assume that the infrastructure-vehicle communication link is likewise based on the IEEE 802.11p mechanism and thus meets the communication behavior captured in the VCOM module.

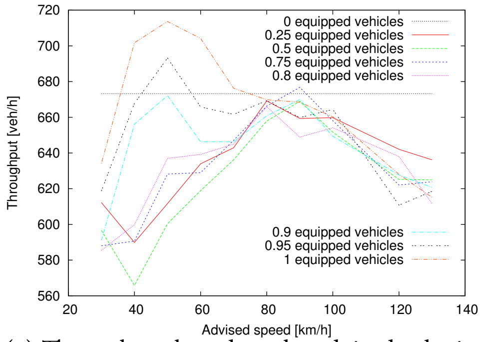
We acknowledge the support of the traffic management authority of the state of Hessian (Verkehrszentrale Hessen) and the effort spent by the Technical University of Munich for calibrating the used motorway track. The underlying complexity of the scenario let us refrain from applying major modifications in order to study 'exceptional' traffic incidents and the potential impact of inter-vehicle communication for mitigation. Therefore, we decided to firstly focus on a small scale scenario and to investigate how an increasing ratio of radio equipped vehicles can effect the throughput performance at a bottleneck situation in more detail. Still, since the hybrid simulation architecture was primarily designed for large-scale scenarios we will return in a second scenario to the Hessian highway and also discuss the runtime performance.

10.2.1 Small-scale scenario

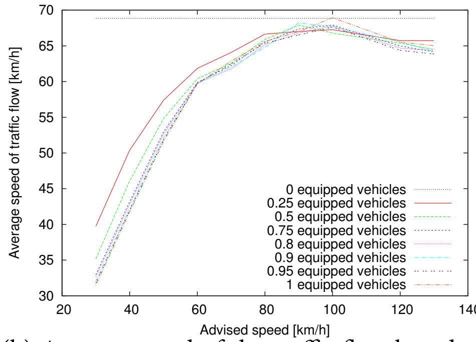
In case of a construction site on highways often driving lanes need to be closed. Nowadays, mostly static traffic signs inform approaching vehicles on the situation and advise the drivers to reduce velocity independently of present traffic conditions. If vehicles are equipped with radio technology directions dynamically given by a traffic management center could improve conditions in front of the construction site. Naturally, in the first instance, only radio equipped vehicle would at all react on disseminated instructions. The following experiment thus explores which speed advices the traffic management center disseminates at best to maximize the throughput at the bottleneck based on the ratio of equipped vehicles and on the current traffic density. In case vehicles do not receive speed advisories they continue driving by the configured default speed distributed around 90 km/h.

Evaluation

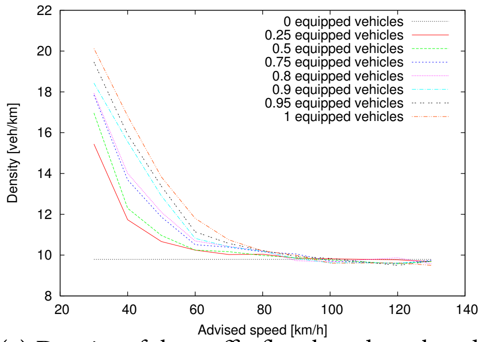
Figure 10.3(a) visualizes how the traffic throughput changes if different velocities are transmitted to the vehicles. Depending on the radio penetration rate a maximum throughput is either achieved for an advised speed of 50 km/h or for 90 km/h which corresponds to the average speed of the non-equipped vehicles. This result may already help traffic authorities to choose proper actions but our investigation expands on the underlying effects. Traffic engineers define traffic throughput as the product of average speed and density of the traffic flow. Figure 10.3(b) depicts a similar average speed of the traffic flow for all investigated radio propagation rates and thus can likely be omitted as key indicator for the differing throughput results. On the other hand, however, the traffic density shows notable deviations for small advised velocities across the penetration rates (cf. Figure 10.3(c)). Furthermore, Figure 10.3(d) illustrates a significantly varying number of conducted overtaking maneuvers along with the differences observed regarding the density. Indeed, the interdependency of both factors, density and overtaking maneuvers, reflects in Figure 10.3(e) which suggests what traffic engineers call a *harmonization* of the traffic flow. In a disharmonized traffic flow velocity discrepancies lead to overtaking maneuvers and interrupt the seamless progress of the flow and, as a consequence, involves a decreasing traffic throughput. Figure 10.3(e) illustrates this effect and visualizes by darker colors a decreasing traffic throughput with an increasing number of overtaking maneuvers for a fixed traffic density. Finally, Figure 10.3(f) summarizes the discussion above and may serve as a lookup table which speed advisory to be used for which conditions: given an



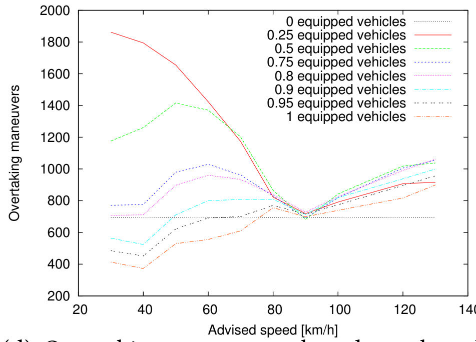
(a) Throughput based on the advised velocity



(b) Average speed of the traffic flow based on the advised velocity



(c) Density of the traffic flow based on the advised velocity



(d) Overtaking maneuvers based on the advised velocity

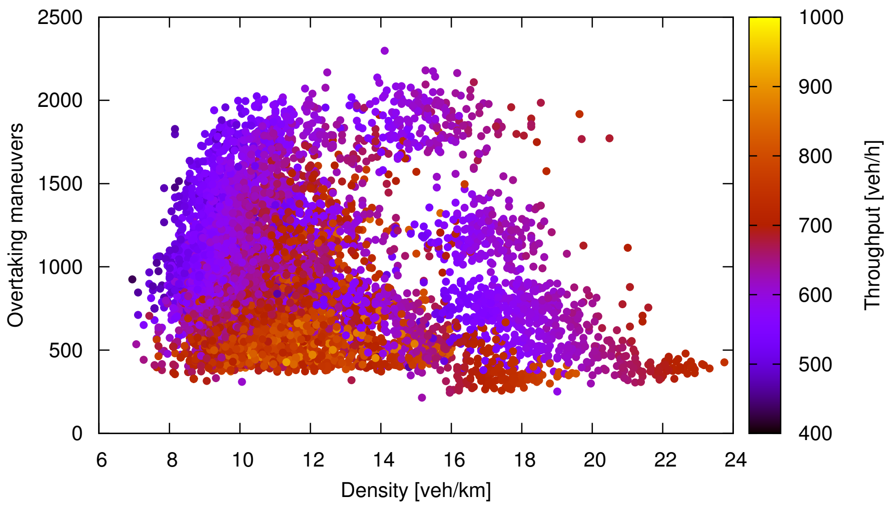
Figure 10.3: Evaluation of the small-scale simulation study

observed traffic density and knowing the ratio of radio equipped vehicles, the figure answers which advisory to be applied in order to maximize the throughout at the bottleneck.

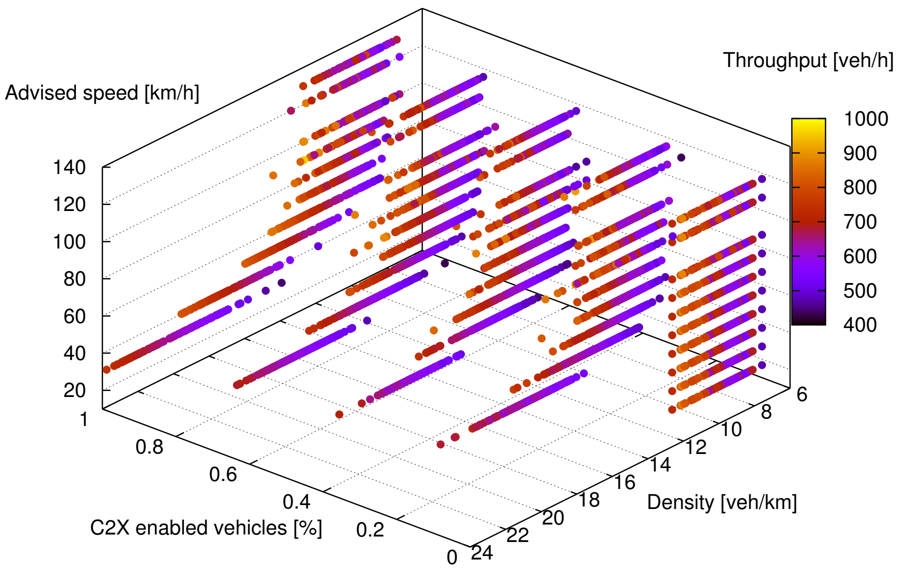
Runtime performance analysis

The presented evaluation study is based on 100 simulation runs lasting for 2 000 s each for all configurations w.r.t. radio penetration rate and speed advice. Depending on the configuration, the number of simultaneously simulated vehicles and the communication effort varies. The most demanding configuration results from a scenario which has all vehicles equipped with radio technology and which advises the vehicles to drive at a low speed. Thereby, the number of simultaneously simulated vehicles and thus the computational effort maximize. For this most demanding scenario, we measured 29 ms in average for a single 1 s time step having involved approximately 100 vehicles all transmitting one message per second. The including communication effort amounts to 12 ms of which 10 ms are owed to a default synchronization effort between VISSIM and the VCOM module.

We refrain from a runtime comparison to a pure discrete-event simulation approach coupling VISSIM with the network simulator NS-2 since a coupling of



(e) Traffic throughput based on overtaking maneuvers and on the traffic density



(f) Traffic throughput based on the density, the ratio of equipped vehicles and on the advised velocity

Figure 10.3: cont'd.

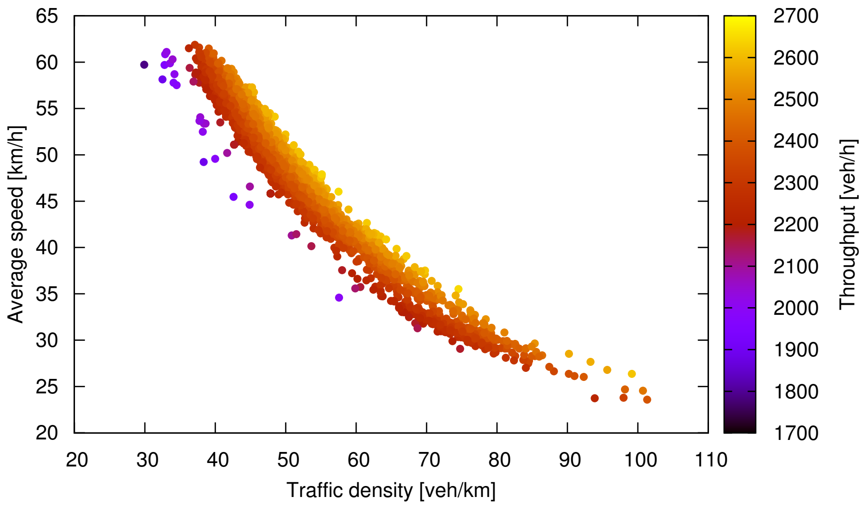
both simulators requires, from a performance perspective, an unfavorable TCP socket connection distorting the comparison. Instead we focus on the effort required for the communication system only and determine the runtime required for NS-2 to simulate one second of 100 communicating nodes all transmitting packets at a rate of one hertz. On an Intel Dual Core processor running at 2 GHz the latest NS-2 release [ns] took in average 100 ms over 100 seeds without considering the configuration overhead like the initialization of nodes, for instance. Although the claimed real time constraints are not endangered, the proposed hybrid simulation approach outperforms NS-2 by a speed-up factor of 50. For an increased number of communicating nodes the proportion further evolves to the benefit of the hybrid simulation approach as being demonstrated in the succeeding large-scale study.

10.2.2 Large-scale scenario

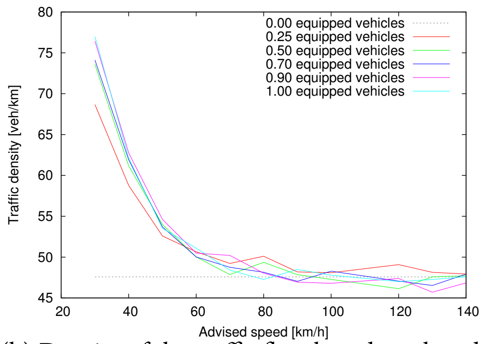
In this scenario we keep the perspective of a traffic management authority and disseminate speed advices in order to maximize traffic throughput. The scenario layout comprises 33 km highway in average populated with 1 200 communicating vehicles. Our modifications to stress traffic conditions concern two inflows to the highway on which an increased number of vehicles enters the street network distributed around an average velocity of 90 km/h. Additionally, we disharmonize the traffic flow by means of a few non-radio equipped trucks running at an average velocity of 50 km/h. Again, goal of the experiment is to determine the most suitable speed advice depending on the ratio of equipped vehicles and the current traffic density.

Evaluation

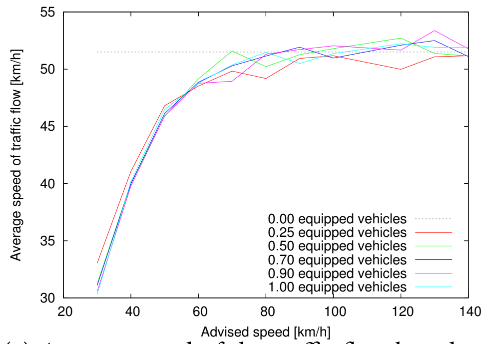
Figure 10.4(a) reintroduces the definition of throughput composed as the product of traffic density and average velocity. Obviously, the maximum throughput is attained at the upper edge of the collected data points. However, this figure does not allow to determine which constellation of average speed and traffic density ensures best performances w.r.t. the traffic throughput. For a traffic management authority it is therefore hard to decide whether their control should attempt conditions for the data point $P_1(\text{density, avg speed}) = (45, 55)$ or for the data point $P_2 = (60, 40)$ both promising a high throughput. Indeed, control on the density and average speed of the traffic flow is given to the road operator by means of speed advices disseminated to radio-equipped vehicles via vehicle-to-x communication. Figure 10.4(b) and 10.4(c) illustrate the impact which speed control may have on the density and the average speed, respectively, which both do not differ much in the radio penetration rate. A mapping of Figure 10.4(b) and 10.4(c) to Figure 10.4(a) is illustrated in Figure 10.4(d) which shows 5 % of the data points of Figure 10.4(a) and reveals the actual consequences of applying speed control mechanisms on a traffic flow. The dashed ellipses in Figure 10.4(d) label clusters of speed advices indicating that above 50 %, the radio penetration rate loses influ-



(a) Traffic throughput based on the average speed and the density of the traffic flow



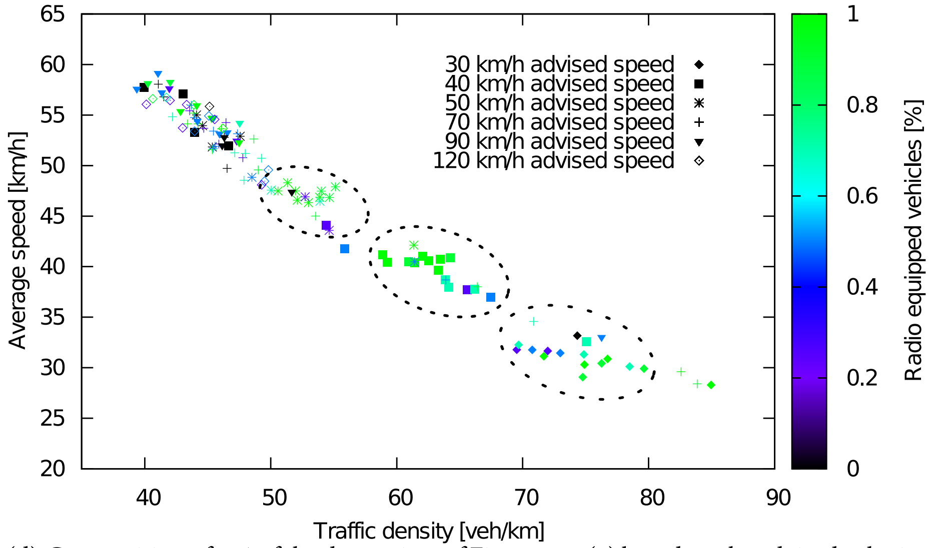
(b) Density of the traffic flow based on the advised velocity



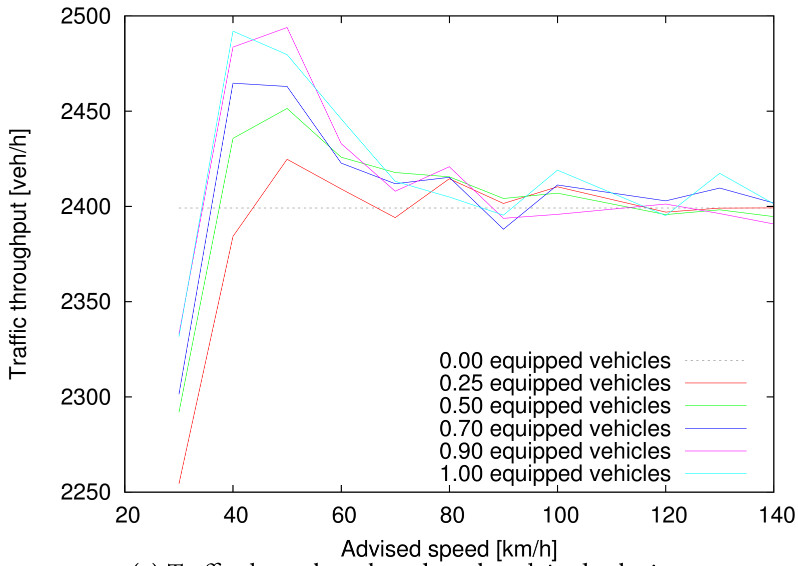
(c) Average speed of the traffic flow based on the advised velocity

Figure 10.4: Evaluation of the large-scale simulation study

ence on the resulting traffic conditions which then only depend on the used speed advice. With this insight we return to the aforementioned question on the traffic conditions the road operator should go for. P_1 turns out to be a mixture of random combinations of advised speed and penetration rate. On the other hand, P_2 is covered by the cluster of 40 km/h advised speed which suggests that these conditions are likely to be obtained when the found speed advice is applied. Figure 10.4(e) backs this suggestion and illustrates the throughput based on the advised speed. Depending on the radio penetration rate the maximum throughput is achieved when a speed order of 40 to 50 km/h is disseminated.

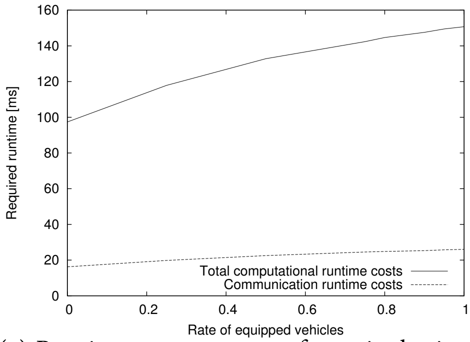


(d) Composition of 5 % of the data points of Figure 10.4(a) based on the advised velocity and the radio penetration rate. Ellipses indicate clusters of data points belonging to the same advised speed.

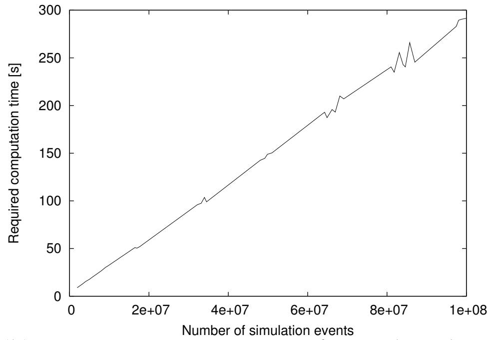


(e) Traffic throughput based on the advised velocity

Figure 10.4: cont'd.



(a) Runtime measurements for a single simulation step and for the communication behavior only, respectively, based on the radio penetration rate. On average, 1 500 communicating vehicles are simulated simultaneously.



(b) Runtime measurements of NS-2 based on the number of simulation events. Measurements were taken on an Intel Dual Core at 2 GHz platform and the latest NS-2 release [ns].

Figure 10.5: Runtime measurements taken for the large-scale simulation scenario using the hybrid simulation approach and for the discrete-event network simulator NS-2.

Runtime performance analysis

We have based this evaluation on 100 simulation runs each comprising 2 000 simulation seconds. Over the entire duration of the scenario 1 000 to 3 000 vehicles have been simultaneously simulated of which 2 400 have been equipped with radio technology at the maximum. On average, 1 500 radio-equipped vehicles have been simulated at the same time. Figure 10.5(a) presents the required average runtime of a single simulation step across all taken steps based on the fraction of radio equipped vehicles. The slight increase of computation time with an increasing radio penetration rate for the total time step as well as for the computation of communication can be fully ascribed to the simulated application behavior which adjusts the desired speed values of vehicles. Without this application implementation the computation of a single time step constantly takes 93 ms and 15 ms for the communication behavior only.

In order to estimate the gain in runtime performance of the hybrid simulation tool compared to a pure discrete-event approach, we carried out a performance evaluation of NS-2. Therefore, we considered various scenario setups and measured the required computation time based on the overall number of simulation events registered in the global scheduler of NS-2. Figure 10.5(b) illustrates the outcome and a computation runtime linearly increasing with the number of simulation events. As a rule of thumb, the figure suggests one minute of computation to be required for 20 000 000 simulation events.

Considering the back of the envelope calculation in Section 7.2.1 which estimates the number of simulation events based on the number of communicating nodes n and their transmission frequency f by $3f(n^2 - n)$, we infer for $n = 1\,500$ vehicles and $f = 1$ Hz 6 745 500 simulation events. The resulting estimated runtime of 23 s slightly falls below measured computation times of 30 s in comparable NS-2 simulations but still shows a performance loss of three orders of magnitude compared to the hybrid approach.

10.2.3 Conclusions

This section has demonstrated the usefulness of the devised hybrid simulation architecture for impact assessments of vehicle-to-x communications on traffic efficiency. In two sample scenarios we have shown that indicators for best control actions taken by a traffic control center can be efficiently gained via the presented tool. The scenarios studied a problem which will likely draw attention when vehicles become equipped with radio transceivers: in the first instance only few cars will have the technology and are able to react on driving orders at all thus leaving uncertainties on the consequences to the overall traffic flow. As a joint conclusion from the two discussed scenarios we deduce that the investigated means of a speed advice seems to effect traffic conditions not before a fraction of 50 % of equipped vehicles is exceeded.

11
Résumé

In this part of the thesis, we took care of a modeling of the building blocks tailored to traffic-efficiency studies. Contrarily to Part I of the thesis, the design criteria of the models became primarily scalability in order to allow for an appropriately large number of communicating vehicles required to assess the efficiency of traffic flows. Among the identified key building blocks, application, mobility, and communication scalability problems have been mainly identified for the latter mentioned research discipline, which has offered accurate but computational consuming models so far. For an implementation in simulation tools, we therefore proposed a hybrid approach that combines a discrete-event simulation of application and mobility with an analytical representation of the communication behavior. A key prerequisite, however, is an appropriate analytical model, which has not been proposed in a comprehensive manner so far.

Since a joint treatment of the multiple factors influencing communication conditions in vehicular ad hoc networks seems too complex to be derived in a pure analytical manner, this work proposed a remedy by empirical model-building. In principle, we considered a problem space that abstracts from the detailed (and thus computationally intensive) behavior of communicating nodes and describes a key metric, the probability of packet reception, based on major parameters of the scenario's layout. The dependencies among input parameters and goal function (probability of packet reception) have been derived analytically for simple, and empirically for more complex, scenarios. The empirically gained knowledge has been derived by exploiting an abundance of simulation traces widely covering the defined problem space. An evaluation against simulation results has proven the validity of the model and thus opened the door for accurate large-scale simulations of VANETs in a hybrid simulation architecture.

Summarizing, this part of thesis proposed the following contributions.

- A method to build an empirical model on the probability of packet reception based on the input parameters distance between sender and receiver, transmission power, transmission rate, and vehicular traffic density has been proposed.

- As has been demonstrated in a sample application, the derived model is capable of serving as a valuable means in parameter configuration problems.

- The integration of the empirical model into a hybrid simulation software architecture enables efficient simulation studies allowing for thousands of communicating vehicles. In two simulation studies, we have demonstrated the usefulness of the architecture to assess inter-vehicle communication-related problems about vehicular traffic.

The demonstrated methodology to abstract from a high fidelity model to more general terms has proven to be a viable possibility to circumvent scalability problems in simulation studies. We have shown the approach's feasibility for a given set of parameters and for one required goal function in vehicular ad hoc networks. Future work can follow the same procedure to obtain results for varying preconditions or changing objectives. For example, regarding the set of assumptions taken in this work, an additional model on the delay of packet delivery might be of use for certain simulation studies.

This part's motivating question on how to manage scalability problems is not necessarily the only reason for abstracting details of a considered system in higher-level models. For many simulation purposes, a comprehensive consideration of all details simply appears superfluous, since small changes in part A of the considered system do not relevantly influence the performance in part B. A radio expert, for instance, who needs to figure out optimal antenna parameters does not inevitably depend on a detailed modeling of an application. In fact, such details could unnecessarily raise the computation effort of the simulation study; a simple model that, for example, estimates the frequency of packet transmissions might turn out to be sufficient for the evaluation goal. We will further elaborate on these considerations in Chapter 12.2, in which future perspectives are addressed.

12 Conclusions and Perspectives of the Thesis

12.1 Conclusions

This thesis took care of an impact assessment of VANETs on the two application domains of vehicular traffic safety and vehicular traffic efficiency. In contrast to previous research on VANETs, which typically investigated quality of service measures of the communication system, the focus of this thesis required a quality of service inspection in the application domain; prime metrics are exemplarily given in the number of traffic accidents or in the traffic throughput. Whether accidents can be avoided or throughputs of traffic flows can be increased can hardly be answered in general terms but rather requires a focus on specific traffic situations. From an engineering perspective, this necessitates the availability of a modeling tool set to create and to evaluate traffic situations that are expected to benefit from the application of VANETs.

Classical research on communication made a distinction between the networking behavior, on the one hand, and the applications operating in the communication system on the other hand. VANETs require the additional consideration of mobility, which influences the application's and communication's behavior alike. The thesis hence identified the three essential building blocks, namely application, mobility, and communication, required to model VANETs. The two pursued evaluation goals, vehicular traffic safety and vehicular traffic efficiency, however, have differing demands of the building blocks, which is also reflected in the design of the applied models. This thesis has discussed the building blocks for traffic safety and traffic efficiency studies, respectively, has implemented simulation tools, and assessed the impact of two VANET applications in simulation experiments. Details are outlined in the following sections.

12.1.1 Vehicular traffic safety

The considered evaluation of improved traffic safety by measuring the number of traffic accidents is challenging, since the rare incident of an accident only results from a very specific constellation of many influencing factors. The thesis was therefore intent on presenting a detailed representation of the building blocks, which is reflected in the following requirements and contributions.

Modeling

1. Communication
   If additional information about the traffic situation can help to prevent accidents from actually happening, it is decisive to know at which point in time the information is available to the car/driver entity. The thesis therefore made use of available simulation models that provide a detailed representation of the networking behavior and thus provide accurate information on packet receptions and the respective points in time.

2. Application
   Even if the communication system could immediately deliver every transmitted message to each intended recipient, an impact assessment on accidents requires knowing how to deal with the gained information set. The thesis addressed this problem, adopted an existing approach to model a decision-control problem, and provided a specification of a traffic safety application based on a Markov Decision Process modeling. The thesis contributed an advanced modeling by providing:

   (a) a mapping of traffic situations to system states,

   (b) a derivation of transition probabilities among system states by making use of vehicular traffic simulators, and

   (c) an advanced modeling of the MDP taking the specific application domain into account. The proposed contribution concerns the discount factor, which is usually required to ensure convergence in the evaluation of MDPs but likewise degenerates the valuation of future system states. In VANETs such a modeling would cause the irrational effect of less severe accidents happening in the future. The modeling of absorbing system states introduced by the thesis, however, avoids the (mathematically) necessary discount factor and thus achieved a more accurate problem specification.

On the other hand, the MDP model has likewise revealed the computational complexity underlying traffic safety applications. As a consequence, the application block will need to consider algorithms based on a relaxed problem specification of vehicular traffic safety.

3. Mobility
The thesis surveyed existing approaches to model mobility in a vehicular environment and referred to advanced models replicating vehicular traces in a somewhat realistic manner. On the other hand, available (vehicular) mobility models have shown inadequacies where traffic safety is concerned since the concept of an accident is not considered. The thesis therefore proposed an extension to the popular Wiedemann mobility model.

   (a) Compared to Wiedemann's original proposal, the thesis suggested a modeling to allow for overtaking maneuvers on highways. An implementation of the extended model has been successfully validated against the traffic simulator VISSIM in sample scenarios.

   (b) The proposed model enables the possibility to consider imperfections introduced by humans and thereby provokes accidents to happen. In particular, careless overtaking maneuvers are addressed by modeling an inattentive driver who does not check for safe traffic conditions.

   The proposed mobility model has been incorporated into the traffic simulator VISSIM and thus allows for traffic safety studies by simulation means.

Simulation study
As a result of the discussion on appropriate models, the thesis has proposed a simulation tool incorporating the results of the respective building blocks. In a simulation experiment, a VANET application is assessed that aims at preventing traffic accidents in overtaking maneuvers. The assessment study has revealed how a varying amount of received information about the traffic situation is reflected in the performance of the application. Performance, thereby, needed to be examined from two perspectives:

(a) the number of actually occurring accidents, and

(b) the quality of the application to correctly perceive dangerous traffic situations. The importance of this criterion becomes obvious upon a second look. If the assessment criterion considered only the number of accidents, a proper design of application could suggest not to move at all.

An evaluation especially of the second criteria turned out to be crucial since the application reacts to a once assumed dangerous situation and thus prevents an actual classification of the situation at the end. Nevertheless, for some scenario configurations, the thesis was able to indicate a decreasing performance of the studied application with regard to the second evaluation criterion.

As a closing statement, the thesis concludes that the investigated application does not show a notable impact on vehicular traffic safety before information on the presence of at least 50 % of vehicles in the surroundings is provided. The occurrence of accidents rapidly falls with increased knowledge of the surroundings. According to the simulation results, approximately 25 % of the accidents that happen when no information is provided can be prevented if the available knowledge of the traffic situation is increased from 90 % to 100 %. Finally, when complete information about surrounding vehicles is given, the evaluated safety application did not allow for any accident.

12.1.2 Vehicular traffic efficiency

In contrast to traffic safety studies, an assessment of VANETs on vehicular traffic efficiency requires consideration of traffic flows and thus a large number of communicating and reacting vehicles. Furthermore, the potential use of VANETs by a traffic control center as a means to mitigate congested traffic conditions demands impact assessment results in real time, i.e., a simulated scenario second should not require more than a second of computation. Hence, the thesis analyzed the building blocks regarding their runtime performances when a large number of vehicles were considered. The results for the respective building blocks are listed subsequently.

Modeling

1. Application
   The thesis restricted the broad spectrum of possible traffic efficiency applications to those considering encapsulated problems from the entire street network. A prime example was given with a speed advice disseminated to adjust the traffic load to the capacity of a specific road. The effect of such a measure mostly concerns an extract of the entire road network, i.e., a single road, and thus does not struggle with the network's complexity. Consequently, scalability problems do not occur for the application block.

2. Mobility
   The thesis sets the number of considered vehicles in traffic efficiency studies to an upper bound of 10 000 vehicles. Available traffic simulators used for traffic safety studies have been demonstrated to calculate such a number of vehicles under real-time conditions. Thus, scalability concerns have not been identified for the mobility block.

3. Communication
   Owing to their devotion to details, available models on the communication system come with computational requirements already exceeding real-

time conditions for a small number of communicating nodes. On the other hand, a neglect of details would not allow for drawing thorough conclusions about the evaluation study at the end. Hence, the thesis suggested a hybrid simulation approach, which combines discrete-event simulations of application and mobility with a mathematical modeling of the communication system. A key requirement for this approach is a mathematical model, the parameters of which have been optimized in extensive off-line simulation experiments. This thesis has for the first time presented and exploited this idea, thereby profiting from high execution speed along with high fidelity of results, as explained in the sequel.

(a) An extensive simulation study has been carried out that explores the probability of packet reception over distance based on three scenario configuration parameters, namely the transmission power, the transmission rate, and the vehicular traffic density.

(b) By means of general linear least squares curve fitting, the data resulting from the simulation study has been captured into a single analytical expression constituting the aimed at empirical model.

(c) The model has been validated against discrete-event simulation results and proved its capabilities to be used as a means in a specific parameter configuration problem.

An integration of the derived empirical model into the traffic simulator VISSIM has created a simulation tool capable of efficiently assessing the impact of VANETs in large-scale simulation studies.

Simulation studies

In two simulation studies, the thesis has demonstrated how a speed regulator disseminated via wireless communication influences the throughput of a traffic flow. In essence, two conclusions have been drawn from the experiments.

(a) Best performance of the speed regulator with regard to traffic throughput has been achieved when a harmonization of the traffic flow has been attained. Harmonization thereby refers to a similar driving behavior among the vehicles in the flow, which is reflected in a lower number of overtaking maneuvers. In the conducted experiment, the harmonization of a traffic flow presented sensitivity to the fraction of radio-equipped vehicles and to the advised speed. A speed regulator advising more than 90 km/h turned out to be counterproductive for any fraction of equipped vehicles.

(b) The effect of a speed recommendation in taking precise control of the resulting average speed in the traffic flow depends on the traffic density and on the rate of radio-equipped, and thus reacting, vehicles. In the conducted experiment, a rate of at least 50 % was needed to effectively control the traffic flow's speed.

The simulation tool was designed to efficiently produce simulation results in order to render a useful tool for a traffic control center, for instance. Compared to a pure discrete-event simulation approach, which makes use of the network simulator NS-2, the presented hybrid architecture yielded runtime accelerations of two to three orders of magnitude (up to an acceleration factor of 1500) in the conducted simulation experiments. Thereby, simulation studies are facilitated that involve thousands of communicating vehicles in a computation time shorter than the simulated scenario duration.

12.2 Perspectives

12.2.1 Expanding the modeling scope

In recent years vehicular ad hoc networks have attracted researchers from various disciplines. At first sight, this particularly holds for the research disciplines related to the building blocks discussed in this thesis, i.e., application, mobility, and communication. As our discussion has already indicated, knowledge from a broader spectrum of research is required to appropriately understand the system and to make appropriate use of the potentials of the system. The mobility behavior notably needs to respect a distinction of (a) the interaction among the vehicles, (b) the movement capabilities given by the physical conditions of a vehicle, and perhaps most importantly (c) the driver's individual reactions to certain incidents based on psychological reasoning. From a safety perspective in particular, a thorough understanding of humans' actions is indispensably required to bridge an application's evaluation from a potential to an actual assessment.

Insights from additional research disciplines will probably also receive increasing attention in the future. Initiatives toward 'green driving', for instance, expect a significant potential of reducing carbon dioxide emissions if knowledge of driving behavior and of traffic conditions is provided. The vision of a comprehensive traffic telematics system, which jointly considers all facets of transport, profits from the communication facilities but needs to regard the manifold peculiarities, like timetables or rush hours, for example. The list of possible applications could be numerously extended; which applications will actually be implemented is also influenced by business models that commercially exploit the then available communication facilities. Indeed, commercial services are intended to play an important role when the challenge of introducing VANETs to the market is addressed [MML04].

12.2.2 A multi-model, multic-scale architecture

Apart from future ideas, the combination of the discussed building blocks already poses a plurality of research perspectives, which require a flexible modeling and simulation approach, respectively. Taking the simulation study of Part I as an example, where the focus was on the performance evaluation of a safety application, the suggested simulation tools have proven to be a suitable choice. However, if we had taken the perspective of a radio expert who needs to optimally design and position antennas at a vehicle, the applied simulation study appears less appropriate since the fundamental radio details have not been considered separately in the applied models. However, on the one hand, a comprehensive representation of all details cannot be accomplished at the same time but, on the other hand, this will not be required for every simulation purpose. Regarding the referred simulation study, the antenna expert likely neither depends on an accurate modeling of the application nor on details of the driving behavior; consequently,

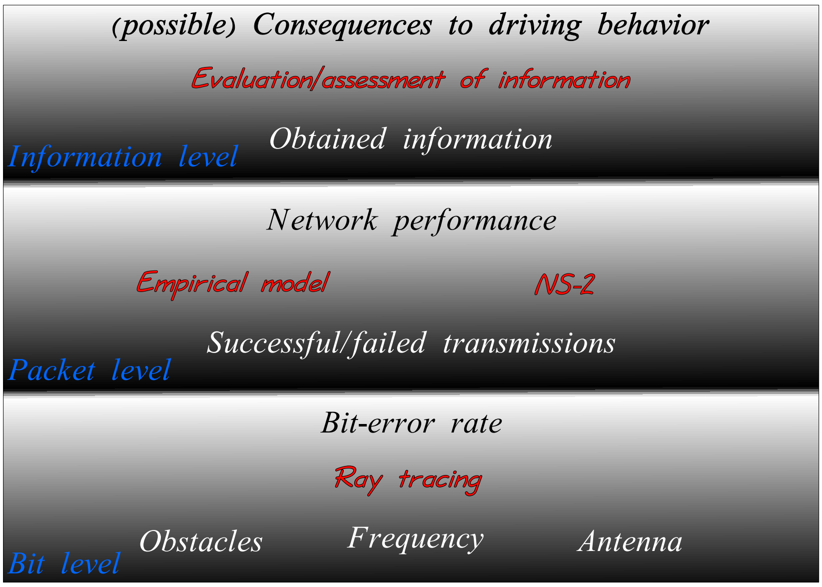


Figure 12.1: Multi-model, multi-scale architecture: varying user needs can be served by an appropriate selection of models at the respective levels.

this perspective would allow treating them in a coarse-grained manner that abstracts from the details.

The discussion reveals that several factors determine to which degree of accuracy a detail needs to be considered. In Part II we have demonstrated a feasible approach on how to cope with differing demands to a simulation tool: Part II served the need to simulate a large number of communicating nodes. Therefore, a model was derived that basically addresses the same issue but shifts the trade-off between an accurate and time-consuming replication on the one hand, and a statistically significant and efficient modeling on the other hand. A continuation of this proposed methodology leads to a bundle of models all covering the same issue but with distinctive properties regarding their implementation. For the sake of clarity, we expand the discussion and focus on the communication block only. Figure 12.1 illustrates the conception of a multi-model architecture, taking account of varying scales in the representation of details. Communication is thereby roughly divided into three levels, distinguishing the processing unit into bit, packet, and information, respectively. Each level considers certain input parameters (colored white), utilizes a set of models and tools for processing (red), and provides output metrics to the next upper level (black). The multi-model aspect is exemplarily indicated by the two processing instances at the packet level: according to the contributions of this thesis, processing units offering an accurate handling for a small number of vehicles (NS-2) and units that allow for statistically significant and large-scale studies (empirical model) are provided. Figure 12.1 is intended to indicate the aimed-for architecture, since more models on each level are required to meet further evaluation purposes; one additional evaluation purpose has been introduced by the aforementioned antenna expert, for example.

Eventually, it is up to the scenario, the use case, and to the evaluation goal as to which model will be used for which represented influencing factor. In that sense, the set of numerous models serves as a basis for a building block system that interlinks selected models for a specific evaluation goal. However, since the Cartesian product of the models leads to a rapidly increasing number of possible model compositions, a multi-model, multi-scale architecture approach needs to be accompanied by recommendations about which combinations of models should be used for which purposes. The research community seems to believe in this approach, as it is exemplarily reflected in the European FP7 project *PREparation for DRIVing implementation and Evaluation of C-2-X communication technology (PRE-DRIVE C2X)*. In the scope of this project, a compound of models and recommendations is envisaged and comes with the label of an 'integrated tool set' which allows for simulating and evaluating the interaction of vehicular traffic, vehicular communication, and the associated applications.

A
Properties of the Update Operator $\mathcal{U}$

Lemma A.1. *For each two valuations* $V^{(n)}$ *and* $V^{(n+1)}$ *successively gained by applying operator* $\mathcal{U}$*, it holds that*

$$\mathcal{U}\, V^{(n+1)}(s) - \mathcal{U}\, V^{(n)}(s) \leqslant \alpha \max_{s' \in S} \left\{ V^{(n+1)}(s') - V^{(n)}(s') \right\}$$

Proof[Put05, Proposition 6.2.4]. Let π denote the policy agreeing with the update of $V^{(n+1)}$, i.e. $\mathcal{U}_\pi\, V^{(n+1)} = \mathcal{U}\, V^{(n+1)}$. Then

$$\begin{aligned} \mathcal{U}\, V^{(n+1)}(s) - \mathcal{U}\, V^{(n)}(s) &\leqslant \mathcal{U}_\pi\, V^{(n+1)}(s) - \mathcal{U}_\pi\, V^{(n)}(s) \\ &= \alpha \sum_{s' \in S} p_{s,s'}(\pi(s)) \left(V^{(n+1)}(s') - V^{(n)}(s') \right) \\ &\leqslant \alpha \sum_{s' \in S} p_{s,s'}(\pi(s)) \max_{s'' \in S} \left\{ V^{(n+1)}(s'') - V^{(n)}(s'') \right\} \\ &= \alpha \max_{s'' \in S} \left\{ V^{(n+1)}(s'') - V^{(n)}(s'') \right\} \end{aligned}$$

Lemma A.2. *For an initial system state valuation* $V^{(0)}(s) = 0,\ \forall\, s \in S$*, the operator* $\mathcal{U}$ *generates a monotone increasing valuation of system states* $\left(V^{(n)}\right)_{n \in \mathbb{N}}$.

Proof. The proof considers induction over the successively gained system states valuations.

$n = 0$. $V^{(0)}(s) = 0,\ \forall\, s \in S$ due to the assumptions of the lemma.

$n = 1$.

$$V^{(1)}(s) = U\,V^{(0)}(s) = \max_{a\in A}\left\{\underbrace{r(s,a)}_{\geqslant 0} + \underbrace{\alpha\sum_{s'\in S} p_{s,s'}(a)V^{(0)}(s')}_{=0}\right\},\ \forall\, s\in S$$

Hence, $V^{(1)}(s) \geqslant V^{(0)}(s)$, $\forall\, s \in S$ and the initial condition of the induction proof is fulfilled.

$n \to n+1$. Let π denote the policy agreeing with the update of $V^{(n)}$, i.e. $U_\pi V^{(n)} = U\,V^{(n)}$. Then

$$\begin{aligned}
U\,V^{(n)}(s) - U\,V^{(n+1)}(s) &\leqslant U_\pi V^{(n)}(s) - U_\pi V^{(n+1)}(s)\\
&= \alpha\sum_{s'\in S} p_{s,s'}(\pi(s))\underbrace{\left(V^{(n)}(s') - V^{(n+1)}(s')\right)}_{\leqslant\ 0,\ \text{due to induction assumption}}\\
&\leqslant \alpha\sum_{s'\in S} p_{s,s'}(\pi(s))\cdot 0\\
&= 0\\
U\,V^{(n)}(s) &\leqslant U\,V^{(n+1)}(s)
\end{aligned}$$

Lemma A.3. *The series of successive valuations $\left(V^{(n)}\right)_{n\in\mathbb{N}}$ gained by iteratively applying operator U to an initial valuation $V^{(0)}(s) = 0$, $\forall\, s \in S$ converges to the system state valuation V_{π^*} corresponding to the optimal policy function π^*.*

Proof.[Wal06, Theorem 1.1] We consider the expected reward received by a stochastic process after N transition steps if policy π is applied.

$$E_\pi\left(\sum_{n=0}^{N}\alpha^n r(X_n,\pi(X_n)) \mid X_0 = s\right)$$

For $N = 0$ we can then upper bound the expected received reward by

$$E_\pi\left(\sum_{n=0}^{0} r(s,\pi(s)) \mid X_0 = s\right) = r(s,\pi(s)) \leqslant \max_{a\in A}\{r(s,a)\} = U\,V^{(0)}(s).$$

For $N = 1$ we likewise obtain

$$\begin{aligned}
E_\pi\left(\sum_{n=1}^{N}\alpha^n r(X_n,\pi(X_n)) \mid X_0 = s\right) &= \underbrace{r(s,\pi(s))}_{\leqslant\, U\,V^{(0)}(s)} + \alpha\sum_{s'\in S} p_{s,s'}(\pi(s))\,\underbrace{r(s',\pi(s'))}_{\leqslant\, U\,V^{(0)}(s')}\\
&\leqslant U^2\,V^{(0)}(s).
\end{aligned}$$

Induction over N then yields

$$E_\pi\left(\sum_{n=1}^{N}\alpha^n r(X_n,\pi(X_n)) \mid X_0 = s\right) \leqslant U^{N+1}\,V^{(0)}(s).$$

Since per definition $\lim_{N\to\infty} E_\pi \left(\sum_{n=1}^{N} \alpha^n r(X_n, \pi(X_n)) \mid X_0 = s \right) = V_\pi(s)$ and $\lim_{N\to\infty} U^{N+1} V^{(0)}(s) = u^*(s)$ we obtain

$$V_\pi(s) \leqslant u^*(s)$$

and, as we have not taken any constraints on the applied policy π, it also holds for the optimal policy π^*, i.e.

$$V_{\pi^*}(s) \leqslant u^*(s). \tag{A.1}$$

Now, with π being the policy corresponding to the update procedure $U\,u^*(s)$, i.e. $U\,u^*(s) = U_\pi\,u^*(s)$, we obtain

$$\begin{aligned} V_{\pi^*}(s) &\overset{\text{Eq. A.1}}{\leqslant} u^*(s) \\ &= U\,u^*(s) \\ &= U_\pi\,u^*(s) \\ &\overset{\text{Lemma A.2}}{\leqslant} U_\pi^2\,u^*(s) \\ &\leqslant \ldots \\ &\overset{\text{Def. of } U_\pi}{\leqslant} V_\pi(s) \\ &\leqslant V_{\pi^*}(s) \end{aligned}$$

and we can conclude $V_{\pi^*}(s) = u^*(s)$.

B
C++ implementation of the *overtaking* procedure

This appendix presents an extract of the C++ implementation of the mobility model proposed in Section 5.1.1. The extract comprises the behavior of the driver/vehicle entity in overtaking maneuvers. Figure B.1 shows the neighboring vehicles which may take influence on the driving decisions taken by the reference vehicle VEH.

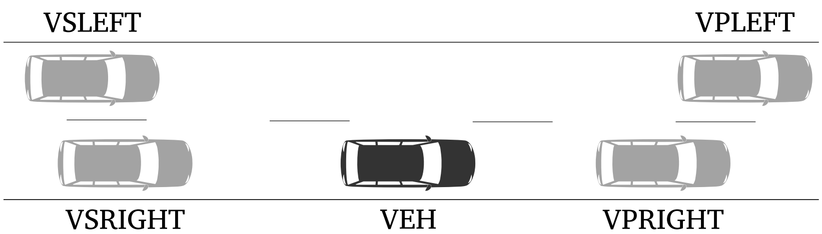


Figure B.1: Notation of vehicles involved in overtaking procedure

The following procedure is entered in each iteration step for each vehicle. The decision whether an overtaking maneuver is started depends on the variable VEH_OTWish which is set by the (external) BRAKEBX procedure. BRAKEBX is entered by a driver/vehicle entity the desired travelling speed cannot be achieved due to a slower front vehicle (cf. Section 4.2.2).

```
/*
 * Key to the variables
 *
 * OT                     1 = change to left lanes, 0 = do not change,
 *                       -1 = change to right lane
 * FD                     Desired follow distance by driver
 *                        (driver dependent variable, is set outside)
 * VEH_OTWish             Wish to overtake (0 = off, 1 = on)
 * VEH_Lane               Driving lane (1 = right, 2 = left)
 * VEH_RTWish             Wish to return to right lane
 * VEH_RTWait             Waiting time before returning to right lane
 *                        (to avoid oscillation in lane changes)
 * RT_STEPS               Default waiting time in time steps
 * VSLEFT                 Succeeding vehicle, left lane
 * VPLEFT                 Preceding vehicle, right lane
 * VSRIGHT                Succeeding vehicle, right lane
 * VPRIGHT                Preceding vehicle, right lane
 * VEH_StopDistance       Distance at which vehicle could stop
 * X_Distance             Spatial Distance to vehicle X
 * X_SpeedDifference      Speed difference to vehicle X
 * RN1, RN2               Driver dependent random numbers
*/

// overtaking wish exists, reference vehicle on right lane
if ((VEH_OTWish == 1) && (VEH_Lane == 1)) {

    // there is no VSLEFT vehicle
    if (((VSLEFT_ID == -1) ||
        // distance to VSLEFT vehicle is larger than desired follow
        // distance
        ((VSLEFT_Distance > FD) &&
         // VSLEFT is slower than reference vehicle
         ((VSLEFT_SpeedDifference < 0) ||
          // VSLEFT would not be forced VSLEFT to brake hard
          (VSLEFT_Distance > 0.5*pow(VSLEFT_SpeedDifference,2)))))
        &&
        // there is no VPLEFT vehicle
        ((VPLEFT_ID == -1) ||
         // distance to VPLEFT vehicle is larger than desired follow
         // distance
         ((VPLEFT_Distance > FD) &&
          // VPLEFT is faster than reference vehicle
          ((VPLEFT_SpeedDifference > 0) ||
           // reference vehicle would not be forced to break hard
           (VPLEFT_Distance > 0.7*pow(VPLEFT_SpeedDifference,2)))))
       )
    {
        // do change lanes
        OT = 1;
    }
}

// overtaking wish exists, vehicle on left lane
else if ((VEH_OTWish == 1) && (VEH_Lane == 2))
{
    // just arrived on left lane -> reset wish to overtake
    VEH_OTWish = 0;
    // initialize minimum sojourn time on left lane
    VEH_RTWait = RT_STEPS;
}

// vehicle drives on left lane, wish to overtake is revoked,
// wish to return not expressed
else if ((VEH_Lane == 2) && (VEH_OTWish == 0) && (VEH_RTWish == 0))
{
    // speed of VSRIGHT vehicle
```

```
    double VSRIGHT_Speed = VEH_Speed - VSRIGHT_SpeedDifference;

    // there is no VSRIGHT vehicle
    if ((VSRIGHT_ID != -1) &&
        // VSRIGHT vehicle is slower
        (VSRIGHT_SpeedDifference > 0) &&
        // distance to VSRIGHT justifies another overtaking maneuver
        (VSRIGHT_Distance < (25 * (1 + RN1 + RN2) *
                            sqrt(VSRIGHT_SpeedDifference) +
                            VEH_StopDistance + 10*VSRIGHT_SpeedDifference))
        )
    {
        // restart overtaking maneuver
        VEH_OTWish = 1;
    }

    // sojourn time on left lane has expired
    else if (VEH_RTWait == 1)
    {
        // express wish to return to right lane
        VEH_RTWish = 1;
        VEH_RTWait = 0;
    }

    // decrease waiting (sojourn) time on left lane
    else VEH_RTWait--;
}

// vehicle drives on left lane, wish to return to right lane is expressed
else if ((VEH_RTWish == 1) && (VEH_Lane == 2))
{
    // there is no VSRIGHT vehicle
    if (((VSRIGHT_ID == -1) ||
        // distance to VSRIGHT vehicle is larger than desired follow
        // distance
        (VSRIGHT_Distance > FD)) &&
        // there is no VPRIGHT vehicle
        ((VPRIGHT_ID == -1) ||
         // distance to VPRIGHT vehicle is larger than des. follow
         // distance
         ((VPRIGHT_Distance > FD) &&
          // VPRIGHT vehicle is faster than reference vehicle
          ((VPRIGHT_SpeedDifference > 0) ||
           // reference vehicle would not be forced to break
           (VPRIGHT_Distance > 0.5*pow(VPRIGHT_SpeedDifference,2)))))
       )
    {
        // change to right lane
        OT = -1;
        // revoke wish to return to right lane
        VEH_RTWish = 0;
    }

}

// returned to right lane
else if ((VEH_RTWish == 1) && (VEH_Lane == 1))
{
    // reset wish to return
    VEH_RTWish = 0;
}

// return decision whether to change lanes
```

```
return OT;
```

Listing B.1: C++ code extract of the Overtaking procedure

C
The *DriverModel*-interface of the Traffic Simulator VISSIM

The traffic simulator VISSIM offers the possibility to alter key parameters of the driving behavior of each vehicle in every time step. Therefore, VISSIM provides the dynamic link library (DLL) *DriverModel.dll* which can be manipulated by users of the simulator. The interface essentially provides three methods, namely DriverModelSetValue, DriverModelGetValue and DriverModelExecuteCommand having the following C++ syntax.

```
int   DriverModelSetValue (long type, long index1, long index2,
                           long long_value, double double_value,
                           char *string_value);

int   DriverModelGetValue (long type, long index1, long index2,
                           long *long_value, double *double_value,
                           char **string_value);

int   DriverModelExecuteCommand (long number);
```

In each time step, VISSIM successively calls DriverModelSetValue, DriverModel ExecuteCommand and DriverModelGetValue iteratively for all vehicles which have the *DriverModel.dll* activated. The DriverModelSetValue provides the user with current parameters of the driving behavior of the vehicles. A subset of these data can be modified and returned to VISSIM using the DriverModelGetValue function. Table C.1 shows a selection of accessible data which are required to interlink our own driver model with VISSIM.

Table C.1: Selected vehicle parameters accessible via the *DriverModel.dll*.

	Parameter
1.	DRIVER_DATA_DESIRED_ACCELERATION Acceleration value applied in next time step to the vehicle
2.	DRIVER_DATA_ACTIVE_LANE_CHANGE Indicator whether the vehicle will change lanes in the next time step (1 = to left, 0 = no change, -1 = to right)
3.	DRIVER_DATA_WANTS_SUGGESTION Indicator whether VISSIM should compute driving behavior (e.g. acceleration, lane change)
4.	DRIVER_DATA_VEH_DESIRED_VELOCITY Desired driving velocity of the vehicle
5.	DRIVER_DATA_SIMPLE_LANECHANGE If set to 1, VISSIM controls the lateral movement of vehicles in lane change maneuvers
6.	DRIVER_DATA_VEH_ID The identifier of the vehicle
7.	DRIVER_DATA_VEH_LANE Index of the lane the vehicle is currently driving on
8.	DRIVER_DATA_VEH_VELOCITY Current speed of the vehicle
9.	DRIVER_DATA_VEH_LENGTH Total (longitudinal) size of the vehicle
10.	DRIVER_DATA_VEH_MAX_ACCELERATION Maximum acceleration possible by the vehicle
11.	DRIVER_DATA_NVEH_ID The identifier of the next vehicle
12.	DRIVER_DATA_NVEH_DISTANCE Distance to next vehicle
13.	DRIVER_DATA_NVEH_REL_VELOCITY Speed difference to next vehicle
14.	DRIVER_DATA_NVEH_ACCELERATION Current acceleration of next vehicle
15.	DRIVER_DATA_NVEH_LENGTH Total (longitudinal) size of next vehicle

The DriverModelExecuteCommand procedure enables the user to take influence on a vehicle at different stages: (a) when the vehicles is created, (b) when the vehicle moves in a time step and (c) when the vehicle leaves the simulation scenario, i.e.

(a) DRIVER_COMMAND_CREATE_DRIVER

(b) DRIVER_COMMAND_MOVE_DRIVER

(c) DRIVER_COMMAND_KILL_DRIVER.

Furthermore, the DriverModelExecuteCommand method allows for taking control at the initialization of the simulation by calling once the (d) DRIVER_COMMAND_ INIT section.

Controlling the driving behavior of vehicles

In each time step, our model considers the DRIVER_COMMAND_MOVE_DRIVER section of the DriverModelExecuteCommand method and modifies the first five listed data in Table C.1. The model determines the driving behavior of each vehicle depending on the vehicles in its surroundings. The necessary data on these vehicles are provided by means of the entries 11 to 15 in Table C.1. The input variables index1 and index2 to the two procedures DriverModelSetValue and DriverModelGetValue allow to specify which neighboring vehicle is concerned (left lane ahead, same lane behind, etc.).

The key functionality of the driver model affects the parameters 1 and 2 in Table C.1. These data determine the longitudinal movement of the vehicles and decide whether the lane change procedure described in Section 5.1.1 will be executed. The decision on acceleration and braking behavior thereby adheres to the model proposed by Wiedemann in 1974 [Wie74].

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