Vehicular Communications for Efficient and Sustainable Mobility

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To Yulia and André

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Abstract

The last decades have been characterized by an alarming growth in urban development, mobility demand and vehicle usage. These facts in combination with other factors (e.g. urban planning) strongly constrain mobility in urban areas, namely by traffic and inefficient private/public transportation. These inefficiencies lead to traffic accidents, congestion, air pollution, noise pollution, increased energy consumption and the associated economic losses.

A large amount of research has been carried out during the last decades to address the challenge of efficient urban mobility. However, there is still the consensus that no single measure can solve transport challenges and that a set of relevant measures is required to have a considerable impact on mobility. Additionally, improved energy economy and reduced emissions levels due to better mobility was less considered in the last decades. Thus, for a more efficient and greener urban mobility, several measures should be taken to enhance the performance of private and public transport. This thesis considers using Vehicular Networks for achieving efficient and sustainable mobility. More specifically, the goal of this thesis is to propose and evaluate Intelligent Transportation Systems enabled by vehicular communications that can improve urban mobility by more efficient vehicle usage (taxi-sharing), enhanced efficiency on road network utilization (virtual traffic lights, self-automated parking) and improved land use (self-automated parking).

The first part of the thesis is devoted to the realistic and large-scale assessment of vehicular networks for studying the solution feasibility and to quantify the system performance under varying conditions. With this aim, we use simulation studies and empirical measurements as tools to study the proposed Intelligent Transportation Systems enabled by vehicular communications. Regarding simulation aspects, we present an integrated simulation platform, consisting of application, network, traffic and pollutant emissions models, that uses real-world data to accurately replicate movements and demand. With respect to empirical evaluations, large-scale field trial data is used to assess single-hop communication performance and the awareness level provided to applications. Experimental results demonstrate that link layer delivery and neighborhood awareness criterion can be fulfilled for safety applications and that the interference to far away nodes can be considerable.

The second part of this thesis addresses the development and assessment of novel applications enabled by vehicular communications. The main goal is to propose and understand how the implementation of transportation systems (e.g. traffic control/management systems, ride-sharing) can lead to improved efficiency and better environmental performance. More specifically, we demonstrate that the Virtual Traffic Light system, a recently proposed infrastructureless traffic control system solely based on inter-vehicle communications and distributed control, can reduce CO_2 emissions up to 18% by improving the traffic flow and by reducing the stop-and-go phenomena. In addition, we propose a distributed and dynamic taxi-sharing system enabled by cellular communications and widespread computation capabilities to provide a cost-efficient, door-to-door and flexible system, offering a quality of service similar to conventional taxis. Simulation results show that the implementation of this system provides advantages mainly in terms of reduced fares, reduced total travel distance and improved operation costs. An automated parking system leveraging on (semi-) autonomous vehicles and vehicular ad hoc networking is also proposed. This new parking concept relies on the collaborative mobility of autonomous vehicles - governed by a parking lot controller and enabled by vehicular communications - to create space for vehicles entering or exiting the parking infrastructure. Simulation results show that the parking space (50%) and the total travelled distance (30%) can be significantly reduced when comparing with conventional parking lots.

Resumo

As últimas décadas foram caracterizadas por um crescimento alarmante do desenvolvimento urbano, da mobilidade urbana e da utilização de veículos privados. Estes factos em combinação com outros factores (por exemplo, um planeamento urbano desadequado) condicionam a mobilidade nas áreas urbanas, nomeadamente devido ao trânsito e sistemas de transporte públicos e privados ineficientes. Estas ineficiências conduzem por outro lado a acidentes, congestão, poluição atmosférica, poluição sonora, consumo energético elevado e as perdas económicas associadas.

Diversos trabalhos de investigação científica realizados nas últimas décadas abordaram a problemática da mobilidade urbana. Contudo, é consensual que uma única medida não é suficiente para resolver os desafios na área dos transportes e que um conjunto alargado de medidas é necessário para ter um impacto considerável na melhoria da mobilidade. Adicionalmente, nas últimas décadas apenas um conjunto reduzido de trabalhos focou-se na optimização da eficiência energética e na redução das emissões de gases poluentes resultantes de uma melhor mobilidade urbana. Consequentemente, diversas medidas devem ser implementadas para melhorar a performance dos sistemas de transporte públicos e privados de modo a tornar a mobilidade urbana mais eficiente e ecológica. Esta tese considera a utilização de Redes Veiculares para atingir o objectivo de mobilidade mais eficiente e sustentável. Mais especificamente, o objectivo principal desta tese é propor e avaliar diversos Sistemas de Transporte Inteligentes (com suporte em redes veiculares) que melhorarem a mobilidade urbana através de uma utilização mais eficiente dos veículos (*Taxi-sharing*), da rede de transportes (*Virtual Traffic Lights*) e do território (Sistema de parqueamento automático).

A primeira parte desta tese é dedicada à análise realista e em larga escala de redes veiculares, incluindo o estudo da viabilidade da solução e quantificação da performance do sistema em condições variáveis. Com este objectivo utilizamos duas ferramentas, nomeadamente simulação e estudos empíricos, para estudar os sistemas de transporte inteligente propostos nesta tese. No que concerne aspectos de simulação, apresentamos um plataforma de simulação integrada que consiste em modelos de aplicação, rede, tráfego e emissões poluentes, e que faz uso de dados empíricos para replicar com precisão os movimentos dos veículos e a procura. Por outro lado, no que concerne a avaliação empírica, utilizamos dados de ensaios de campo em larga escala para determinar a performance da comunicação directa entre veículos e o nível de conhecimento fornecido a aplicações. Os resultados experimentais obtidos demonstram que os critérios mínimos para taxa de recepção de pacotes e para o nível de conhecimento da vizinhança podem ser atingidos para aplicações de segurança e que a interferência para veículos distantes pode ser considerável.

A segunda parte desta tese visa o desenvolvimento e a avaliação de novas aplicações com suporte de redes veiculares. O objectivo principal é propor sistemas de transporte (por exemplo, sistemas de controlo/gestão de tráfego, sistemas de partilha de veículos) e perceber como a implementação destes melhora a eficiência energética e o índice de desempenho ambiental. Mais especificamente, demonstramos que o sistema *Virtual Traffic Lights* - um sistema original de controlo de intersecção apenas baseado em comunicações inter-veículo e controlo distribuído - pode reduzir as emissões de dióxido de carbono até 18% através da optimização do fluxo de tráfego e da redução do fenómeno pára-arranca. Nesta parte da tese também propomos um sistema distribuído e dinâmico de partilha de táxis que faz uso de comunicações celulares e computação distribuída para fornecer um serviço acessível, porta a porta, flexível e com qualidade de serviço semelhante aos táxis convencionais. Os resultados de simulação mostram que a implementação deste serviço proporciona reduções de tarifas, distância total percorrida, e custos operacionais. Um sistema de parqueamento automático baseado em veículos (semi-) autónomos e comunicações *ad hoc* inter-veículo é igualmente proposto. Este conceito inovador de parqueamento assenta no movimento colaborativo de veículos autónomos - regulado por um controlador e suportado em comunicações veiculares - para criar espaço para veículos que entram e saem do parque de estacionamento. Os resultados de simulação mostram que o espaço de parqueamento (50%) e a distância total percorrida (30%) podem ser reduzidos significativamente quando comparando com os sistemas de parqueamento tradicionais.

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Acronyms

ACC Adaptive Cruise Control

ADAS Advanced Driver Assistance Systems

API Application Programming Interface

AU Application Unit

BTP Basic Transport Protocol

CA Cooperative Awareness

CACC Cooperative Adaptive Cruise Control

CAM Cooperative Awareness Message

CAN Controller Area Network

CDF Cumulative Distribution Function

CIS Central ITS Station

CMEM Comprehensive Modal Emission Model

CO Carbon Monoxide

CO_2 Carbon Dioxide

CH_4 Methane

DbW Drive-by-Wire

DENM Decentralized Environmental Notification Message

DIVERT Development of Intervehicular Reliable Telematics

DSRC Dedicated Short Range Communication

EC European Commission

EMIT EMIssions from Traffic

ETSI European Telecommunications Standards Institute

EO Engine-out

EU European Union

EV Electric Vehicle

FOT Field Operational Test

FR Fuel Rate

GDP Gross Domestic Product

GNBTP Geo-Networking Basic Transport Protocol

GNBTPAPI Geo-Networking Basic Transport Protocol Application Programming Interface

GPRS General Packet Radio Service

GPS Global Positioning System

HC Hydrocarbons

HCI Human Computer Interaction

HMI Human Machine Interface

ICE Internal Combustion Engine

IRT Inter-Reception Time

IVE International Vehicle Emission

IDM Intelligent Driver Model

ISA Intelligent Speed Adaptation

ITS Intelligent Transportation Systems

LAN Local Area Network

LOS Line of Sight

LTE Long Term Evolution

MOVES Motor Vehicle Emission Simulator

MOBIL Minimizing Overall Braking decelerations Induced by Lane changes

MPC Model Predictive Control

NAR Neighborhood Awareness Ratio

NARR Neighbors Above Range Ratio

NIR Neighborhood Interference Ratio

NLOS Non Line of Sight

NO_2 Nitrogen Dioxide

NO Nitrogen Oxide

N_2O Nitrous oxide

O/D Origin/Destination

OBD On Board Diagnostic

P Engine Power

PDR Packet Delivery Ratio

PHEM Passenger Car and Heavy Emission Model

PIR Packet Inter-Reception time

PLC Parking Lot Controller

P_{tr} Tractive Power

QoS Quality of Service

RIS Roadside ITS Station

R&D Research & Development

RNARI Ratio of Neighbors Above Region of Interest

RNAR Ratio of Neighbors Above Range

RSU Road Side Unit

SCOOT Split Cycle Offset Optimization Technique

TCP Transmission Control Protocol

TIS Traffic Information System

TLVC Traffic-Light-to-Vehicle Communication

TP Tailpipe

TRANSIMS Transportation Analysis and Simulation System

TSP Traveling Salesman Problem

UMTS Universal Mobile Telecommunications System

US United States

UTC Urban Traffic Control

VANET Vehicular Ad Hoc Network

V2I Vehicle-to-Infrastructure

V2V Vehicle-to-Vehicle

VIS Vehicle ITS Station

VNS Vehicular Networks Simulator

VT-Micro	Virginia Tech Microscopic
VTL	Virtual Traffic Lights
WAVE	Wireless Access in Vehicular Environments

Chapter 1

Introduction

1.1 Motivation

In the European Union (EU), the majority of the population (72%) and economic development [85% of the Gross Domestic Product (GDP)] concentrates in urban areas according to [10]. However, mobility in these areas is strongly constrained, namely by traffic and inefficient (private and/or public) transportation. These inefficiencies lead to congestion, pollution, noise, increased energy consumption and the associated economical losses. For instance, in the United States (US) congestion wastes a massive amount of time, fuel and money: 1.9 billion gallons of wasted fuel, 4.8 billion hours of extra time, and 101 billion dollars of delay and fuel cost [11]. In the EU, congestion costs 1% of the total GDP, annually [12]. According to recent studies [13] [14], the transportation sector alone accounts for 25 % and 32 % of the total Carbon Dioxide (CO_2) emissions in the EU and in the US, respectively.

One of the main causes for these inefficient practices is the predominant use of private cars, which accounts for 77 % of all motorized passenger transport in the EU [15]. One aggravating factor is the ever-increasing traffic levels in some regions of the World. However, individual transport is becoming less attractive due to significant increases in fuel prices and personal transport operating costs (e.g. tolls, congestion zones) in the last decade. Ineffective public transportation, where users' needs are often not met (e.g. lack of coordination between different transport modes) or where capacity is wasted, also contributes to current situation. Thus, to improve urban mobility several measures should be taken to enhance the performance of private and public transport.

Intelligent Transportation Systems (ITS) combine sensing, processing and communication technologies to improve transportation systems. The widespread availability of processing units (e.g on-board computers, smartphones) and the increasing deployment of different sensing technologies (e.g. video cameras, GPS, radar) have created new opportunities for ITS. Heterogeneous communication technologies, i.e. short-range and long-range communication systems, also play a major role in ITS. These enable extending the sensing range, by enabling distributed computing and by providing several communication channels, which considerably improves the range and performance of transportation systems.

ITS is a vast research field encompassing aeronautical, maritime and rail systems as well as the most commonly know road transportation systems. In the scope of this thesis, we focus on road transportation systems enabled by vehicular communications, either short-range (e.g. ITS G5/802.11p) or cellular communication systems. Extensive research has been carried out in this field, which resulted in the design and evaluation of a considerable number of applications and advanced supporting systems. The European Chauffeur (1995-2003)/DRIVE-C2X (2010-2014) project, the Japan Energy ITS (2008-2012) project and the US Grand Challenge (2004-2005) are good examples where advanced research has been carried out and evaluated. It should be also noted that several ITS (e.g. toll collection, Adaptive Cruise Control (ACC)) have already deployed in the market and provide considerable advantage to all involved parties and the society as a whole.

Traditionally, the main goal of ITS has been considered to improve safety and the efficiency of transportation systems, which are already two main societal benefits. However, the deployment of advanced ITS could also lead improved energy efficiency and reduced emissions levels. Analyzing the carbon footprint induced by road transportation is of major importance due to the recent findings in global warming and climate change. Due to these reasons the policy scene implemented measures toward low-carbon and resource-efficient economies, which poses additional challenges to development of ITS that now also ought to improve the environmental efficiency of the road transportation sector. These paradigm shift leads then to new research questions, solutions and implications. In the following we present sample research questions for this new branch of road transportation systems:

1. What is the environmental performance of current or proposed road transportation systems?
2. How can current systems be modified for improved environmental performance?
3. How to perform the specific design of ITS for green mobility?

Due to the complexity and wide-scope of these research questions, this thesis mainly focus on the first two aspects for three selected applications. However, it should be noted that the scope of the thesis is wider than solely the environmental impact assessment. Herein, we consider the utilization of ITS enabled by vehicular communications for improving the performance of road transportation. The main argument is that (urban) mobility can be improved due to the deployment of novel systems in public and private transport. In this thesis three transportation systems are proposed and realistically evaluated: (1) distributed traffic light controller, (2) taxi-sharing system and (3) automated parking system.

The realistic impact assessment of novel systems involves studying the solution feasibility and the quantification of the system performance under varying conditions. The systems performance is determined making use of a number of measures (e.g. travel distance, costs) being given special emphasis in this thesis to the environmental impact evaluation. A properly defined set of performance indicators and varying conditions allow better understanding how the system design of novel technologies/systems influences the overall performance benefits and identifying the involved trade-offs.

The most common approaches for assessing applications or systems enabled by Vehicular Networks are simulation studies and field operational trials. Each of these methods has different advantages and drawbacks. On one hand, simulation allows control of the input parameters and allows replicating varying conditions but the development and integration of accurate simulation models is challenging task. On the other hand, field trials allow a more realistic and close to the market assessment of systems but can have serious cost, safety, repeatability, scale and technological constraints. In this thesis, we use both techniques to evaluate the proposed applications and the underlying communication system.

1.2 Contributions

This thesis considers using Vehicular Networks for achieving efficient and sustainable Mobility. More specifically, the goal of the thesis is to propose and evaluate ITS enabled by vehicular communications (cooperative awareness) that can improve urban mobility by more efficient vehicle usage (taxi-sharing) and enhanced efficiency on road network utilization (virtual traffic lights). This section summarizes the main thesis contributions and constituting parts. Additionally, the relation between the main thesis parts and previously published scientific publications is given. As shown in Fig. 1.1 the main contributions of this thesis can be then summarized into two main parts that are closely interconnected:

- *Realistic and Large-scale Assessment of Vehicular Networks (Part I)*:
  In this part the main alternatives for simulating and assessing the performance of Vehicular Ad Hoc Networks (VANETs) and related applications, namely simulation studies and field trials, are given and compared against. Regarding simulation, we present a simulation platform that closely integrates traffic, network and energy consumption models. Additionally, in our studies we consider realistic and large-scale evaluation of applications and systems. In this context, we use real-world data (e.g. taxi mobility traces, Origin/Destination (O/D) data) to accurately replicate vehicle movements (e.g. taxi operation and taxi demand aspects). This integrated and realistic simulation tool is used in part II to evaluate the proposed systems. With respect to empirical evaluations, we use large-scale field-trial data to assess the performance of a specific feature of the underlying communication system, i.e. Cooperative Awareness Messages. In this study we mainly analyze the performance of the communication link and the level of awareness provide to neighboring vehicles.
  The main contributions related to the realistic assessment of VANET have been peer-reviewed and published in IEEE Transactions on Intelligent Transportation Systems (simulation aspects: [1] [2] and field operational trials: [2]), as well as presented at major conferences conferences in the communications and ITS area (simulation aspects: [4] [5] [6] and empirical evaluation of Cooperative Awareness: [7][1]). A journal article on the assessment and modeling of Cooperative Awareness in Vehicular Communications Systems [9] is being currently finalized.

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[1] This article has won the Best Paper Award at IEEE VTC Spring 2014.

- *Efficient and Sustainable Mobility enabled by Vehicular Networks (Part II)*:
  This part addresses the development and assessment of applications enabled by vehicular communications. The main goal is to understand how the implementation of transportation systems (e.g. traffic control/management systems, ride-sharing) can lead to improved efficiency and better environmental performance. More specifically, we demonstrate and explain how the Virtual Traffic Light system, a recently proposed infrastructureless traffic control system solely based on Vehicle-to-Vehicle (V2V) communications, provides improved environmental performance. In addition, we propose a distributed and dynamic taxi-sharing system enabled by wireless communications and widespread computation capabilities. The system is evaluated following a simulation modeling approach, including a realistic and accurate replication of taxi operation using empirical data. Thirdly, we propose an automated parking system leveraging on semi or fully-autonomous vehicles and vehicular ad hoc networking. This new parking concept lies on the collaborative mobility of autonomous vehicles - governed by a parking lot controller and enabled by vehicular communications - to create space for vehicles entering or exiting the parking infrastructure. All systems are evaluated using the realistic and large-scale simulation platform presented in part I.

  The main contributions related to efficient and sustainable mobility have been peer-reviewed and published in IEEE Transactions on Intelligent Transportation Systems - Virtual Traffic Lights [1] and Survey on ITS for Sustainable Mobility [2] - and IET Intelligent Transport Systems (distributed taxi-sharing system [3]). The following papers have accepted for publication at major conferences in the area (taxi-sharing: [4] [5] and self-automated parking: [8]).

1.3 Organization

The remainder of this thesis is organized as follows. The realistic and large-scale Assessment of Vehicular Networks is discussed in Part I. Chapter 2 introduces the methods for assessing the feasibility and performance of transportation systems enabled by vehicular communications. Subsequently, the evaluation methods are compared and the main conclusions on individual advantages and drawbacks are taken. Chapter 3 presents the main simulation models for the realistic assessment of complex applications and provides an overview the related architecture. In addition, we present the coupling between a method for assessing the environmental impact of ITS and a taxi fleet operation model. Chapter 4 shortly introduces Field operational trials. Chapter 5 presents the empirical assessment of Cooperative Awareness in Vehicular environments.

Part II addresses the design and evaluation of ITS enabled by Vehicular Networks. To begin with, Chapter 6 introduces the concept of Green ITS and the main variables and measures for more efficient and sustainable road transport systems. Chapter 7 presents and evaluates the environmental performance of the Virtual Traffic Lights (VTL) system. The proposal and realistic evaluation of a dynamic and distributed Taxi-sharing system is given in Chapter 8, including the assessment

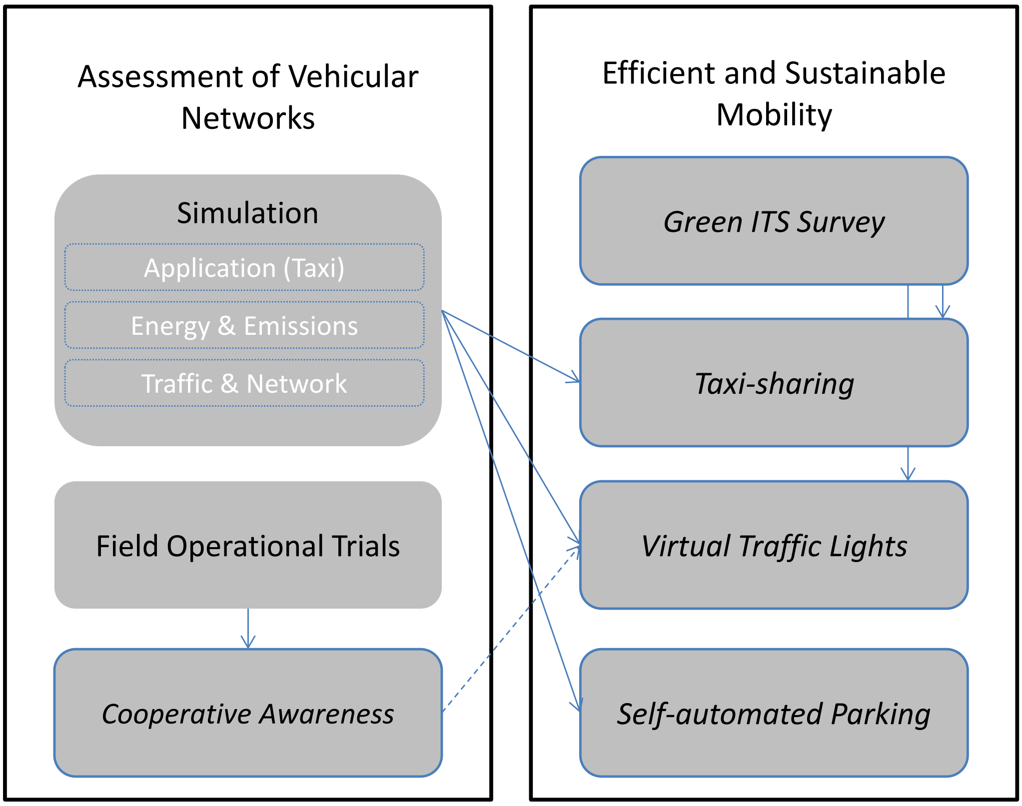

Figure 1.1: The thesis is divided into two main parts: I) Realistic and Large-scale Assessment of Vehicular Networks and II) Efficient and Sustainable Mobility enabled by Vehicular Networks. The systems proposed in part II, namely Taxi-sharing, Virtual Traffic Lights and Self-automated Parking, are realistically evaluated using the simulation platform presented in part I. Results of the empirical evaluation of cooperative awareness demonstrate the feasibility of the Virtual Traffic Lights system for what concerns neighborhood awareness in challenging environments.

of transport, economic and environmental aspects. Chapter 9 provides details on an automated parking system for autonomous vehicles enabled by vehicular communications. In Chapter 10, the main thesis conclusions and future research directions are provided.

Part I

Realistic and Large-scale Assessment of Vehicular Networks

Chapter 2

Introduction

The development of efficient and sustainable mobility solutions - enabled by vehicular communications - implies the determination of the main system properties. The assessment of the proposed system consists on two main stages, i.e. the study of the solution *feasibility* and the quantification of the system *performance* under varying and/or realistic conditions. The system performance is usually determined making use of performance indicators (e.g. CO_2, traffic flow, throughput) that are selected depending on the system under study (e.g. traffic lights) or depending on the characteristics of interest (e.g. environmental impact). Thus, performance evaluation allows understanding the system under study and evaluating its properties and related performance.

To assess the system performance a number of methods or techniques can be applied. In the context of vehicular communications, the most common approaches are the following: 1) analytical studies; 2) computer-based simulation; and 3) field trials. The first two approaches imply creating or re-using available models of the system to be evaluated. A model is a representation of the construction and working of a system, and incorporates its salient features [16]. Although the model should be an accurate representation of the system it will include a number of assumptions to maintain the model simplicity. On the other hand, field trials imply the development of new platforms (e.g. hardware and software components) or usage of already available systems to make empirical evaluations.

Analytical studies make use of mathematical models, i.e. a system of equations, that may have a closed form solution. As these make use of mathematical models, usually, a great number of simplifying assumptions needs to be taken. Furthermore, the system dimension or dynamism (e.g. realistic vehicular movement) may impair or limit the usage of analytical studies for performance evaluation of ITS. In the case several system blocks need to be evaluated simultaneously, this type of assessment method may lead to complex analytical evaluations and models. Finally, the validation of the mathematical models may be difficult.

Computer-based simulations are a popular tool for evaluating the performance of transportation systems and communication networks. Besides mathematical model (as with analytical evaluation), simulation studies rely on a number of logical and process simulation models. These various models are interdependent and rely on interaction to build a full simulation platform. One of the main advantages of simulation is that the user has control of the main simulation parameters and input data, which allows testing the system under varying conditions and configurations. Additionally, researchers can make use of already available simulators to test new protocols or systems without needing to validate individual models. Although simulation studies and field trials allows studying the system dynamics (e.g. time evolution or model interactions), the first method offers the opportunity to perform assessments in an even larger scale. However, this method relies on simplifying assumptions to models, which may reduce the system realism (e.g. when compared to field trials) if the platform is not thoroughly validated and if realistic input data (e.g. taxi mobility patterns) is not available.

The third evaluation method is field trials that make use of real software and hardware platforms to empirically evaluate the feasibility and performance of ITS. This assessment method usually involves the design, development, integration and final system evaluation. Field Operational Tests (FOTs) allow evaluating applications and systems in a real-world environment and are an essential stage towards deployment. However, there are a number of challenges that limit the scope of field trials. Cost, practical and organizational reasons are three of the main factors that limit the scale and repeatability of FOTs. Safety constraints and externalities (e.g. congestion) also often mandate that tests are performed under controlled conditions and in closed tracks. However, field trials provide new insights to the system that cannot be obtained otherwise and are closer the market, which can result in product-grade products ready to real deployment.

To conclude, among other reasons, cost, safety, repeatability, scale and practical requirements usually lead researchers to rely on simulated environments of vehicular applications. However, recently, large-scale field-operational trials have been proposed to specifically analyze the performance of ITS. Empirical evaluations act as a complement to simulation-based evaluations as both have different goals and advantages. Simulation-based assessment of ITS have cost, repeatability and scale benefits but need accurate and interconnected models for obtaining realistic results. On the other side, FOTs allow deploying and testing the system under realistic conditions but suffer from cost and scale constraints. Furthermore, in naturalistic field trials it is more difficult to isolate externalities (e.g. traffic, driver behavior) that affect results.

In the context of this thesis, Vehicular Networks are evaluated using realistic and large-scale simulation methods and field trials. More specifically, the performance of three transportation systems, i.e. VTL, Taxi-sharing and Self-automated Parking, is investigated using computer-based simulations. In Chapter 3, we provide a short description of the main simulation models for assessing ITS enabled by vehicular communications and give the three main model interactions (e.g. interaction between the traffic model and the Network model). To realistically simulate the operation of a taxi fleet the behavior of individual taxis has been accurately modeled in the simulation platform. In our studies special emphasis is given to the assessment of the environmental benefits arising from the implementation of these systems. In Section 3.3.3 the integration of a Energy & Emissions Model (EMIT) and a Traffic Model (DIVERT/VNS) is detailed. Chapter 4 presents briefly the main characteristics of Field Operational Tests (FOTs). In the scope of the large-scale FOT DRIVE-C2X, we empirically evaluate the awareness level provided to applications obtained by the periodic exchange of single-hop, broadcast vehicle information.

In this thesis we also argue that the aspects of *large-scale* and *realistic* evaluations are of utmost importance. Regarding the scale of the assessment, the majority of studies presented in this field are solely evaluated in a simple and/or small-scale scenario (e.g. containing a small number of vehicles or intersections). For what concerns the realism of the evaluations, often researches do not consider integrated simulations platforms and realistic input parameters. Depending on the application type, we argue that ITS should be evaluated in large-scale scenarios (e.g. entire cities for simulation), where traffic, road network and communication characteristics are correctly replicated. In a large-scale road network a multitude of factors (e.g. intersection distance, number of vehicles, congestion) can influence the performance of systems. In the studies presented in this thesis we have made large-scale simulation studies containing, for instance, thousands of vehicles and covering entire cities. The simulation platform integrates a number of simulation models and whenever possible we used realistic information for the studies (e.g. realistic O/D matrix, realistic taxi movements). With respect to FOTs, the considered evaluation scenarios encompass a considerable number of vehicles and related equipment.

Chapter 3

Simulation

Simulation is a powerful tool for evaluating transportation systems enabled by communication networks. Simulation studies rely on models of the system under evaluation (e.g. vehicular movement, communication network), which are representations of the last considering simplifying assumptions. Simulation is often considered as a compromise between model realism and performance/scale. Depending on the model complexity, simulation studies can allow large-scale evaluation of the system dynamics (e.g. time evolution or model interactions) and performance. These various simulation models are interdependent and rely on interaction to build a full simulation platform. One of the main advantages of simulation is that the user has control of the main simulation parameters and input data, which allows testing the system under varying conditions and configurations. Additionally, researchers can make use of already available simulators to test new protocols or systems without needing to validate individual models.

The realistic simulation of vehicular applications is a challenging task that implies the integration of a number of simulation models (see Fig. 3.1):

- *Application*: represents the functioning of the ITS application under test;
- *Energy & Emissions Model*: models the dynamic behavior of a multitude of vehicles and allows computing the energy efficiency and pollutant emissions;
- *Network Model*: replicates the communication between nodes in the vehicular network;
- *Traffic Model*: mimics the individual behavior of vehicles and their interactions in a road transportation network. External traffic source (e.g. Global Positioning System (GPS) traces) can enhance the realism of the mobility model.

Optionally, a *Driving Model* may be included in the simulation platform. This model allows to incorporate emulated vehicle(s) commanded by the driver(s') inputs into a simulated scenario, which may be useful for evaluating applications where Human Computer Interaction (HCI) must be carefully designed. This way novel interaction forms with the driver can be tested and benchmarked.

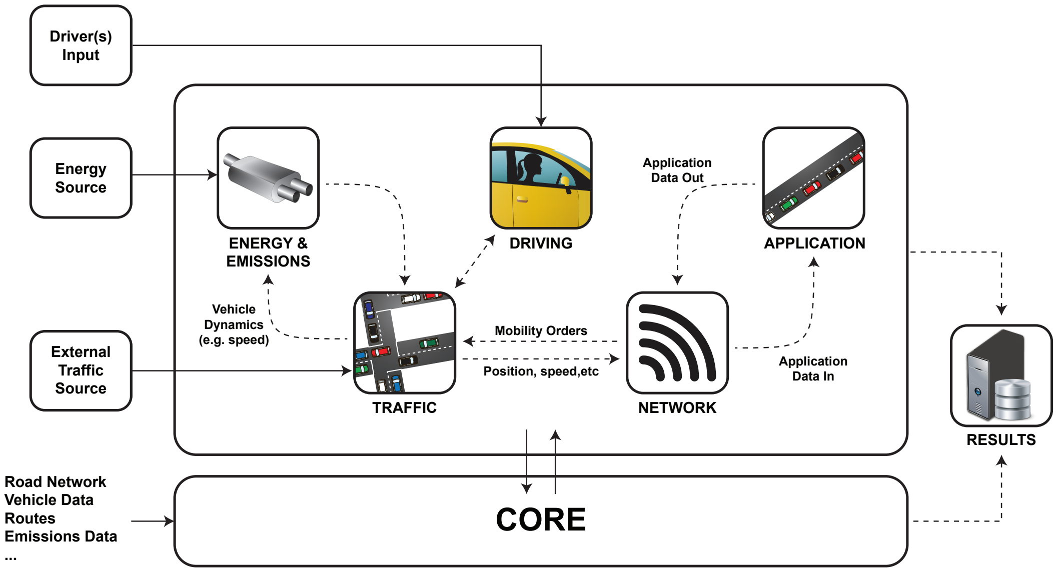

Figure 3.1: Main blocks for Simulation-based Evaluation of ITS and corresponding interactions.

Each of these simulation models is presented in more detail in Section 3.1 along with the current state of the art whenever appropriate or relevant for the scope of this thesis. In Section 3.2 the main interactions between simulation models are described. The main thesis contributions related to Simulation of ITS are summarized in the corresponding sections and presented in more detail in Section 3.3.

3.1 Simulation Models

3.1.1 Application Model

The main objective of the application model is to reproduce the functioning of a specific ITS application. According to a layered network design, applications use the services provided by underlying layers. Thus, the services of the network model are used to by the application model. Applications supported by vehicular networks need to exchange information between different nodes of the network to perform their tasks. The information exchanged between application and network models is dependent on the specific application. The performance and reliability of wireless network is of critical importance to applications and consequently networking aspects should be modeled in great detail whenever possible.

Contribution (Taxi Mobility Model) : We have realistically modeled the operation of the largest taxi fleet in the city of Porto using real data, namely passenger demand, taxi stand positions and others. The specific operation mode in the city and the current tariff system have been replicated as well.

3.1.2 Driving Model

Driving simulators may very usefully be employed to evaluate and develop Intelligent Transportation Systems (ITS), such as cooperative systems and Advanced Driver Assistance Systems (ADAS) [17]. This model allows having a number of real users interacting with simulated vehicles in a common scenario. Users rely on a vehicle unit, displays and driver controls to interact with the simulation platform.

The inclusion of the driving model into the methodology augments the number and depth of ITS application studies that can be performed. In the scope of this thesis, the inclusion of the driving simulator allows to study the behavior of real users moving in a realistic scenario. The environmental impact of simulated and real users can be then compared to understand the human behavior on novel systems. This can lead to several other improvements for novel applications. Furthermore, the user can understand how his/her driving pattern affects fuel consumption and the level of pollutant emissions, which can lead to improved eco-driving.

3.1.3 Energy & Emissions Model

Currently, fossil fuels (e.g. oil) are the major fuel supply for the transportation sector. The combustion of these fuels leads to a number of dangerous sub-products [e.g. Carbon Monoxide (CO), CO_2 or Nitrogen Oxide (NO)]. CO_2 is considered as the main by-product of fossil fuels combustion. To be able to estimate fuel consumption and emissions, researchers resort to different Energy & Emissions Models depending on the scope of the analysis.

Emission models can be broadly categorized into macroscopic, mesoscopic and microscopic models. Macroscopic models (e.g. [18]) estimate pollutant emissions and fuel consumption mainly based on average travel speed of the traffic flow. These macroscopic models entail enormous simplifications on the accuracy of physical processes involved in pollutant emissions [19], which leads to reduced accuracy in calculations. Moreover, these models cannot capture individual speed fluctuations and cannot take into account individual operation conditions, which are of crucial interest when analyzing systems that consider network and vehicle dynamics. Mesoscopic models (e.g. [20]), use more disaggregate trip variables, such as average speed, number of stops, and stopped delay, to estimate vehicle's emission rates on a link-by-link basis. Microscopic models estimate pollutant emissions and fuel consumption based on individual vehicle dynamics and on a short time frame. Since microscopic emission and fuel consumption models have higher temporal precision, and better capture the effects of vehicle dynamics and their interactions, they are usually used to evaluate the environmental gains/losses derived from ITS measures.

The calculation of Energy & Emissions using microscopic models is based on instantaneous individual vehicle variables that can be obtained frequently (e.g. 1 Hz) from a microscopic traffic simulator or another alternative source (e.g. GPS data logger). The calculation is then influenced by a number of fixed and variable parameters, which can be divided into two categories: vehicle parameters and traffic/road parameters. Vehicle parameters include, among others, vehicle mass, fuel type, engine displacement, vehicle class. On the other hand, network parameters (traffic and road conditions) account for instantaneous vehicle kinematics (e.g. speed or acceleration) or for road characteristics (e.g. road grade).

Several microscopic models have been proposed by the scientific community. These models can be classified into emission maps (speed/acceleration lookup tables), purely statistical models and load-based models [21]. Major contributions in this field were given by Akcelik et al. [22], Barth et al. [23] with the Comprehensive Modal Emission Model (CMEM), Ahn et al. [24], Cappiello et al. [21] with the EMIssions from Traffic (EMIT) model, US Environmental Protection Agency [25] with the Motor Vehicle Emission Simulator (MOVES), Hausberger et al. [26] with the Passenger Car and Heavy Emission Model (PHEM) model, Rakha et al. [27] with the Virginia Tech Microscopic (VT-Micro) model, Davis et al. [28] with the International Vehicle Emission (IVE) Model, among many others.

The selection of emissions model should be done carefully. Firstly, the aggregation level (e.g. macroscopic) of the model should be taken into account the available data and the application under test. Secondly, the selected model should have been extensively validated using empirical data of a variety of scenarios (e.g. highway, urban). Thirdly, it should be investigated whether the model provides calibrated parameters for different vehicle manufacturers, vehicle types and engine types. A proper selection of the Energy & Emissions Model is of major importance for the validity and correctness of the obtained results.

3.1.4 Network Model

Applications use the services provided by the Network Model for information exchange between participants. The main objective of a network model for vehicular networks is to replicate the functioning of a wireless ad-hoc or infrastructure-centric network. In the ad-hoc paradigm, the communication between nodes can take two forms: Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), whenever Road Side Units (RSUs) are necessary for the application functioning. Efforts have led to the standardization of VANET network protocols, namely IEEE 802.11p for the PHY/MAC layers and IEEE 1609.4 Wireless Access in Vehicular Environments (WAVE) for the remaining layers in the US or ITS-G5 in Europe Although nowadays the main focus for communication is given to WLAN-based vehicular networks, some studies [29, 30] indicate that third generation (e.g. Universal Mobile Telecommunications System (UMTS)) and fourth generation (e.g. Long Term Evolution (LTE)) mobile communication technologies can be used in vehicular networks, especially for non safety-critical applications (e.g. traffic information system). The inclusion of new radio access technologies has created heterogeneity in VANETs and novel challenges for researchers.

Several general-purpose network simulators have been developed, namely JiST/SWANS [31], OMNET++ [32], OPNET [33] and NS-3 [34]. However, for a given technology, the level of detail and the number of implemented functions of the protocol stack vary immensely among simulators. Furthermore, simulation platforms should consider the heterogeneity on the radio layer by providing implementations of different radio access networks (e.g. LTE). Apart from performance, another important aspect to consider is the validation of the different models. In [35] the performance of several network simulators is compared.

3.1.5 Traffic Model

Traffic models replicate mobility patterns of vehicles. Vehicular mobility is usually considered at various modeling layers:

- *trip modeling* - macroscopic motions according to an O/D matrix;
- *path modeling* - end-to-end paths followed by vehicles based on drivers' preferences, traffic or speed;
- *flow modeling* - interactions between vehicles as flows [36].

Depending on the specific application a number of these modeling layers should be implemented.

Regarding flow models, three classes are commonly considered, namely macroscopic, microscopic and mesoscopic models depending on the granularity of the flow:

- *Macroscopic models*: model the traffic flow as a whole through cumulative characteristics (e.g. density, flow, mean speed) using fluid dynamics equations. These present an aggregate view of the traffic flow but allow for an efficient computation.
- *Microscopic models*: simulate the movement of individual vehicles and their interactions (vehicle-vehicle and vehicle-infrastructure) in a road transportation network. These present a higher level of realism - due to the more detailed modeling - at the cost of higher computational complexity.
- *Mesoscopic models*: combine the advantages of macroscopic and microscopic models by integrating microscopic behavior (individual vehicles model) into macroscopic simulation based on aggregated relationships. The traffic flow is divided into sets of vehicles or clusters.

In this thesis, we will focus on realistic and microscopic models since these are the main used type and have the finest granularity (individual vehicles) and level of detail. Microscopic traffic models allow simulating individual vehicles and their interactions. Car Following Models (e.g. Intelligent Driver Model (IDM) [37] or Krauss Model [38]) or Cellular Automata Models [39] are the most cited microscopic flow models. To account for transversal dynamic, lane-changing has also to be included. IDM (resulting in Minimizing Overall Braking decelerations Induced by Lane changes (MOBIL) [40]), Krauss model, or the Cellular Automata Models have extensions to include lane-changing behavior. A complete survey on microscopic traffic and lane-changing models is given in [36, 41]. In [42] Jie et al. present a method for calibrating microscopic traffic models for emissions calculation.

By refining synthetic models and going through an intense validation process based on real traces or behavior surveys, some companies or research teams gave birth to realistic traffic simulators [41]. AIMSUN [43], CORSIM [44], SUMO [45], TRANSIMS [46] or VISSIM [47] are examples of validated microscopic traffic simulators.

3.2 Model Interactions

Using selected simulation models in isolation presents a number of advantages and drawbacks. Individual simulation models are able to more accurately replicate some specific aspects but may lack realism in other important simulation behavior. For instance, traffic models are able to replicate accurately the movement of individual vehicles and their interactions, but lack realism in the replication driver behavior. Driving models allow incorporating real drivers in a simulated scenario but lack realism in the simulation of other vehicles and the interaction between them. Network simulators replicate communication between nodes but need accurate models for realistic vehicle movement. Thus, in order to improve the realism of simulation a number of models should be integrated in a single simulation platform. Fig. 3.1 depicts the architecture of an integrated simulation platform.

Regarding model interactions, the interfaces of the Traffic Model with the Network Model, the Energy & Emissions Model and the Driving Model need to be considered. Firstly, communications and road traffic aspects should be modeled in detail and fully integrated in order to have an holistic view of the network functioning. As Sommer et al. have discussed in their paper [48], the functioning of one component affects the behavior of the counterpart, and consequently there must exist a bidirectional connection between traffic and network models. The mobility of vehicles affects network connectivity and performance. Thus, information from vehicle positions is passed to the network model. On the other hand, the exchange of information between nodes simulated by the network module can affect the mobility of vehicles. In this case application-specific information is passed to the traffic simulation model in order to alter individual vehicle mobility. For instance, a red-light traffic signal message received by a vehicle (network model) implies the car stoppage (traffic model). The integration of these two modes is usually done using Transmission Control Protocol (TCP) sockets (especially in the case of commercial simulators) or at a code level (in the case of open-source simulators). As networks models are more computational intensive these usually pose performance limitations to combined simulation models by limiting the effective number of simulated vehicles.

Secondly, the interaction between the Traffic Model and the Energy & Emissions Model is considered. The interaction between these models is also bidirectional by nature. At each time step, the traffic model provides vehicle dynamic information (e.g. velocity and acceleration) to the emissions model. Afterwards, by analyzing the physics behind the dynamic behavior of each vehicle, the energy consumed and related pollutant emissions are calculated. On the other hand, the information stored by the Energy & Emissions Model (e.g. CO_2 emissions at each link) may be used to alter the mobility of individual vehicles. As an example please consider the case of Eco-routing, where vehicles select the route with the lowest fuel consumption or pollutant emissions.

Thirdly, the interaction between the Traffic Model and the Driving Model is analyzed just for completeness reasons. The need for bidirectional coupling between traffic and driving models has been discussed in [17, 49]. The coupling between traffic and driving models is bidirectional because vehicles move in a common environment and consequently affect the mobility of each other.

Table 3.1: Integrated Simulation Platforms

	Model			
	Driving	Energy & Emissions	Network	Traffic
Punzo et al. [17]	SCANeR			AIMSUN
Gomes et al. [49]	*proprietary*			DIVERT
Hirschmann et al. [26]		PHEM		VISSIM
Several (e.g. [50])		CMEM		VISSIM
NCTuns [51]			*proprietary*	*proprietary*
TraNS [52]			NS-2	SUMO
OpenEnergySim [53]	OpenSim	CMEM		Avenue
IntelliDrive [54]		CMEM	*proprietary*	PARAMICS
iTETRIS [55]		HBEFA	NS-3	SUMO
VEINS [48]		EMIT	OMNET++	SUMO
VNS [56]		EMIT	NS-3	IDM/MOBIL
VSimRTI [57]		PHEM	OMNET++/.../NS-3	VISSIM/SUMO

The driving model needs to inform the traffic simulator of the dynamics (e.g. speed, position, etc) of the emulated vehicle(s) such that simulated vehicles adapt their flow model. On the opposite direction, the traffic simulator simulates vehicle movements according to the implemented traffic model and sends periodical updates of the dynamics of these vehicles to the driving simulator; the driving simulator in its turn updates the driving scenario shown to the end user.

In Table 3.1 a number of integrated microscopic simulation platforms is presented reflecting the the state of the art at the time of writing of this thesis. Early simulation platforms solely considered interactions between two simulation models. The most recent proposals already consider simultaneously three models, namely Energy & Emissions model, Network model and Traffic Model, which considerably improves the detail and accuracy of simulations. The level of integration needed will depend on the specific application under test and the aspects that need to be analyzed.

3.3 Realistic Simulation of ITS

In this section, we present a simulation tool for the realistic and large-scale evaluation of VANET applications and systems. The platform closely integrates traffic, network, application and energy consumption models. This framework uses real-world data (e.g. taxi mobility or vehicle O/D data) to accurately replicate vehicle movements (e.g. taxi operation) and interaction with existing infrastructure (e.g. traffic lights). The integrated simulation platform has been used for the evaluation of the VTL (section 7), a taxi-sharing system (section 8) and an automated parking system for Autonomous Vehicles (section 9).

This integrated simulation platform has been constructed incrementally. As basis for the development it has been used an open-source and scalable microscopic traffic simulator, which replicates the microscopic behaviour of vehicles and their interactions. DIVERT [58] is a sophisticated

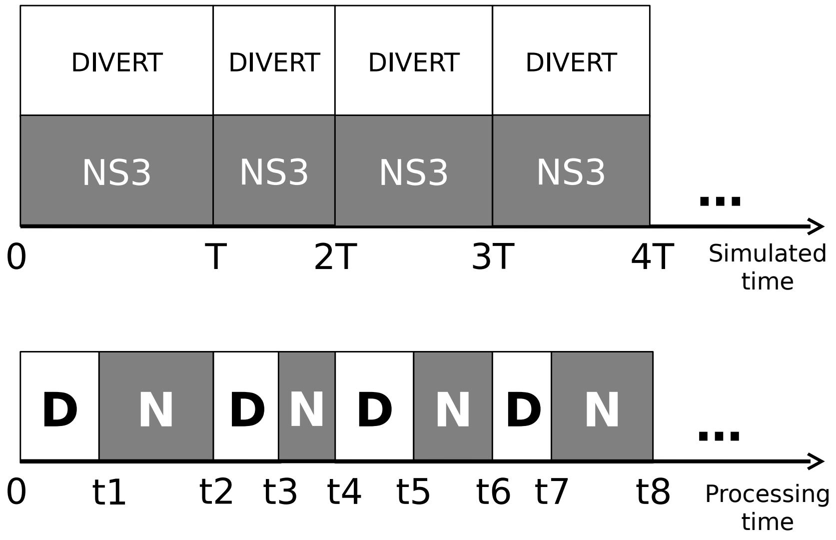

Figure 3.2: Simulation Execution

microscopic traffic simulator based on IDM [37] with a validated mobility model [59]. The lane-changing model is based on the MOBIL model proposed by Kesting et al. in [60]. This simulator also contains a simple V2V communication model.

Contribution (Integrated Simulation Platform) : In [6], we have proposed a very tightly integrated simulation platform to assess heterogeneous vehicular networks. The existing microscopic traffic simulator (DIVERT) has been extended to add support for a validated and widely used network simulator (NS-3). The performance of the platform is closely related and constrained by the performance of NS-3 network simulator. In addition, in other publications we presented the coupling of a microscopic emissions model (EMIT) to the simulation platform to asses the environmental impact of ITS and related applications. To realistically replicate the operation of the taxi fleet, we have integrated into the simulator a realistic taxi mobility model. This model uses real data, such as passenger demand or taxi stand positions, to mimic the specific operation mode of the largest taxi fleet in the city of Porto.

3.3.1 Integrated Mobility and Network Models

The realistic assessment of the vehicular networks requires detailed modeling and integration of the several simulation aspects. The integration of communication and vehicle mobility models in a single simulation platform is one of the most important aspects as is the basis for many studies of interest. In [6], we have proposed an integrated simulation platform that combines the DIVERT microscopic traffic simulator with the well know NS-3 [34] network simulator. The design of the simulation platform followed three main principles:

- using widely used, tested and scalable simulators [1];
- performing a full and clean integration at code level;
- code extensibility with minor or no changes.

The bi-directional coupling of traffic and network simulators has been realized by extending DIVERT capabilities by adding NS-3 support. The coupling is bi-directional since the both simulators influence each others operation and system behavior. However, it should be highlighted that the simulators operate independently but need to receive information from the other to perform the simulations accurately. The traffic simulator provides a realistic VANET mobility model to the network simulator. In this exchange node information (e.g. position) is periodically updated in the network simulator. The network simulator also needs to provide information to the traffic simulator. The exchange of information between the nodes in the Network simulator may lead to a change in behavior of the nodes (e.g a controller node sends messages to the vehicles to inform the state of the traffic light ahead and, in the case the traffic light phase is red, the vehicles will need to stop at the intersection). Thus, the mobility pattern may be affected by the exchange of information. The changes of the vehicle or driver behavior are application-specific.

The proposed approach takes advantage of both simulators being written in C++. Unlike other loosely (e.g. using TCP connections) or other tightly-integrated approaches to provide synchronization between different simulators, in this work, simulators are transparently integrated at the programming level, sharing the same memory space and processing time. A modular architecture was followed to enable independent development of both simulators. Modularity also means that, with the current implementation, a different simulator could be integrated with little effort into DIVERT. This VANET simulator can be classified as a *very tightly-integrated* simulator. The main advantages of the tight integration are the improved performance and modularity. This results in a complete integration, enabling the design and on-line simulation of network applications that may affect the traffic behavior and vice versa.

NS-3 is an event-based simulator where the event scheduler keeps track of simulation time and releases all the events in the event queue by invoking appropriate network components, which fits well with the DIVERT functioning, where the simulation time is discretized into a number of small time intervals. Since NS-3 is fully contained within the core of DIVERT, our approach consists in executing both network and traffic simulation steps inside the DIVERT execution loop. More precisely, after a given traffic simulation step, all the network scheduled events within the same time step are executed in a synchronized fashion. In DIVERT the total simulation time is discretized into small steps N. Each step is responsible for executing T seconds of the simulation time, consuming P seconds of the processing time. Figure 3.2 illustrates this behavior but involves the execution of both DIVERT and NS-3. For each execution step, traffic simulator executes T seconds of the simulation time, followed by the same T seconds executed by the network simulator. However, traffic and network components may consume different processing times as illustrated

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[1] The NS-3 network simulator has been selected for the integration as a recent study by Weingartner et. al [35] demonstrated that this delivers the best overall performance.

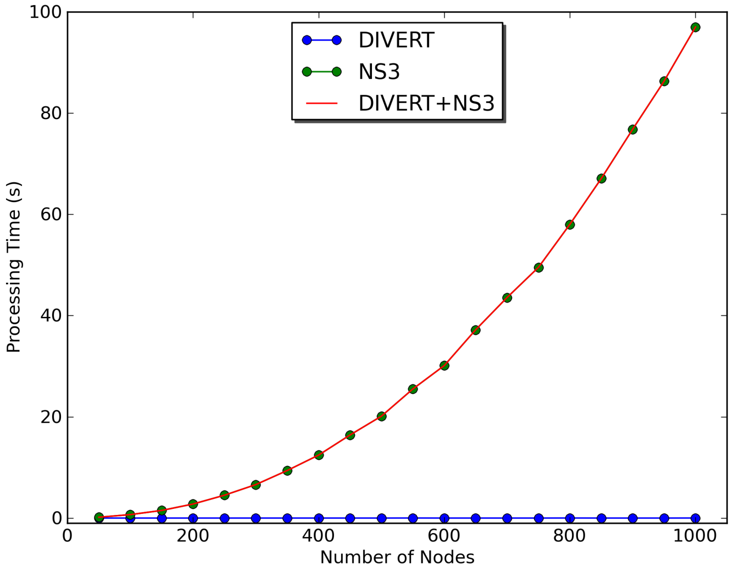

Figure 3.3: DIVERT+NS-3 Integration

in Figure 3.2. The simulation is fully controlled by DIVERT, being possible to start, stop, pause, restart and finish the execution or even to run it in fast or real-time mode.

DIVERT has a number of realistic traffic generation models, which does not only allow the creation of vehicles at the beginning, but also during the simulation. Hence, for every vehicle created or removed in the traffic component, DIVERT also needs to create or remove[2] the correspondent ns3::Node in NS-3. Since vehicular movements must be reflected in the correspondent nodes in NS-3, the ns3::mobility module has been extended to design a new mobility model - *DivertMobilityModel*. This model is the key point in the interaction between traffic and network components. Network nodes that correspond to vehicles in the traffic component have this mobility model by default, which stores a pointer to the correspondent vehicle. Thus, a possible network application is able to access its vehicle mobility in a transparent way, as well as to affect its behavior. Thus, the mobility pattern may be affected by the exchange of information. The changes of the driver behavior will be application-specific. DIVERT was also extended to provide an initialization and termination setup phase of the NS-3 simulation. Thus, before a simulation is started, user can setup the network as normally does in NS-3, enabling the creation of heterogeneous networks that may interact with VANET. For instance, cellular networks or road side units can be created in static positions and cooperate with vehicles.

Accurate simulation of vehicular mobility and wireless communications is time-costly. Application design, testing and validation require the assessment of the system in different scenarios with large numbers of vehicles. Thus, scalability and processing time are two of the main performance metrics for the realistic assessment of VANETs. To measure the performance of the

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[2] As the current version of NS-3 does not allow node removal, removed nodes are stored in a queue and reused whenever a new node is required.

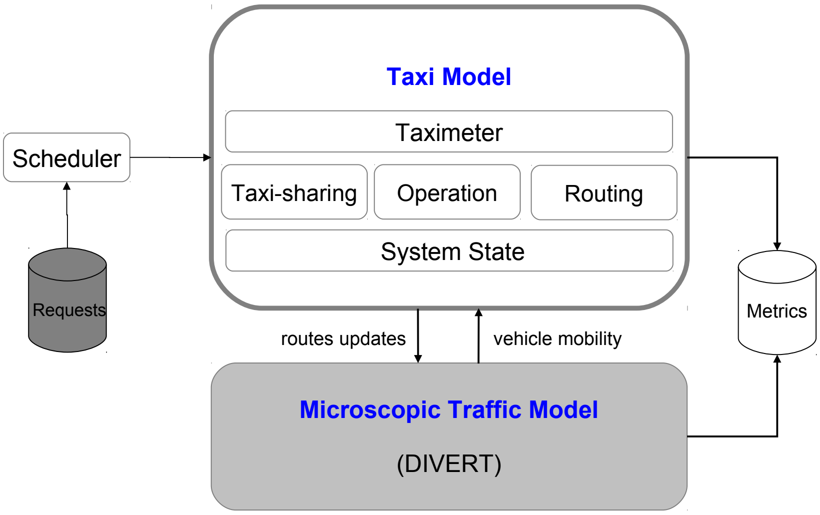

Figure 3.4: Simulation Platform for assessing the operation of taxi fleet.

framework the metric “processing time required to simulate 1 second scenario” has been selected.

The system’s performance has been tested in a scenario where each vehicle periodically (each 100 ms) broadcasts beacons of 100 Bytes in order to inform other nodes in the neighborhood about its dynamic variables (e.g. position, speed, heading). Simulations have been repeated for different numbers of vehicles. Figure 3.3 shows the performance of the integrated system. The computational overhead of DIVERT is almost insignificant when comparing to the integrated framework. Thus, the performance and scalability of the proposed VANET simulator is comparable to NS-3 performance standalone. The performance [61] and support for network simulators [56] of the integrated simulation platform has been further improved by Fernandes et al. in subsequent work.

3.3.2 Taxi Fleet Operation Model

The assessment of the operation of a taxi fleet requires a detailed and realistic modeling of taxi behaviour and related mobility patterns. More specifically, in this section, we present how the operation of the largest taxi fleet in the city of Porto has been replicated using real data, namely passenger demand, taxi stand positions, tariff system , among others. Furthermore, we detail how the model has been integrated into the DIVERT microscopic traffic simulator.

A conceptual representation of the simulation platform for assessing the operation mode of a taxi fleet is depicted in Fig. 3.4. The simulation platform comprises of two main models that are closely interconnected:

1. *Taxi Model*: replicates the operation mode of a taxi fleet;
2. *Traffic Model*: mimics the individual behaviour of vehicles.

These two components have been bi-directionally coupled to allow the operation of one to influence the operation of the other. The taxi model provides the microscopic traffic model (DIVERT)

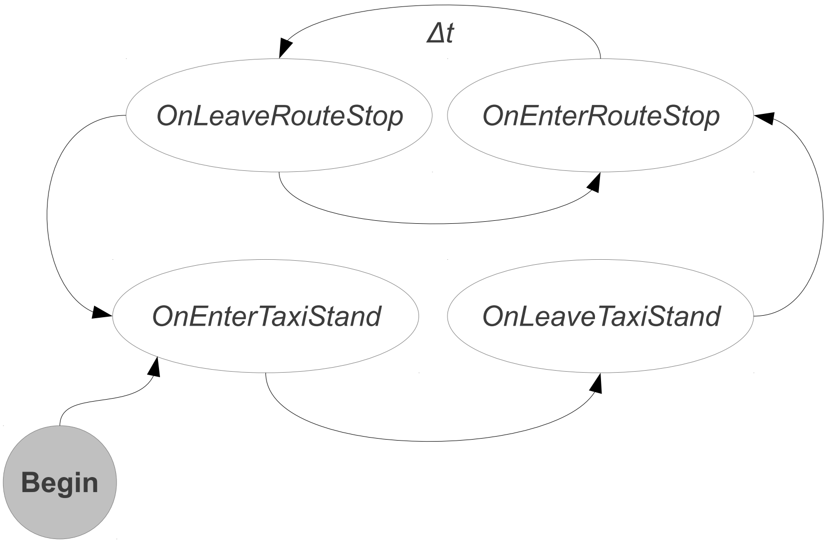

Figure 3.5: Taxi operation state diagram.

with new routes updates, which influences the mobility pattern of individual vehicles. On the other hand, the microscopic traffic model supplies vehicle mobility data to the taxi model (e.g. current taxi positions), which is used for service assignment and other algorithm.

The taxi operation model mimics the all the operations of a taxi fleet. It considers conventional taxi services (i.e. only one paying customer per trip), taxi-sharing services (i.e. several paying customers per trip) or any other hybrid format. To achieve this goal two main aspects have to be modelled in great detail:

- Passenger demand.
- Taxi operation;

Realistic input data is provided by the service scheduler, which emits service requests at the defined timestamp to mimic passenger demand. This request drives then the operation of the taxi operation model that replicates taxi behaviour. Output data is continuously collected in logs for off-line processing to quantify the current performance of taxi fleet operation. In the following, we provide a short description of the taxi operation models.

The passenger requests block corresponds to modelling the demand for taxi services and, consequently, for available capacity in vehicles. Passenger demand has been modelled as a service scheduler that issues pickup requests at the defined timestamp. We have used a list of real taxi requests obtained from a taxi fleet in the city of Porto as input to the simulation scheduler. Since each O/D field in the request is given by a GPS coordinate, the tool first matches this to the closest road segment in the map. After this procedure is completed, the result is stored in a file. Different service demands can be evaluated by modifying the service timestamp by a fixed value (e.g. 1.5, 2.0) for all services in the same simulation, which results in the concentration of services in a shorter period of time and consequently in an increased service request rate (services/s).

The taxi model was divided into five main blocks: operation, routing, taximeter, system state and the optional other operation modes (e.g. taxi-sharing). Taxi operation corresponds to the sequence of stages (e.g. leave taxi stand) that taxis follow to service clients and thus functions as a state machine in which state transitions occur under certain conditions. In the simulator we have selected to explicitly model the taxi stop states and implicitly model the *Movement* state by updating the taxi path. Due to this, the following states have been included: *OnEnterTaxiStand*, *OnLeaveTaxiStand*, *OnEnterRouteStop* and *OnLeaveRouteStop*. Fig. 3.5 depicts the taxi operation state diagram. The transition between the *OnEnterRouteStop* and the *OnLeaveRouteStop* states occurs after a pre-defined timeout has been reached (e.g. 20 s). The Taxi Routing component is responsible for providing the shortest path and the associated cost to the remaining blocks. The Taximeter component replicates the functioning of a tariff system based on distance and time, and when performing taxi-sharing, the tariff system presented in section 8.3.2. The System State component stores relevant information for the algorithm functioning (e.g. current taxi state (e.g. busy), current position). This model receives continuously updated information of the taxis' positions and other parameters from the microscopic traffic model and pre-timed service requests from the event scheduler.

3.3.3 Assessing the Environmental Impact

The assessment of the environmental impact of transportation systems requires vehicular movement/interactions and energy consumption models, and the integration of both. Due the characteristics of the systems under evaluation, herein we consider that these models are microscopic. Estimation of pollutant emissions and fuel consumption is based on instantaneous vehicle variables (e.g. acceleration, speed) obtained frequently (e.g. 1 Hz) from a microscopic traffic simulator. Output values are influenced by vehicle parameters (e.g. mass, fuel type) and network (traffic/road) parameters (e.g. traffic congestion or road grade).

In this context, we have integrated the EMIT model into the DIVERT/VNS simulation platform. At each time step, the traffic model DIVERT/VNS provides vehicle dynamics information (e.g. velocity and acceleration) to the emissions model. Following, the physics behind the dynamic behavior of each vehicle are analyzed, which allows determining the vehicle tractive power. Finally, the energy consumed and related pollutant emissions are calculated making use of the EMIT model. This model has been selected due to computational performance and accuracy reasons.

EMIT is a simple dynamic emission model that was derived from statistical and load-based emission models. This first estimates the instantaneous Tractive Power (P_{tr}) using Equation 3.1, which has as main parameters the vehicle velocity (v in m/s) and acceleration (a in m/s^2):

$$P_{tr} = A \cdot v + B \cdot v^2 + C \cdot v^3 + M \cdot a \cdot v + M \cdot g \cdot sin\vartheta \cdot v \tag{3.1}$$

, where the variables are defined as follows: A - rolling resistance; B - speed-correction; C - air drag resistance; M - vehicle mass; g - gravitational constant; and ϑ - road grade). Depending on the value of P_{tr} the Fuel Rate (FR) can be expressed as:

$$FR = \begin{cases} \alpha_i + \beta_i v + \gamma_i v^2 + \delta_i v^3 + \zeta_i a v & \text{if } P_{tr} > 0 \\ \alpha_i^{'} & \text{if } P_{tr} = 0 \end{cases} \tag{3.2}$$

where α_i, β_i, γ_i, δ_i, and ζ_i are constants associated to individual vehicles.

The EMIT model allows to simultaneously calculate several pollutant emissions sub-products, namely CO, CO_2, Hydrocarbons (HC) and NO. This calculation is divided into two main phases: Engine-out (EO) and Tailpipe (TP). The formula to calculate EO pollutant emissions has the same structure as Equation 3.2 due to the linear relationship with FR:

$$EO_i = \alpha + \mu \cdot FR \tag{3.3}$$

CO_2 is the main by-product of the combustion of fossil fuels and consequently it is proportional to FR. The values of CO_2 EO emissions are estimated directly from fuel consumption estimates. Due to this linear relationship, the terms FR or CO_2 can be used interchangeably when analyzing the environmental impact of an ITS technology.

After estimating the EO emission for the sub-products of combustion, the EMIT model calculates the Tailpipe (TP) emission rates. This emission rate is a fraction of the Engine-out (EO) emission rate that leave the catalytic converter:

$$TP_{CO_2} = \begin{cases} \alpha_{CO_2} + \beta_{CO_2} v + \delta_{CO_2} v^3 + \zeta_{CO_2} a v & \text{if } P_{tr} > 0 \\ \alpha_{CO_2}^{'} & \text{if } P_{tr} = 0 \end{cases} \tag{3.4}$$

where α_{CO_2}, β_{CO_2}, δ_{CO_2}, and ζ_{CO_2} are constants associated to individual vehicles that Cappiello et al. [21] obtained using ordinary least square linear regressions. The calibration of the parameters of Equations 3.1 and 3.4 resorted to light-duty vehicle data that was gathered for the CMEM model. These EMIT model parameters are presented in Table 3.2 for a vehicle category 9. Vehicle category 9 represents a normal emitting car (Tier 1 emission standard) with accumulated mileage greater than 50000 miles and high power/weight ratio. The definition of other vehicle/technology category of the modal emissions model can be found in [62].

Fig. 3.6 depicts the CO_2 emissions surface for a given input parameter set (acceleration and velocity) with a resolution of 0.1 (m/s^2 and m/s, respectively). It should be stressed that negative values for the CO_2 can be obtained with the EMIT model. This problem was addressed by considering a minimum value for the emissions that is equal to the constant $\alpha_i^{'}$ when P_{tract} is equal to zero.

Table 3.2: Calibrated EMIT Model parameters for Vehicle Category 9

Formula	Parameter	Description	Value	Unit
Vehicle (3.1)	A	rolling resistance	0.1326	$kW/m/s$
	B	speed-correction	2.7384e-3	$kW/(m/s)^2$
	C	air drag resistance	1.0843e-3	$kW/(m/s)^3$
	M	vehicle mass	1.3250e3	kg
	g	gravitational constant	9.81	m/s^2
	ϑ	road grade	0	$degrees$
CO_2 (3.4)	α_{CO_2}		1.1	g/s
	β_{CO_2}		0.0134	g/m
	γ_{CO_2}		-	$g\ s^2/m^2$
	δ_{CO_2}		1.98e-6	$g\ s^2/m^3$
	ζ_{CO_2}		0.2410	$g\ s^2/m^2$
	α'_{CO_2}		0.973	g/s

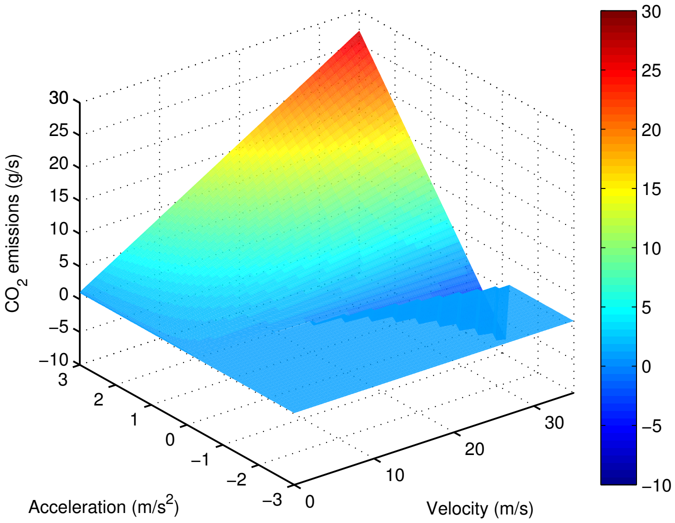

Figure 3.6: CO_2 Emissions surface as a function of the vehicle acceleration and velocity; increasing values for this metrics lead to increase CO_2 emissions. The EMIT model can produce negative values.

Chapter 4

Field Operational Trials

4.1 Introduction

In the last decades we have witnesses considerable advancements in the field of Intelligent Transportation Systems (ITS). First, during this period a number of research projects (e.g. Chauffeur, CarTalk, CVIS) has been carried out to improve the current state of the art,ranging from communications or security aspects to cooperative systems. Further, during the last years several ADAS, such as in-vehicle navigation systems or adaptive cruise control, have been brought to market. As the systems are becoming more mature, rigorous and systematic assessment methods based on empirical evaluations are deemed necessary for novel systems. In this context Field Operational Tests (FOTs) allow evaluating ITS systems and applications under realistic conditions before deployment in large-scale.

After successfully conducting FOT often there is an intermediate step towards deployment that is named Pilot projects. Pilot projects are pre-deployment projects that demonstrate how systems and applications can be deployed in real-world scenarios. In the EU these projects (e.g. FREILOT [1], In-Time [2]) are deployed in a number of cities/regions and provide valuable business, practical and technical lessons to be used during large-scale deployment. Often these initiatives result in the deployment of solutions after the pilot trials and the extension to more cities or regions. To conclude, FOTs are an important assessment stage between research, standardization and real-world (large-scale) deployment as depicted in Fig. 4.1. In [63] Festag et al. present FOTs as a tussle between research, standardization and deployment, and provide relevant details of the DRIVE-C2X project FOT.

FOT have been defined by the European Commission (EC) as "large-scale testing programmes aiming at a comprehensive assessment of the efficiency, quality, robustness and acceptance of ICT solutions used for smarter, safer and cleaner and more comfortable transport solutions". The same institution has defined the following set of objectives for FOT:

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[1] `http://www.freilot.eu/`

[2] `http://www.in-time-project.eu/`

Figure 4.1: Field Operational Tests between research and real-world (large-scale) deployment.

- Validate the effectiveness of ICT based systems for safer, cleaner and more efficient transport in a real environment
- Analyse driver behaviour and user acceptance
- Analyse and assess the impact of intelligent safety and efficiency functions using real data
- Improve awareness on the potential of intelligent transport systems and create socio economic acceptance
- To obtain technical data for system design and product development
- To ensure the transferability of the FOT results at National, European and International level.

FOT allow then testing technical and funtional behaviour, performance and acceptance of applications and systems in real-world conditions. Furthermore, these trials allow collecting data for more detailed evaluations and allows raising awareness for new technologies. Several trials have been or are being conducted in several parts of the world. In the following, example trial projects for three active world regions in the area of ITS are provided:

- Europe: DRIVE-C2X[3], euroFOT[4], FOTsis[5], PRESERVE[6], simTD[7], teleFOT[8]
- Japan: EnergyITS, SKY, SMARTWAY[9]
- US: IVI, Safe Trip-21[10]

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[3] `http://www.drive-c2x.eu/`
[4] `http://www.eurofot-ip.eu/`
[5] `http://www.fotsis.com/`
[6] `http://www.preserve-project.eu/`
[7] `http://www.preserve-project.eu/`
[8] `http://www.telefot.eu/`
[9] `http://www.nilim.go.jp/`
[10] `http://ntl.bts.gov/lib/38000/38500/38510/safetrip_cfr.pdf`

4.2 Methodology

Empirical evaluation of ITS applications usually involves three main stages: I) design, II) development and III) system evaluation. The first two stages are closely related to the design and development of applications as well as of the underlying system. The support system usually consists of a software and hardware platform where communication (e.g. ITS-G5, UMTS, LTE), sensing (e.g. Controller Area Network (CAN), GPS), computation and other core technologies (e.g. digital maps, security, logging) are incorporated. The details and content of the support platform will depend on the specific applications as well on design choices. For instance, the choice of the development language can depend on the requirements of applications. Applications are then build on top of the underlying software and hardware platform that provides basic and common application functions. Applications use then the services provided by the lower layers in the protocol stack. Functionality is distributed by the different stations in the system (e.g. vehicle, central, road side, personal ITS stations).

After the complex system design and development process, applications and enabling systems are evaluated under realistic conditions in stage III. In the following we provide more detail on large-scale field trials as part of this thesis centers on the realistic assessment of communication performance. To be effective (e.g. cost) and to produce sound results, FOT should follow standard procedures and best practices in the field. Accumulated knowledge in previous FOT has made possible the compilation of a handbook of good practices, which is know in Europe as FESTA (Field Operational Test Support Action).

Fig. 4.2 depicts the FESTA methodology, which provides and describes the main stages of this process, namely planning, preparation, execution, analysis and reporting. The FESTA methodology can be divided into three high-level functions, i.e. *Preparing*, *Using* and *Analysing*. In the first stage of FESTA a research-oriented approach is followed to identify the main performance indicators and associated measures and sensors. After the identification of the main functions and use cases for further investigation, the main research questions and hypothesis are defined. FESTA is a V-model with increasing complexity and level of detail when converging and diverging from the *Using* function. In the *Analysing* stage, first researchers consider detailed evaluation to later assess the societal impact of applications and systems. Ethical and legal issues are considered throughout the process.

In the data acquisition phase, drivers perform planned test runs while a logging system collects information (e.g. CAN data, GPS position, exchanged messages) during the route. Additionally, data can also be collected automatically from other sensors in vehicles, such as video-cameras (e.g. for eye-tracking) or radars, or by means of questionnaires, driver logs or surveys for subjective data. These test drives can be classified into:

- *naturalistic* in case realistic driven conditions are emulated (e.g. urban scenario, no restrictions imposed to driver (e.g. route))

- *controlled* when restrictions are applied (e.g. closed test track)

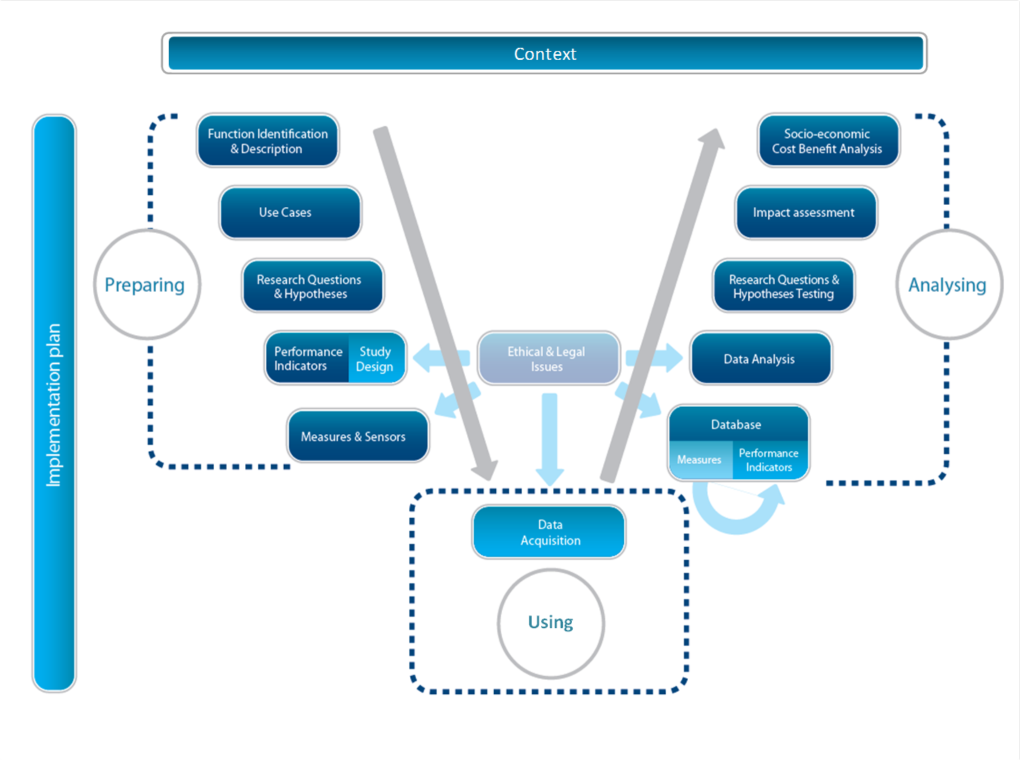

Figure 4.2: FESTA methodology [64].

, which has an impact on the test drive realism, externalities isolation and consequently on the final results. Data should be collected for sufficiently long periods to allow statistical relevance during processing and to allow inferring relevant conclusions, which can be used to improve the proposed systems. After the acquisition phase, data should be (automatically) collected from all stations and transmitted to a central storage location (e.g. central FTP) for further processing To conclude, assessment using empirical evaluations requires properly designed evaluation plans, availability of infrastructure (e.g. vehicles, equipment, software), testers (e.g. drivers) and statistically relevant data.

After being collected, the quality of the data should be analyzed. In case the logged data is considered valid it can be used for further assessments. In this phase, system and application functionality is studied using the previously defined performance metrics. This allows understanding the system performance, identifying possible implementation issues or possible design faults. At the end, this analysis allows also addressing the research questions and accepting/rejecting the hypothesis. Finally, the results are used for socio-economic impact assessment where higher level research questions can be addressed (e.g. safety, efficiency or sustainability).

4.3 Contribution

In this thesis, we analyze vehicular networks using empirical data collected within the scope of the European project DRIVE-C2X. DRIVE-C2X is a large-scale FOT that analyses safety and traffic efficiency applications and systems. More specifically, we assess cooperative awareness - enabled by short-range communication (ITS-G5) - that is at the core of many of these and other applications (e.g. Virtual Traffic Lights). Cooperative awareness can be defined as the ability to detect surrounding vehicles, including their locations, speed and heading. By empirically analyzing selected performance metrics, the performance of cooperative awareness provide to applications can be realistically analyzed. The main research question is to understand in a real-world scenario and with a statistically relevant data set, if the level of awareness provided by the communication system meets applications requirements. A detailed study in this topic is provided in Chapter 5.

Chapter 5

Empirical Evaluation of Cooperative Awareness in Vehicular Networks

5.1 Introduction

VANETs are envisioned to enable novel cooperative ITS applications. Cooperative awareness is the basis for a number of safety and traffic efficiency ITS applications [65]. More specifically, innovative applications, such as Overtaking Systems [66], VTL [1] or Cooperative Adaptive Cruise Control (CACC) [67]rely on the exchange of cooperative awareness messages between vehicles. he main premise is that, by knowing their neighborhood, vehicles (in coordination with their drivers) are better equipped for decision-making in hazardous situations (e.g., emergency braking) and more adept at finding better routes to their destination (e.g., by avoiding congested roads).

The exchange of local dynamic information (e.g. direction, position, speed) allows creating a precise picture of the evolving neighborhood and the dynamics of surrounding vehicles. Thus, in order to have up-to-date neighbor information, vehicles periodically send single-hop broadcast messages containing awareness information. To enable this service, the European Telecommunications Standards Institute (ETSI) and other standardization bodies have introduced CAM for periodical update of vehicles' location, speed, and other salient information. However, improved awareness level comes at the cost of higher channel load and the associated packet collisions. Eenennaam et al. [67] studied the solution space of single-hop beaconing and concluded that the number of nodes, the beacon frequency and size, and the transmit power impact the beacon reception rate considerably. Adaptive power/rate beaconing [68] or selective beacon forwarding [69] can improve network conditions, especially in high load situations.

In this thesis, we focus on the effectiveness of CAM message exchange. Specifically, we study the performance of cooperative awareness under realistic conditions and configurations by using measurements collected during large-scale FOTs of the DRIVE-C2X project[1]. Our main goal is to determine the feasibility and performance of periodic beaconing and to assess the awareness level

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[1] `http://www.drive-c2x.eu/project`

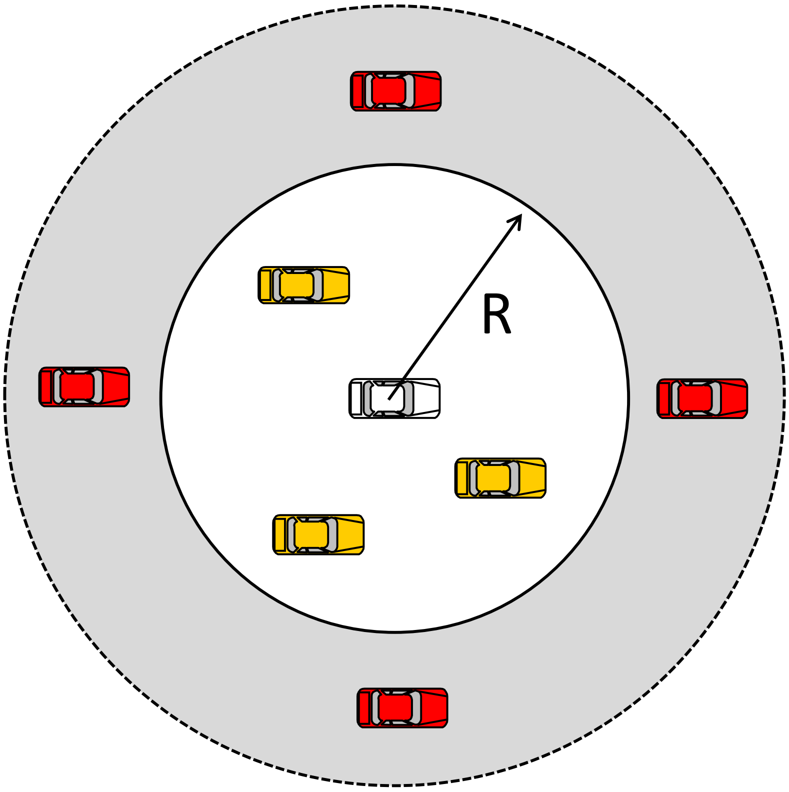


Figure 5.1: Neighborhood awareness is based on the broadcast of periodic messages and allows gathering relevant information on the evolving neighborhood (white awareness zone with radius *R*). However, increased awareness can also result in interference from distant vehicles (grey interference zone) that are less relevant than the nearby vehicles.

provided to applications. Furthermore, we aim at understanding how these performance indicators are affected by external parameters (e.g. transmitter-receiver spatial separation). With this aim, we analyze link quality in terms of Packet Delivery Ratio (PDR) and cooperative awareness efficacy in terms of Neighborhood Awareness Ratio (NAR). We study how these metrics are affected by the surrounding environment and node separation. While CAM messages increase the awareness, at the same time they have a negative impact on interference. Therefore, to gauge the level of interference that both CAMs and other messages generate, we analyze the proportion of neighbors above a certain range from which a given vehicle receives messages. This metric is of interest for understanding the side-effects of higher level of distributed/local information and in combination with the previous metrics can be useful in the design of congestion control algorithms.

The remainder of this Chapter is organized as follows. In Section 5.2, we present the work related to evaluating cooperative awareness. Section 5.3 provides an overview of the experimental evaluation platform, including assessment methodology, evaluation metrics, and experimental scenarios. Section 5.4 details and discusses the results of communication performance and its impact on the application-level performance. Section 5.5 concludes this Chapter with the main conclusions.

5.2 Related Work

Extensive research has been conducted to study communication performance as well as application performance in VANETs, with most studies resorting to analytical models or simulations. Mittag et al. [70] compared single and multi-hop broadcast performance using simulations. They concluded that a limited benefit is achieved when using multi-hop communication instead of single-hop for cooperative awareness. Van Eenennaam et al. [67] showed how different beaconing configurations support Cooperative Adaptive Cruise Control (CACC). Noori et al. [71] performed simulations to study the probability of beacon delivery in an urban scenario and showed how the delivery is impacted by increasing vehicle density and different road types.

Regarding empirical evaluation of communication and application performance in VANETs, a number of studies has been presented. The main objective of most studies was to understand real-world performance characteristics of this type of network. Martelli et al. in [72] analyze the Packet Inter-Reception time (PIR). Their results showed that PIR follows a power-law distribution (i.e., long-lasting outages occur with certain periodicity). Furthermore, PIR is strongly affected by Line of Sight (LOS) conditions, with up to five-fold performance drop in case of LOS obstruction by vehicles. Bai et al. [73] performed an extensive study on the impact of controllable parameters (transmit power, modulation scheme) and uncontrollable factors (distance, environment, velocity) on the performance of IEEE 802.11p [74] radios. The authors solely use PDR as the metric for the performance assessment. Vlavianos et al. [75] performed a measurement-based study to assess the link quality in IEEE 802.11 networks. The authors concluded that different evaluation metrics reveal relevant aspects of the link quality. Boban et al. [76] demonstrated the importance of accurate channel model selection for correctly simulating the application-level performance in terms of throughput, packet delivery, and latency.

Apart from analyzing the conventional communication performance (e.g. throughput, delay) several studies proposed using information-centric metrics. The main metrics that have been defined are:

- awareness quality [70, 77];
- update delay [the time elapsed time while expected CAMs from j are not received by i] [78];
- PIR [the time interval between consecutive received beacons] [68].

These metrics allow for a better understanding of the impact of the underlying vehicular communication system on application-level performance. As pointed out in [77], awareness, as an intermediate step between network and application layers, can be used to establish relationships between layers and facilitate performance evaluation of applications.

5.3 Experimental Evaluation of Communication Performance

5.3.1 Experimental platform

DRIVE-C2X project designed and evaluated a set of applications (e.g., traffic jam ahead warning, road works warning, in vehicle signage) enabled by V2V and V2I communication in test sites throughout Europe. The project ETSI-compliant architecture comprises of central, roadside and vehicle ITS stations. In our study, we are concerned with V2V communication only. In this section we present in more detail the DRIVE-C2X experimental platform for assessing the performance of cooperative systems. Below we describe the main system components of the DRIVE-C2X system; more details on the overall architecture and on individual system components can be found in [63].

The DRIVE-C2X system uses ITS-G5 compliant radios that operate in the 5.9 GHz frequency band. The devices have dual transceivers for multi-channel operation on the control and service channels. The default value for transmit power is set to 21 dBm. Omni-directional antennas are placed on the roof of personal vehicles with heights ranging from 1.44 meters to 1.66 meters. Vehicles had different antenna setups that created variations of the effective transmit power output. Antenna installation and cable properties may vary from test site to test site. The radios also contain software for implementing the Geo-Networking and Basic Transport Protocol (BTP) standards.This software component provides packet routing in vehicular networks using geographical positions. Furthermore, Geo-Networking provides services to the BTP. The BTP implements an end-to-end, connection-less transport protocol in vehicular networks. Its main purpose is the multiplexing of messages from different processes at the ITS Facilities layer (e.g. CAM) for the transmission of packets via the Geo-Networking protocol as well as the de-multiplexing at the destination. A GPS receiver is used for collecting vehicle position data.

The radios transmit CAMs that are in line with the ETSI standard [79]. The main functions of CAM module are to generate, process and decode this message type. CAMs contain node information (e.g., position, speed, and sensor information) and are broadcast to one-hop neighbors over the control channel. Since different safety applications defined by ETSI require different beacon frequencies (e.g., vulnerable road user warning application requires 1 Hz frequency, while emergency electronic brake lights requires 10 Hz [65]), the default beacon frequency was set between 1 Hz and 10 Hz. The size of the beacon is 100 Bytes. Each vehicle collects and stores all CAMs that have been received and transmitted. Since logging is performed in all stations, several metrics can be calculated to assess the performance of cooperative systems. To be able to accurately compare the results, identical settings are kept for all possible static parameters (e.g. transmit power, message size). Furthermore, tight time synchronization between node clocks is necessary for accurate analysis.

It has to be noted that, since the generation rate of the messages was low and the frequency was the dedicated 5.9 GHz spectrum, the results herein shown can be considered virtually interference free, thus exhibiting the upper bound of performance for the system.

5.3.2 Methodology

FOTs play an important role after basic research, during standardization, and prior to the deployment of cooperative systems. Deep knowledge on the realistic assessment of cooperative systems and applications is vital for a successful deployment of technology. Although restricted by cost, safety, and size reasons, these experimental tests allow better understanding real-world constrains and requirements that are not easily simulated. To assess the feasibility and performance of single-hop beaconing, we have then resort to an large-scale empirical evaluation study.

In the following we give a methodology for studying study the performance of cooperative awareness from both communication and application perspective. Our main objective is to understand how cooperative awareness behaves under varying conditions. More specifically, we investigate in detail how different uncontrollable factors, namely node spatial separation and propagation environment, impact the performance of cooperative awareness as seen by individual vehicles. Furthermore, we aim to study empirically the drawbacks of cooperative awareness.

Cooperative Awareness messages are generated by Vehicle ITS Stations (VISs) and Roadside ITS Stations (RISs). The dataflow for message generation is initiated by the Cooperative Awareness (CA) Basic Service. The CA Basic Service generates a CAM which contains status information of the transmitting node (e.g. position, heading, speed and acceleration). This CAM is sent to the logging system for later processing and to Geo-Networking Basic Transport Protocol Application Programming Interface (GNBTPAPI) which forwards it to Geo-Networking Basic Transport Protocol (GNBTP). The GNBTP component broadcasts the CA message to all its 1-hop neighbours. The GNBTP component of the receiving node implementation may receive the CAM message and forwards it to the GNBTPAPI component. The GNBTPAPI component forwards the CAM to the CA Basic Service which decodes it and provides the contained information to the logging system. The complete flow of information, from transmitting station to receiving station is illustrated in Fig. 5.2. At each station, the logging component records all the transmitted and received CA messages.

The evaluation is based on the dynamic node behavior of a fleet of vehicles induced by cooperative applications and the analysis of logging information. As nodes record all received and transmitted messages, a number of key performance indicators can be calculated by comparing message sets of different nodes. For the list of measurands and key performance indicators considered in this study please refer to Sections 5.3.3 and 5.3.4, respectively. Initially, the results are calculated between pair or pairs of vehicles to understand the pair-wise performance. Following, the results are aggregated in order to have a network-level view of the performance. To be able to accurately compare the results identical settings are kept for all possible static parameters (e.g. transmit power, message size). However, since node mobility is planned according to application requirements (no specific communication tests) different mobility behavior can be observed (e.g. variable transmitter-receiver distance, vehicle speed). The advantage of this approach is the large amount of data to be analyzed since all applications rely on the exchange of beacons.

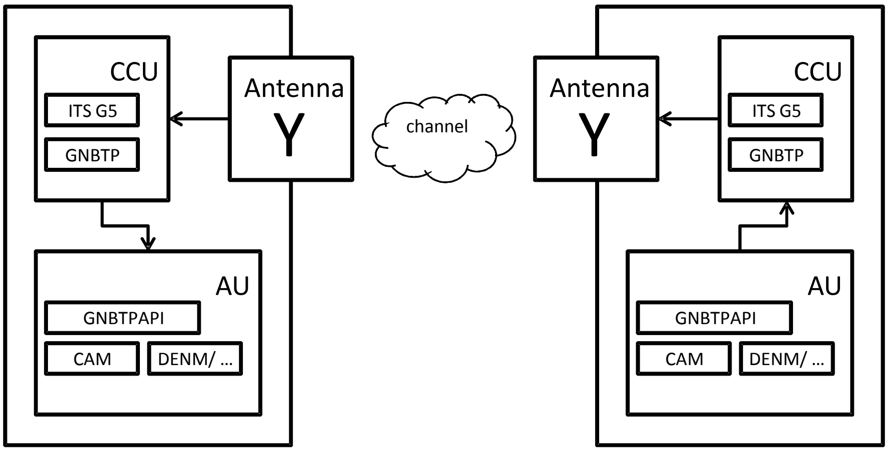


Figure 5.2: Cooperative Awareness Message Flow between ITS stations, either Vehicle ITS Stations (VISs) or Roadside ITS Stations (RISs).

5.3.3 Measurands

Herein, we present the data collected during FOTs of the DRIVE-C2X project that is relevant for communication evaluation. In Table 5.1 the main measurands of the CAM and Logger components are given.

Table 5.1: Cooperative Awareness Message (CAM) measured variables

Measured Variables	**Explanation**	**Signature**	**Component**
Logger station ID	Local log node identifier	n/a	Logger
Timestamp	Log entry creating timestamp	n/a	Logger
Generation time	Point in time when a CAM message is generated by the CA Basic Service of the station	generationTime_high32bit, generationTime_low32bit	CAM Manager
Action (sent/received)	Action that triggered the logging event	Action	CAM Manager
StationID	Station identifier	stationId_high32bit, stationId_low32bit	CAM Manager
Reference Position	Position of the transmitting or receiving station	refPosLong, refPosLat	CAM Manager

5.3.4 Metrics

Cooperative awareness relies on single-hop broadcast of local node information (e.g. vehicle speed, location). To evaluate cooperative awareness in vehicular environments, we analyze the following three performance indicators.

1. *Packet Delivery Ratio (PDR)*: the ratio of the number of correctly received packets to the number of transmitted packets. Formally, for a vehicle i, the PDR is calculated as:

$$PDR_i = \frac{PR_i}{PT_i} \tag{5.1}$$

, where PR_i is the number of packets sent by i that were correctly received by the surrounding vehicles and PT_i is the total number of packets sent by i. This metric is closely related to the performance of the communication system (i.e., the higher this metric is, the better the performance of the system). However, it is also strongly affected by static and dynamic parameters. On one hand, there are static parameter as node configuration parameters (e.g. transmit power). On the other hand, there are dynamic factors that cannot be controlled (e.g. surrounding environment, node speed or inter-node distance), which also impair the probability of packet delivery. This metric allows also inferring the sustainable communication range between nodes.

2. *Neighborhood Awareness Ratio (NAR)*: the proportion of vehicles in a specific range from which a message was received in a defined time interval. Formally, for vehicle i, range r, and time interval t, the NAR is defined as:

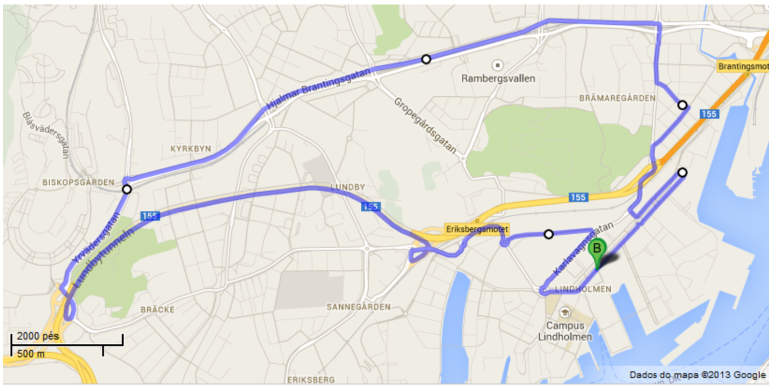
$$NAR_{i,r,t} = \frac{ND_{i,r,t}}{NT_{i,r,t}} \tag{5.2}$$

, where $ND_{i,r,t}$ is the number of vehicles within r around i from which i received a message in t and $NT_{i,r,t}$ is the total number of vehicles within r around i in t (we use t=1 second). Referring to Fig. 5.1, for the white vehicle in the center, NAR is the proportion of nodes in the inner (white) circle from which the observed vehicle received a message.

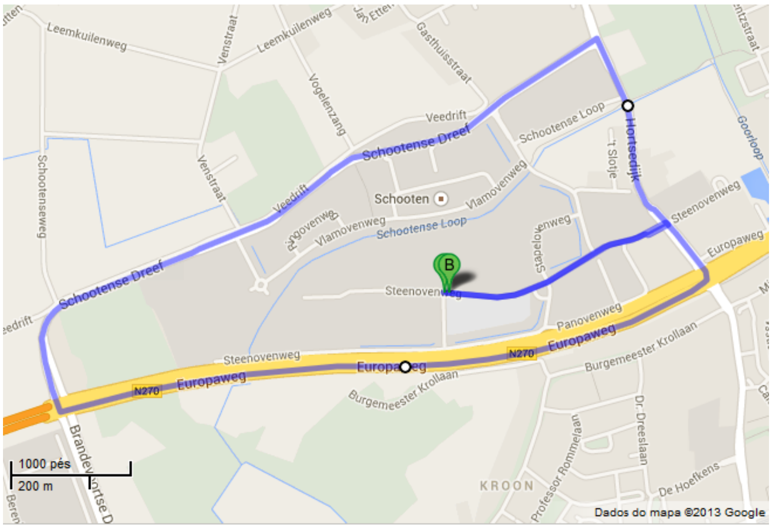
3. *Neighborhood Interference Ratio (NIR)*: for a vehicle i, range r, and time interval t, the ratio of neighbors that are above a certain distance from the observed vehicle is defined as:

$$NIR_{i,r,t} = \frac{NA_{i,r,t}}{N_{i,t}} \tag{5.3}$$

, where $NA_{i,r,t}$ is the number of vehicles above r from which i received a message in t (again, we use t=1 second) and $N_{i,t}$ is the total number of vehicles from which i received a message in t (irrespective of r). Referring to Fig. 5.1, for the white vehicle in the center, NIR is the proportion of vehicles from which it received a message within the time interval and which are outside the inner (white) circle, divided by the total number of vehicles from which a message was received. This metric is important for interference analysis, as it sheds light on the proportion of nodes that are overheard, but are not necessarily relevant. It has to be noted that, since the generation rate of the messages was low and the frequency was the dedicated 5.9 GHz spectrum, the results herein shown can be considered virtually interference free, thus exhibiting the upper bound of performance for the system. Thus, the NIR metric is



(a) Gothenburg



(b) Helmond

Figure 5.3: Experiment routes.

a reflection of the potential interference in future, fully deployed system, rather than the interference exhibited in the small-scale measurements.

5.3.5 Experimental Scenarios

In the following, the test scenarios are presented in more detail and the collected datasets are briefly described. he datasets used in the analysis were collected over several days between 9 a.m. and 5 p.m. in Gothenburg, Sweden (in June, 2013), and in Helmond, Netherlands (in September, 2012).

The test site in Gothenburg is depicted in Fig. 5.3a. This route was driven repeated times anti-clockwise by all vehicles. Along this 11 km route a number of events occurs (e.g., a car breakdown) that allows for realistic assessment of cooperative applications and also of the underlying communication platform. Vehicles were driven in normal traffic conditions with the presence of other vehicle types and respecting traffic rules. This test route compromised of a mixture of suburban-like environment (approximate coordinates in lat,lon: 57.710316,11.94238) and an

Table 5.2: Description of Experiment Locations and Parameters

Location	**Gothenburg** (Fig. 5.3a)	**Helmond** (Fig. 5.3b)
Scenarios	Suburban (57.710316,11.94238)	Suburban (51.472803, 5.622418)
	Urban highway (57.718424,11.918331)	Open road (51.477243,5.620085)
Number of Vehicles	6	7
Route Length	11 km	5.5 km
Vehicle Type	Personal	Personal
Antenna Type	Omni-directional	Omni-directional
Antenna Location	Rooftop	Rooftop
Antenna Height	approx. 1.55 m	approx. 1.44 - 1.66 m

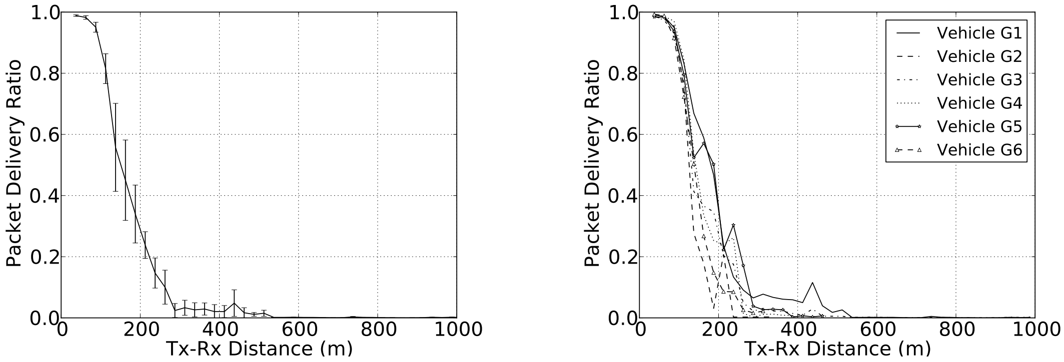
urban highway (approximate coordinates in lat,lon: 57.718424,11.918331). Vehicles also drove through a 2.5 km tunnel that is not considered in the study since no CAMs are generated when the GPS receiver has no lock. The other test site, located in Helmond, Netherlands (Fig. 5.3b) is comprised of a suburban and open road environment with occasional buildings and foliage around the road. More details on the experimental setup are given in Table 5.2.

5.4 Results

In this section we present and discuss the empirical results of Cooperative Awareness in Vehicular Communications. Fig. 5.4 shows the Packet Delivery Ratio (PDR) as a function of distance for V2V communications. As expected, PDR decreases as the node separation increases. In both scenarios, correct decoding of packets occurs predominantly at distances up to 500 meters, although occasionally communication is possible up to 1000 meters (e.g., in case of straight open road). The harsh propagation environment, including frequent Non Line of Sight (NLOS) conditions due to surrounding objects (e.g. other vehicles, buildings, and trees), and high vehicle mobility affect the link quality considerably. This results in fluctuations of PDR for a given distance. Furthermore, even for line of sight (LOS) channels, fluctuations over distance arise, mainly due to the dominating two-ray ground reflection model [76].

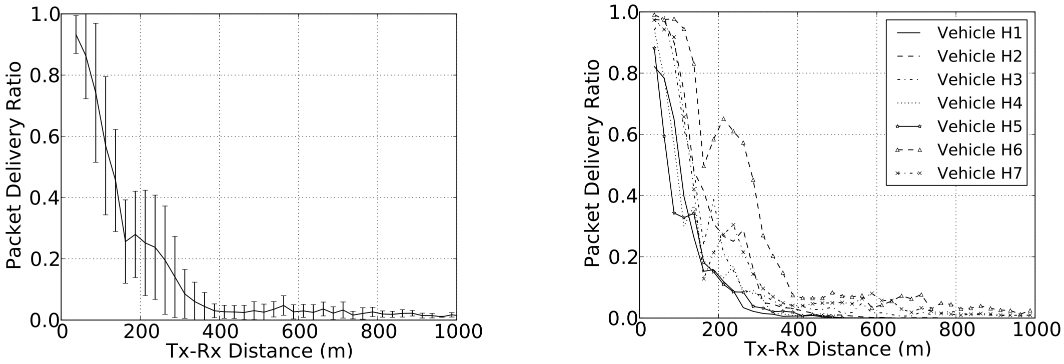
Our results are in line with the analytic results given by An et al. [77]. Under more favorable conditions, such as highway scenario and in case of V2I communications, the results presented by Visintainer et al. [80] show that high PDR is possible for communication ranges over 300 meters. Similarly, increased effective transmit power would result in higher PDR for a given distance.

Since the measurement locations were a combination of open road and (sub)urban environments, along the route there was considerable shadowing due to both buildings [81] and other vehicles [82]. This resulted in reduced average transmission range (as shown in Fig. 5.4), which affected the neighborhood awareness. As demonstrated by An et al. [77] and confirmed by Fig. 5.4 and Fig. 5.5, there is a strong correlation between neighborhood awareness and PDR. Fig. 5.5a and Fig. 5.5c show that the neighborhood awareness is above 90% for distances up to 100 m with



(a) Overall results – Gothenburg.

(b) Per-vehicle results – Gothenburg.



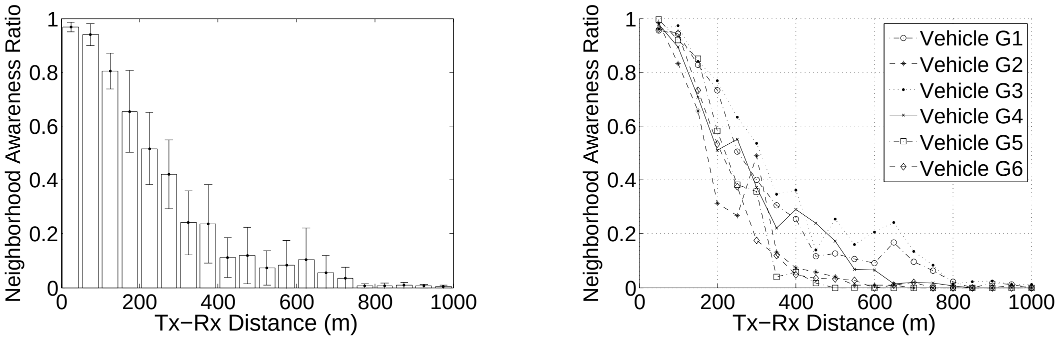
(c) Overall results – Helmond.

(d) Per-vehicle results – Helmond.

Figure 5.4: Packet Delivery Ratio (PDR). Each distance bin is 25 meters, with the plotted data point centered in the middle of the distance bin. Error bars represent one standard deviation around the mean PDR of each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.

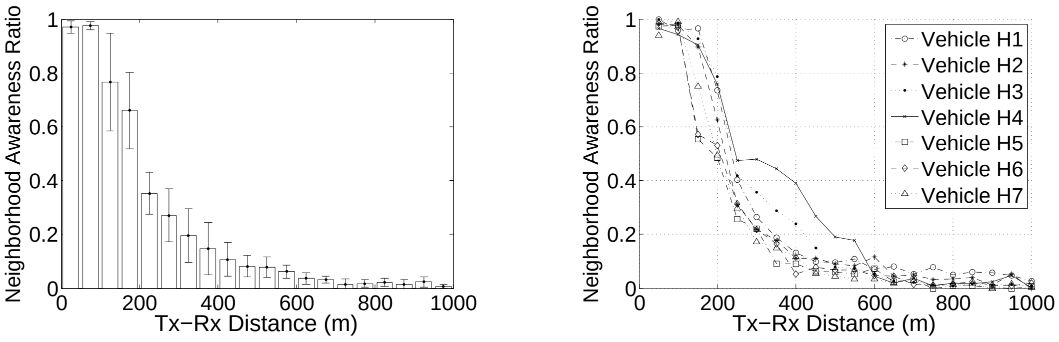
a progressive decrease to 10% around 500 m. The comparatively complex propagation environment explains why the neighborhood awareness results are worse than the results obtained through simulation by Mittag et al. [70], where a two-ray ground reflection model was used to represent line of sight communication. Fig. 5.5b and Fig. 5.5d show the per-vehicle neighborhood awareness: while the trends are comparable, for a given distance bin there are differences exceeding 20% for different vehicles. Therefore, even in the same environment, different vehicles can have a significantly different perception of their surroundings, depending on their exact location and the performance of their communication systems.

With regards to the interference, Fig. 5.6 sheds some light on the effect that the distant neighbors can have in terms of interfering with contextually more relevant nearby neighbors. Fig. 5.6a and Fig. 5.6c show that the interference level from vehicles above approximately 300 meters is quite limited, with their proportion contained within 10%. Situation is somewhat more complex when the region of interest is 100 meters, since in that case the extraneous neighbors can comprise more than half of the total number of neighbors. Fig. 5.6b and Fig. 5.6d show that the per-vehicle



(a) Overall results – Gothenburg.

(b) Per-vehicle results – Gothenburg.



(c) Overall results – Helmond.

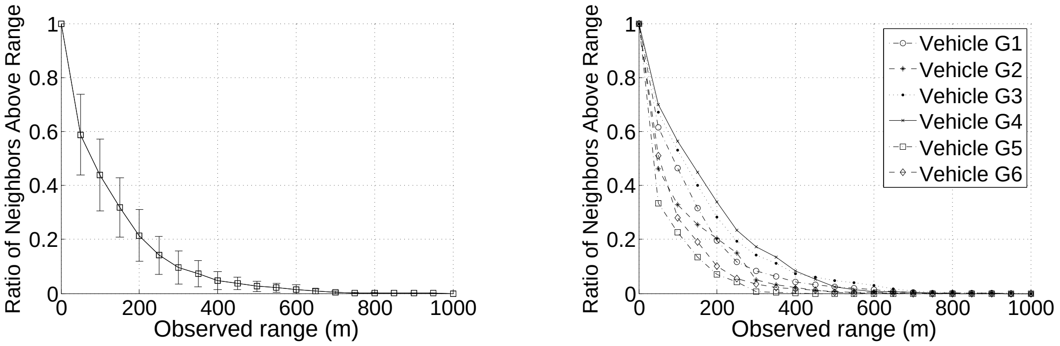
(d) Per-vehicle results – Helmond.

Figure 5.5: Neighborhood Awareness Ratio (NAR) results. One second window was used for determining the reception of messages from direct neighbors. Each distance bin is 50 meters, with the plotted data point centered in the middle of the distance bin. Error bars represent one standard deviation around the mean ratio of detected neighbors for each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.

variation can be considerable, with certain vehicles having more than 40 percentage points difference in NIR for a given distance.

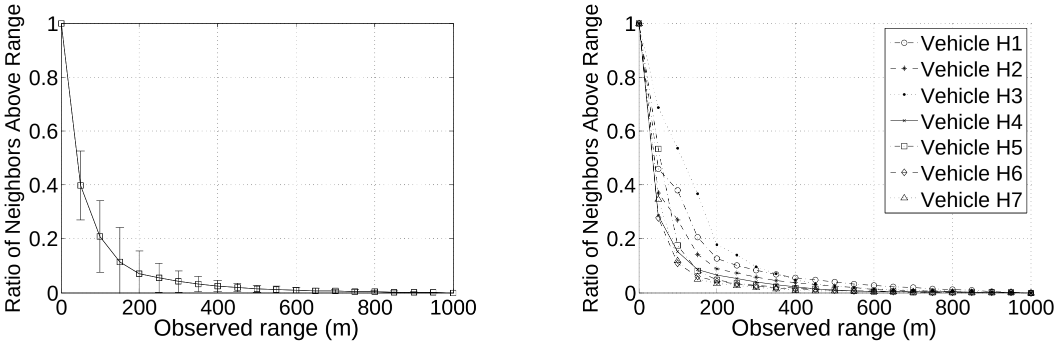
From the perspective of cooperative applications (e.g., Cooperative Collision Warning [65, 83]), the results shown in Fig. 5.5 indicate that the applications requiring above 90% of neighborhood awareness can function within 100 m. Increased awareness can be achieved by increasing the transmit power, at the expense of increased interference.

more detailed analysis of the results has also shown that there are considerable variations in local awareness and interference levels between vehicles in similar environments. This could have significant repercussions on the design of congestion control algorithms. Specifically, most existing studies that analyzed congestion control were based on simulation studies where the large-scale shadowing effects – in particular, the transition between LOS and NLOS – were neglected (e.g., the authors of a recent study provide a discussion on this [68]). Therefore, the impact of the neighborhood awareness variation should be accounted for in the design and performance evaluation of the congestion control algorithms.



(a) Overall results – Gothenburg.

(b) Per-vehicle results – Gothenburg.



(c) Overall results – Helmond.

(d) Per-vehicle results – Helmond..

Figure 5.6: Neighborhood Interference Ratio (NIR) results. One second window was used for determining the reception of messages from direct neighbors. Each distance bin is 50 meters, with the plotted data point placed at the end of the distance bin. Error bars represent one standard deviation around the mean ratio of detected neighbors for each vehicle. For statistical relevance, we consider solely bins with at least 40 data points.

Furthermore, the results shown in Fig. 5.6 indicate that a distance based rate/power control schemes might not be directly applicable for all regions of interest, since in certain cases the distance to a neighbor does not necessarily signify the level of the interference on a link. This emphasizes the importance of proper network configuration and power and rate control in V2V communication.

5.5 Conclusions

he broadcast of CAM creates awareness between vehicles in close proximity. Safety and traffic efficiency applications use the local awareness information to improve their performance or to enable their functioning. In this study, we empirically studied the performance of single-hop beaconing using large-scale experiments performed in two locations encompassing a wide variety of environments, including open roads, urban highways, and suburban-like roads.

The results demonstrate that cooperative awareness is strongly dependent on the transmitter-receiver separation and the propagation conditions. Furthermore, we show that application-specific requirements can be met even in harsh propagation environments: in both test sites, the neighborhood awareness was above 90% within 100 meters. Using the neighborhood interference ratio as a metric, we show that the far-away neighbors can cause considerable interference; for example, in the Gothenburg test site, approximately 30% of the neighbors are more than 200 meters away. The per-vehicle results indicate that local awareness and interference levels can vary significantly between vehicles. Our results show that vehicles will need to employ carefully designed transmit power control mechanisms that will enable cooperative awareness, at the same time reducing the unnecessary interference.

Although the results presented in this work refer to a limited set of data (two test sites, fixed values of transmit power, etc.), the trends shown in Figs. 5.4, 5.5, and 5.6 are likely to hold for a variety locations and parameters. For example, varying transmit power might shift the curves in the figures, but the shape of the curve is likely to remain similar.

As future work, we plan to analyze the behavior of PDR, NAR, and NIR in distinct V2V environments (e.g., urban, highway, suburban). Furthermore, we plan to investigate the same metrics in case of V2I links. Additionally, the proposal and study of novel metrics or combined metrics might provide new insights into the performance of cooperative awareness.The analyzed measurement datasets contained up to seven communicating vehicles. To investigate the behavior of the aforementioned metrics on a large network involving thousands of communicating vehicles, we plan to perform a large-scale simulation study using a realistic channel model (e.g., [84]). It is also of interest to understand how these results can be used for the design of congestion control algorithms.

Part II

Efficient and Sustainable Mobility enabled by Vehicular Networks

Chapter 6

Introduction

ITS combine a number of technologies, namely sensing, processing and communication technologies, to improve transportation systems. The widespread availability of processing units (e.g on-board computers) and the increasing deployment of different sensing technologies have created new opportunities for ITS. Heterogeneous communication technologies play a major role in ITS by extending the sensing range, by enabling distributed computing and by providing several communication channels, which considerably improves the range and performance of these systems.

The main goal of ITS is to improve the efficiency and safety of transportation systems. The deployment of advanced ITS can lead to improved road safety, decreased congestion, improved energy efficiency/emissions levels, among other benefits. Thus, it is important to understand how these benefits can be attained using novel technologies and systems engineering concepts. More specifically, in the context of this thesis we aim at studying how ITS can deliver more efficient and sustainable mobility. In the following, we present in more detail Green ITS, including definition, variables and performance metrics, as this is a more recent area in the field of transportation. Additionally, the main strategies for more efficient and greener mobility are presented in Section 6.3.

6.1 Green ITS

Green ITS refer to the development and deployment of communication and information systems for improved energy consumption and reduced pollutant emissions. Improved environment performance may derive *directly* from the specific design of eco-friendly algorithms (e.g. eco-routing), where the main objective is to reduce fuel consumption or pollutant emissions, or *indirectly* as a corollary of the deployment of ITS applications. As an example please consider a traffic signal control with two different main optimization objectives: a) minimizing the total energy consumption or pollutant emissions or b) maximizing the traffic flow while delivering acceptable safety performance. In case b), eventual gains in terms of reduced energy consumption and pollutant emissions are solely an additional outcome arising from the implementation of traffic signal control systems.

Green ITS have as main objective to improve air quality, reduce energy consumption and reduce noise levels. Noise levels could also be improved by Green ITS measures but will not be considered in this thesis. Thus, these measures can be evaluated using a number of performance metrics, namely:

1. air pollutants (e.g.)
    - Carbon Monoxide (CO)
    - Nitrogen Oxide (NO)
    - Nitrogen Dioxide (NO_2)
2. energy consumption (e.g. gasoline, diesel)
3. greenhouse gases (e.g.):
    - Carbon Dioxide (CO_2)
    - Methane (CH_4)
    - Nitrous oxide (N_2O)

6.2 Variables affecting Mobility

For a greener and more efficient mobility, one needs to first understand the parameters that have a higher impact on energy consumption (e.g. fuel) and on pollutant emissions (e.g. CO_2). These dependent on the vehicle characteristics and functioning, the road network that is transversed and a number of externalities (e.g. traffic, weather), namely:

- vehicle dynamics and functioning (e.g. velocity, acceleration, gear choice, A/C usage);
- vehicle characteristics (e.g. vehicle mass, fuel type, engine power, age, catalysts, condition);
- vehicle category (e.g. bus, car, motorcycle);
- road network characteristics (e.g. road slope, topology);
- traffic conditions & congestion (e.g. flow, stops);
- external conditions (e.g. weather, temperature).

From the previous list solely a number of parameters can be enhanced through Green measures (e.g. vehicle speed, road selection, driving behavior). More specifically, vehicle dynamics and functioning, road network characteristics and traffic conditions & congestion can be modified by the deployment of intelligent systems. For instance, consider the following examples: a) vehicle dynamics and functioning can be modified by speed management systems; b) appropriate road network characteristics can be selected by navigation devices (eco-routing); c) traffic conditions can be improved through the use of traffic management systems. In the following the impact that a number of vehicle, road network and traffic-related variables has on energy consumption and emissions is studied. In the current paradigm vehicles are manually driven and consequently the environmental performance will depend on the driver characteristics. However, in an autonomous driving scenario the performance will be related to the controller design and system configuration.

The *driving style* has a great influence on fuel consumption and emissions. Aggressive drivers are known for a higher energetic bill. In [85] Ericsson analyzed the impact of driver behavior on environmental performance metrics. The study concluded that driving patterns with specific acceleration and power demand (high), gear changing behavior (late) and certain speed intervals have a significant negative effect on energy consumption and emissions. Another study [86] demonstrated the importance of timely gear shifting and adequate acceleration levels for fuel consumption reduction. The authors proposed a fuel efficiency support tool that achieved savings of 16% when comparing with non-assisted driving.

Related to the road network characteristics, we present in the following the impact of road infrastructure and road grade on environmental performance. The work [87] by Brundell-Freij et al. further investigated the influence of *road network characteristics* (e.g. traffic light controlled intersections) and driver type on driving patterns. The study concluded that the main four effects are caused by: a) density of traffic lights; b) speed limit; c) street function and d) type of neighborhood. The largest comprehensive effect is the density of junctions controlled by traffic lights; higher densities causing lower average travel speeds, higher speed oscillation, and higher shares of heavy acceleration and high-power demand [87]. In [88] the authors have shown, through experimental work, that *road grade* has a considerable impact on the energy consumption and emissions at link level as well as at route level (the fuel economy of a flat route may be 15% to 20% superior to a hilly route). This relation influences the design of eco-friendly routing engines so that map elevation is considered in the calculations.

With regard to traffic conditions, the impact of full vehicle stops and traffic congestion in energy consumption and emissions is detailed. In [89] Rahka et al. studied the impact of *vehicle stops* on fuel consumption and emissions. The study indicated that vehicle fuel consumption and emission rates increased considerably as a vehicle stop was introduced, especially at high cruising speeds, and that the aggressiveness of a vehicle stop did have a significant impact on vehicle emission rates [89]. Treiber et al. have investigated in [90] the effect of *traffic congestion* on energy and emissions using an empirical data set. The authors found out that, for the used data set, traffic congestion typically lead to an increase of fuel consumption of the order of 80% and that the influence of congestion on fuel consumption is distinctly lower than that on travel time [90].

Thus, to improve the performance in environmental terms, three main players in urban mobility, namely vehicles, road network and drivers, need to be addressed by ITS (Fig. 6.1). Firstly, the driving behavior should be smoother (less acceleration/deceleration), vehicles should be operated at fuel-optimal speeds and gear changing should be done timely. Secondly, the design and utilization of road networks and its infrastructure should be done wisely (e.g. selection of routes without high gradient and many traffic lights). Thirdly, traffic conditions should be considerably improved (e.g. decrease congestion) to reach a smoother traffic flow.

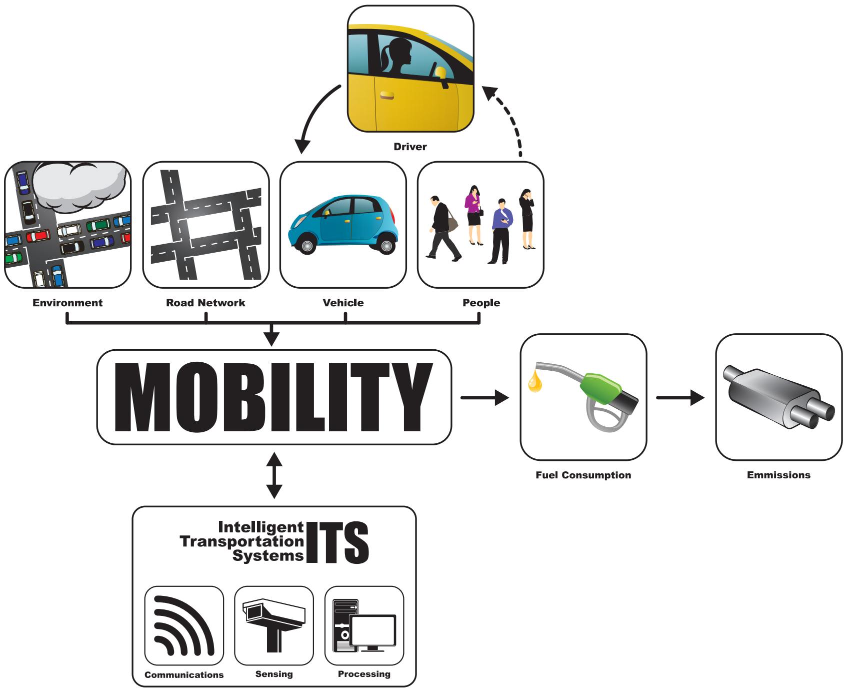


Figure 6.1: Key factors influencing Mobility. Intelligent Transportation Systems (ITS), which combine communication, sensing and processing, can improve mobility by more efficient vehicle usage and enhanced efficiency on road network utilization.

6.3 Strategies for Efficient and Sustainable Mobility

To achieve a more efficient and greener mobility a number of strategies can be conducted. Firstly, improvements to the design and efficiency of vehicles (e.g. use less and cleaner energy, weight reduction) and infrastructure (e.g. reduce slopes, additional roads, operation mode) should continue to be made. Alternatively, improved mobility can be attained through the management of mobility and demand, namely by promoting public transport, better integration of transport models and novel transportation paradigms (e.g. ride-sharing). Furthermore, novel capabilities and systems should be incorporated to the existing traffic paradigm. Thus, for improved system efficiency and better environmental performance, modifications to the operation mode of three main players in vehicular mobility (people (including drivers), vehicles, road network) must be carried out with the assistance of ITS (e.g. see Fig. 6.1).

In this sense, Intelligent Transportation Systems (ITS), which combine sensing, processing and communication technologies, present as a viable strategy for improved mobility. More efficient *vehicle usage* and enhanced *efficiency on road network utilization* can be attained through:

- improved perception of the current status of vehicles and traffic conditions through monitoring and information dissemination (e.g. eco-routing);
- optimized or novel traffic efficiency and management (e.g. adaptive traffic lights);
- improved vehicle operation and driver behavior (e.g. eco-driving)

- increased vehicle occupancy and operation modes (e.g. taxi-sharing).

ITS measures can be categorized according to the control decision level: *microscopic* when the operation of vehicles and driver behavior is individually induced, *macroscopic* when the operation of the main players in vehicular mobility is coordinated by traffic management entities and *hybrid* when the operations result from a mix of microscopic and macroscopic measures. In this thesis, we will consider microscopic decision although the macroscopic decision level also presents interesting characteristics.

Chapter 7

On the Impact of Virtual Traffic Lights

7.1 Introduction

Considering that the transport sector is responsible for an increasingly important share of current environmental problems, measures should be taken to help solve this issue. In parallel with the effort to develop more efficient and environmentally friendly vehicles, the design of mechanisms that improve the efficiency of road utilization, namely real-time traffic information systems and collaborative routing systems [91] [92], highway platooning [93] or adaptive traffic signal control [94] [95], can produce substantial additional benefits towards the reduction of the carbon footprint of road transportation. In the critical fraction of $CO_2\ g/km$ we argue that more emphasis should be put on the *mechanics* of how each kilometer is traveled, including the route choice and the traffic control signage that is in place. In-vehicle ITS technologies will play a key role in this more efficient utilization of the road, as we witness the inclusion of routing engines and traffic signs as in-vehicle systems.

Besides improving safety and road network efficiency, we argue that ITS measures lead to significant improvements in terms of environmental impact. Thus evaluating and quantifying the impact of such technologies in terms of CO_2 emissions is very important and can eventually lead to its integration in the assignment of the emissions value of new cars, which is relevantly reflected in the final price/yearly taxes and can contribute to a more rapid dissemination of such technologies.

In this study, we focus on the evaluation and quantification of the impact in terms of CO_2 emissions of the recently proposed concept of VTL [95], where the traditional road-based physical traffic signals are replaced by in-vehicle representations, supported only by V2V communication. Our main goal is to provide evidence of the significant reductions in average network emissions that can be obtained through a novel ITS technology enabled by VANET.

The remainder of this Chapter is organized as follows. In the next section, we briefly present the relevant related work in traffic signal control. Then, Section 7.3 introduces the VTL concept and the main system characteristics. Section 7.4 provides a methodology for evaluating carbon emissions and the impact that the VTL system has on pollutant mitigation. Section 7.5 details the simulation scenario and evaluation metrics, and discusses the main results (individual and aggregated). Section 7.6 closes this work with the main conclusions.

7.2 Related Work

Traffic signal control has attracted much attention from the research community over the last decades. Classical control concepts assume a cyclic operation of traffic signals, where the flows of different directions are served periodically [96]. Main control strategies can be broadly categorized into static and adaptive control.

Static control strategies, also commonly named pre-timed, run precomputed and fixed signal plans. Signal plans are determined making use of historical data to infer the best parameters (e.g. green split) for each intersection. However, pre-timed control is incapable of responding to real-time traffic variations and often results in inefficient utilization of intersection capacity [97].

On the other hand, adaptive control strategies change signal plan in adaptation to the varying traffic conditions. Intelligent systems use basic sensors and optimization algorithms to increase traffic flow while others use more complex technology to gather more information for the traffic signal to make a decision [98]. Systems, such as SCOOT [99] or SCATS [100], make use of detectors placed in the vicinity of intersections to adapt to variations in the traffic demand.

The advent of VANETs made possible a variety of new strategies that leverage on V2V and/or V2I communications. Additional and more precise information (e.g. vehicle speed and position) on each vehicle can be exchanged among vehicles or with a centralized control unit. On the most simple setting, the traffic signal periodically broadcasts its scheduling information over the wireless medium to vehicles in its vicinity [101]. In [94] the authors describe an adaptive traffic signal control system based on wireless communication between vehicles and a controller node placed at the intersection; control delay and queue length metrics are exchanged using a VANET data dissemination platform. Cai et al. propose a Dynamic Programming algorithm using vehicle speed, position and waiting time as state variables [102]. In [103] a distributed multi-agent-based approach is adopted to develop a traffic-responsive signal control system. The adaptive behavior of this type of systems uses information of vehicles (e.g. speed and position) that can thus overcome the shortcomings of traffic signal control systems based on detectors placed at fixed locations. The stop or go message is conveyed to drivers through the traditional road-based lamp. A decentralized signal control strategy has been recently proposed by Laemmer and Helbing in [96].

7.3 Concept

The road network has become ubiquitous such that, in the conterminous US, for example, we can get no farther from a road than 35 km [104]. It is geometrically unavoidable that these millions of kilometers of roads meet at some points, forming road junctions of different topologies. Based on the 2009 Tiger/Line data [105], it was computed that the number of intersections in the US amounts to approximately 50 million [95]. In terms of traffic flow, these junctions constitute critical points, which are the subject of a vast amount of research toward its optimization. This optimization can either be based on a topological/geometrical approach (through grade separation or roundabout design, e.g., [106]), or on a signalization approach, particularly through intelligent traffic signals, (e.g. [107]).

In this work, we focus on the role of VANET for the optimization of road intersections based on intelligent traffic signals. One common aspect to all the strategies presented in Section 7.2 is the utilization of fixed infrastructure to support the operation of intelligent traffic control strategies. Furthermore, many of these strategies assume the existence of a centralized control unit and cyclic operation. In this work, we propose a new paradigm, named Virtual Traffic Lights (VTL), in which control is decentralized and self organized, operation is acyclic, and traffic signal information is individually and directly presented in each vehicle. In our system vehicles behave as sensors in the road transportation network.

In [95], we presented the VTL concept, advocating for a paradigm shift from traffic signals as road-based infrastructures to traffic signals as in-vehicle virtual signs supported only by V2V communication. The implementation of the VTL system results in improved traffic flow due to the optimized management of individual intersections, which is enabled not only by the neighborhood awareness of VANET protocols but due to the scalability of the solution as well, which renders signalized control of intersections truly ubiquitous. This ubiquity allows the maximization of the throughput of the complete road network rather than the reduced number of road junctions that are currently managed by physical traffic signals.

The principle of operation of VTL is relatively simple and is illustrated in Fig. 7.1. Each vehicle has a dedicated Application Unit (AU), which maintains an internal database with information about intersections where a virtual traffic light can be created. When approaching such intersections, the AU checks whether there is a VTL running that must be obeyed or a VTL needs to be created as a result of perceiving crossing conflicts between approaching vehicles [see Fig. 7.1(a) and Fig. 7.1(b)].

Beaconing and location tables, which are features of VANET geographical routing protocols (see e.g. [108]), are used to determine whether a VTL needs to be created. Each node maintains a location table that contains information about every node in its vicinity, which is constantly updated through the reception of new beacons. The periodicity of these beacons can be increased as vehicles approach an intersection.

If a VTL needs to be created, then all vehicles approaching the intersection must agree on the election of one of the vehicles as *leader*, which will be responsible for creating the VTL and broadcasting the traffic signal messages [see Fig. 7.1(c)]. This vehicle works as a *temporary virtual infrastructure* for the intersection and takes the responsibility of controlling the VTL. Once this leader has been elected, a VTL cycle for the intersection control is initiated with a red light for the leader approach/lane. This condition ensures that the leader will remain in the intersection for the duration of a complete cycle. Based on the number of vehicles in each approach, the leader can set the traffic signal parameters, such as the phase layout and the green splits assigned to each approach, in an optimized manner. During the existence of a VTL *leader*, the other vehicles act as

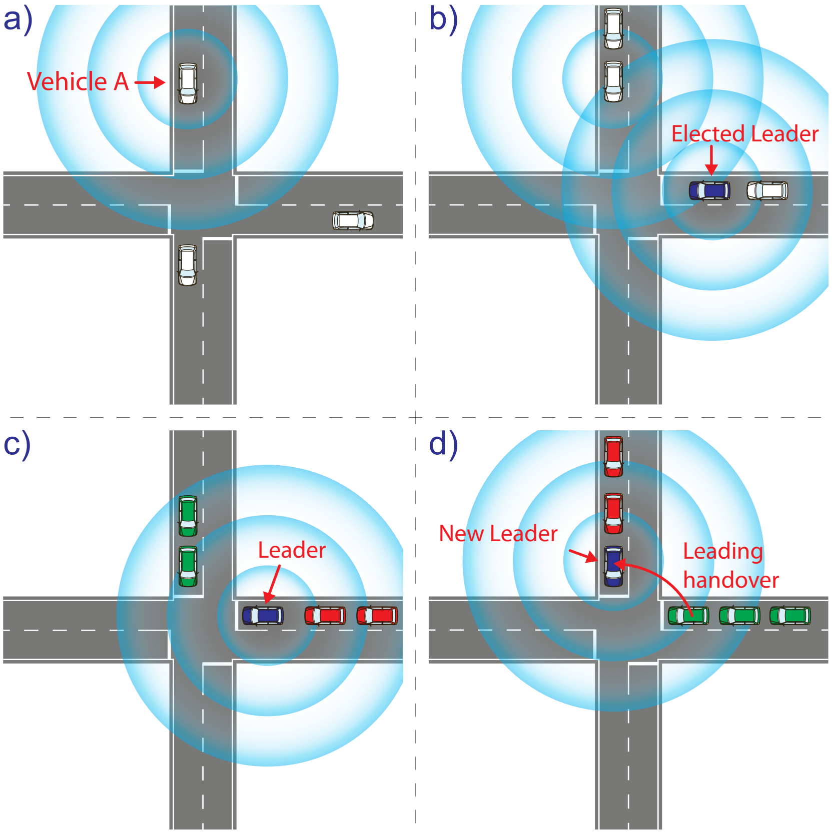


Figure 7.1: Virtual Traffic Lights (VTL). Frame a) depicts a conflict-free intersection. Vehicle A uses periodic beaconing to advertise its position and heading as it approaches the intersection. No conflicts are detected and it is not necessary to create a VTL. In frame b) the periodic beaconing of concurrent vehicles results in the detection of a crossing conflict and in the need to create a VTL. One of the conflicting vehicles is elected as the intersection leader and will create and control the VTL. This leader stops at the intersection and replaces a road-based traffic signal in a temporary control of the intersection. In frame c), the leader is stopped at the intersection and optimizes the functioning of the VTL based on the number of vehicles in each approach, and periodically broadcasts VTL messages with the color of each approach/lane. In frame d), when the cycle ends and the green light is assigned to the leader approach/lane, the current leader selects a new leader from the vehicles stopped under red lights. This new leader continues the cycle. If there are no stopped vehicles under red lights, then the VTL ceases to exists.

passive nodes in the protocol, listening to traffic signal messages and presenting these messages to the driver through in-vehicle displays.

During a complete VTL cycle, the leader commutes the traffic light phase among the conflicting approaches/lanes. When the green light is in the leader's lane, the control of the VTL system must be handed over to a new leader in a different approach/lane. If there are vehicles that stopped under the red light at the intersection, the current leader selects one of these vehicles to become the new leader, which will maintain the intersection control in a consistent sequence [see Fig. 7.1(d)]. If there are no stopped vehicles under the red light, then a new leader will be elected through the previously explained process whenever necessary.

In a primal paper, where the VTL concept was presented, the dynamic performance of the system has also been studied. The selected mobility metric was the average increase in flow rate of the VTL protocol versus the real physical traffic signals as a function of vehicle density. Large-scale simulations that emulate a real dense urban scenario provided compelling evidence on the viability and significant benefits of the proposed scheme in terms of the mobility metric (up to 60% increase at high densities). This new self-organizing traffic paradigm thus holds the potential for revolutionizing traffic control, particularly in urban areas [95].

The interaction between vehicles and pedestrians also needs to be considered. The most direct and traditional approach that could be foreseen is the communication of the traffic signal information to pedestrians through smart phones or simple road infrastructure. The virtual indication of traffic signals by the leading vehicle is also proposed.

An immediate effect of the shift of paradigm of traffic signals as road-based infrastructures to in-vehicle virtual signs is the elimination of physical traffic signals from roads. According to [109], in 1998, there were approximately 3.25 million traffic lamps were approximately permanently lighted in the road infrastructure of the US based on an estimated number of 260 000 signalized road junctions. We estimate that the electric power consumption of traffic lights in the US can total an amount around 2 MWh/year, which is equivalent to 1.2 million metric tons of CO_2 per year according to report [110]. Although this is a significant value, it is almost irrelevant when considering the total emissions of personal vehicles in the US, which emit around 300 million metric tons of CO_2 per year [111]. VTLs, on the other hand, enable the universal deployment of semaphore-based control on the intersections of the road network, with virtually no impact on energy consumption or carbon emissions[1].

7.4 Methodology

Our goal is to quantify the impact of the VTL technology on CO_2 emissions mitigation. We should thus analyze CO_2 emissions of vehicles that interact with physical traffic signals and compare those with CO_2 emissions of vehicles that use VTL. To isolate the benefit of the VTL approach, each of the alternatives for intersection control should have identical settings in all possible *static* variables. These include the characteristics of vehicles and drivers, the road scenario, and the routes. The differences in the two analyses result from a different mobility behavior of each vehicle that is affected by *dynamic* aspects, which correspond to different traffic conditions due to alternative schemes of intersection control.

To perform these two analyses, the EMIT emissions model previously described was integrated into a microscopic traffic simulator. The microscopic traffic simulator outputs the mobility behavior of each vehicle in the form of a virtual GPS trace. By processing this GPS trace, a set of variables can be derived, such as acceleration and speed, which then feed the microscopic

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[1] The low power consumption of in-vehicle semaphores and associated V2V communications could just resort to energy recovery mechanisms from the kinetic energy of vehicles to power the electrical systems.

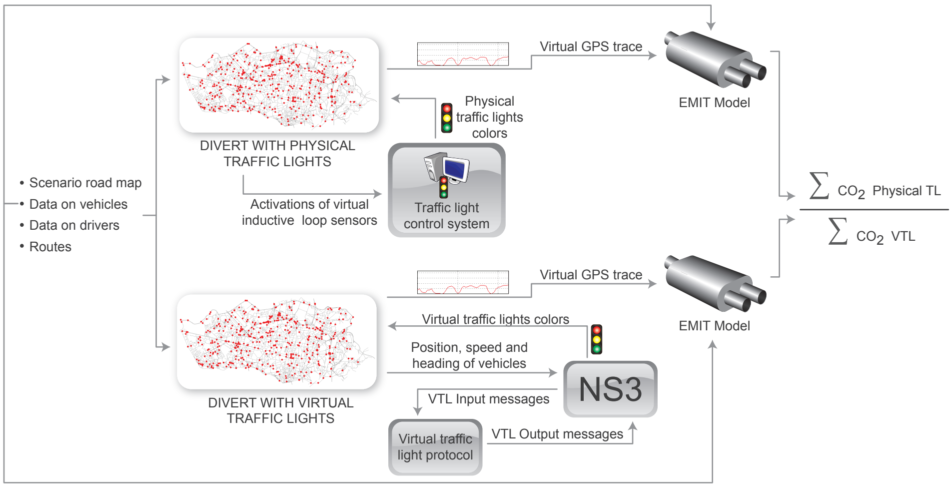

Figure 7.2: The main component is the DIVERT/VNS microscopic traffic simulator, whose two instances are used to produce virtual GPS traces. The scenario road map, data on vehicles and drivers, and the route of each vehicle are fed to an instance of DIVERT/VNS with physical traffic signals and to another instance where the VTL protocol is simulated. The simulation of the network layer of the VTL protocol is done by NS-3. The virtual GPS traces are then fed to two instances of the EMIT model to compute and compare the aggregated values of CO_2 emissions.

emissions model. The emissions of each vehicle are then aggregated to quantify the overall positive impact of VTL system. Fig. 7.2 illustrates this architecture and its main components. The main component of the simulation-based evaluation of the de-carbonization impact of VTL is the DIVERT/VNS microscopic traffic simulator [58].

The implementation of physical and virtual traffic lights in DIVERT/VNS is relatively simple and leverages on the car-following equations included in the IDM [37] that affect the acceleration and deceleration patterns of each vehicle. In terms of mobility simulation, physical and virtual traffic signals are implemented identically in DIVERT/VNS. For each lane of an approach to an intersection, the traffic simulator creates a temporary dimensionless vehicle on the stop line associated to the lane. This dimensionless vehicle is created under a red light and disappears under a green or yellow light. Variable aggressiveness parameters of each driver result in different behaviors under yellow lights, as a function of the distance to the stop line. The intermittent creation of this dimensionless vehicle is thus mandated by the traffic signal control system or the VTL protocol (see Fig. 7.2) and transparently affects the mobility of vehicles based on the car-following model that governs the acceleration and deceleration variables.

The differences in the two instances of DIVERT/VNS illustrated in Fig. 7.2 refer to the geographic location of physical and virtual traffic lights, and to the method used to derive the traffic light color shown to each vehicle. Regarding the geographic location of physical traffic signals, we have replicated the existing deployment in the city of Porto. The implemented physical traffic light approach is also a loyal representation of the existing scenario. In the current version of DIVERT/VNS, the traffic signal control system is very simple and uses fixed green splits for each of the approaches of an intersection. Such simplistic functioning is, however, a good approximation of the current functioning of most of the deployed traffic signals. A recent study has reported that $70-90\%$ of the deployed traffic signals work under fixed parametrization of cycle duration and green splits [112].

The geographic location of virtual traffic lights is not fixed and is determined by traffic conditions in confluent approaches of an intersection. Depending on traffic density, such virtual traffic signals can be present at all intersections or almost non-existent. Instead of the data from fixed traffic counters, the optimization of cycle duration and green splits of a VTL resorts to more complete information, which includes the position, speed and heading of all vehicles approaching the intersection. This information is provided by DIVERT/VNS and the simulation of its beaconing by each vehicle is done by NS-3. Leader election and the virtual light messages are broadcast by the leader are also simulated in NS-3 and provide the traffic signal colors that are shown to each vehicle in DIVERT/VNS.

7.5 Results

The results and analysis presented here are based on the methodology provided in section 7.4 (see also simulation framework depicted in Fig. 7.2). The two strategies (physical TL and VTL) are compared against making use of the simulation platform in a large-scale scenario (see 7.5.1) and a number of performance metrics (see 7.5.2). Firstly, individual vehicle dynamics are studied (see 7.5.3). In order to determine the overall benefit arising from the implementation of the VTL system, individual outputs are consolidated (see 7.5.4).

7.5.1 Simulation Scenario

To give scale to the analysis of the benefits of VTL, we evaluate carbon emissions of vehicles in the road scenario of an entire city. The city of Porto, in Portugal, which is the second largest in the country, spanning an area of 41.3 km^2 and having a road network comprising 965 km. Due to a recent stereoscopic aerial survey over the city, where the location of all moving vehicles was pinpointed and their traveling speeds were derived, together with the inference of a 5-second route [59], realistic traffic data is available for Porto. In the aerial survey a total of $10,566$ vehicles were pinpointed. The observed distribution of vehicles per road segment was used to (decrease) increase density to (non) rush-hour values in order to evaluate the impact of VTL under different conditions. In this study four different densities of vehicles moving in the city of Porto are then considered:

- 24 veh/km^2 (low);
- 120 veh/km^2 (medium-low);
- 251 veh/km^2 (medium-high);
- 333 veh/km^2 (high).

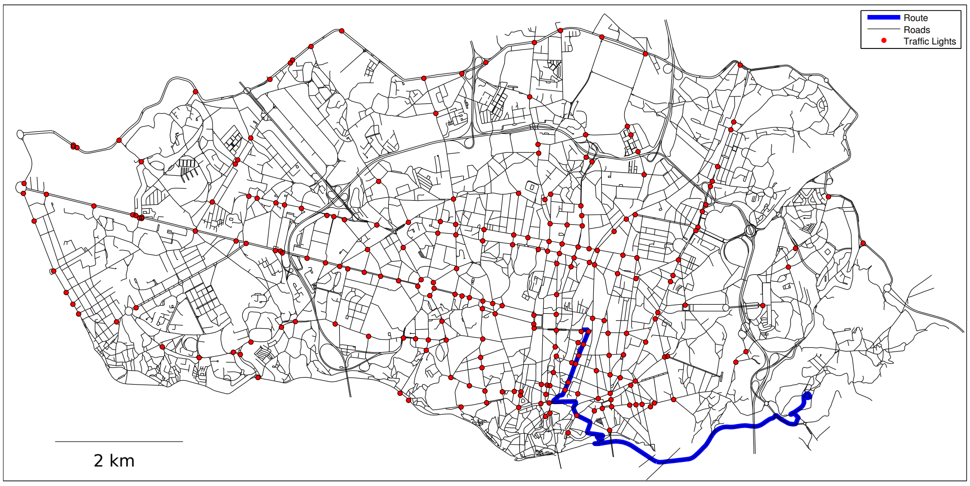

Figure 7.3: The road network of the city of Porto comprises 965 km of extension. The red dots display the location of the 328 intersections that are managed by physical traffic signals. The blue line represents an example of a route traversed by a vehicle in our study.

Regarding the route of each vehicle, random origin/destination pairs that are based on the observed distribution of vehicles from the aerial survey are generated. We evaluate mobility propagation using wireless transmission ranges of 150-250 m as defined in [59]. In this study Stereoscopic Aerial Photography was used to model urban mobility in order to compute connectivity and path availability. Communication is mostly direct (1-hop communication) between the leader and vehicles in the vicinity of an intersection.

The road network of the city of Porto has a total of 1991 intersections. Physical traffic lights control 328 of these 1991 intersections (16%). Fig. 7.3 depicts the road network, the location of signalized intersections and one example route followed by a vehicle [2]. Each scenario was evaluated for a period of 30 minutes.

7.5.2 Performance Metrics

To demonstrate the benefits of the VTL system, a number of variables needs to be analyzed. In [95] the impact on traffic flow of VTL was evaluated for the same scenario of the city of Porto. Results have shown an increase of up to 60% in flow rate for high density scenarios. Here, we want to analyze the environmental impact of VTL, comparing the individual and aggregated CO_2 emissions of vehicles traveling the exact same number of kilometers on the exact same roads, with and without the VTL system.

For this analysis, the definition of each variable, application domain, whether for individual vehicle analysis or aggregated investigations, and unit is given bellow:

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[2] A zoom-able webmap showing the road network, the location of signalized intersections and the position of vehicles from the aerial survey is available at `http://drive-in.cmuportugal.org/porto/`

- *Instantaneous CO_2 emissions ($E^i_{CO_2}$)* [individual] (g/s): calculated for vehicle i using Equation 3.2 after knowing the outcome of Equation 3.1 with appropriate coefficients (see Table 3.2);
- *Route CO_2 emissions* [individual] (g): Cumulative sum of an individual vehicle CO_2 emissions for its complete route;
- *Average CO_2 emissions per vehicle* [aggregated] (g): defined as follows

$$\frac{\sum_{t=0}^{end}\sum_{i}^{n_{cars}} E^i_{CO_2}}{n_{cars}} \tag{7.1}$$

where t iterates over the seconds of the simulation and i iterates over all the individual cars.

7.5.3 Individual Vehicle Results

Before analyzing the aggregated results of CO_2 emissions for all vehicles in the city of Porto scenario, we analyze the relevant variables for an individual vehicle, highlighting important differences between a route traversed with the VTL system and with the deployed physical traffic lights system (TL). These preliminary analysis using a single vehicle gives some intuition for the understanding of the aggregated results.

The vehicle selected for the current analysis traversed the city following a route (see Fig. 7.3) that combines a major arterial road and a dense urban area with permanent intersection conflicts, which clearly have distinct characteristics and can lead to different performance. In this study medium traffic density is considered (190 $vehicles/km^2$). Although this overall density is the same with TL and VTL, the distribution of vehicles can be very different, as a result from the distinct traffic control schemes.

Fig. 7.4 depicts the main variables (velocity, acceleration, instantaneous CO_2 emissions and Route CO_2 emissions) for TL (in blue/continuous line) and VTL (in red/dashed line). The variables velocity and acceleration were obtained from the virtual GPS logger. Observing these variables it is evident that without the VTL system the car remained stopped for longer periods mainly due to the semaphored intersections and increased congestion. This fact is particularly evident when the vehicle enters the city center area, which contains a higher density of physical traffic signals and of vehicles. The ubiquity of the VTL solution also led to faster intersection conflict resolution and contributed to congestion dissipation. Another interesting fact to mention is that with the TL system the car takes approximately more 25% of the time to travel the same route for this traffic density. Stated otherwise, the average velocity of the vehicle with the VTL system is considerably increased when compared with the physical TL system.

Observing the graphic of the instantaneous CO_2 emissions depicted in Fig. 7.4, the correlation between this output and the velocity/acceleration metrics is evident. Increasing acceleration/velocity values leads to increasing instantaneous pollutant emissions. On the other hand, a stopped vehicle has a constant emission rate. The instantaneous emissions cannot be compared

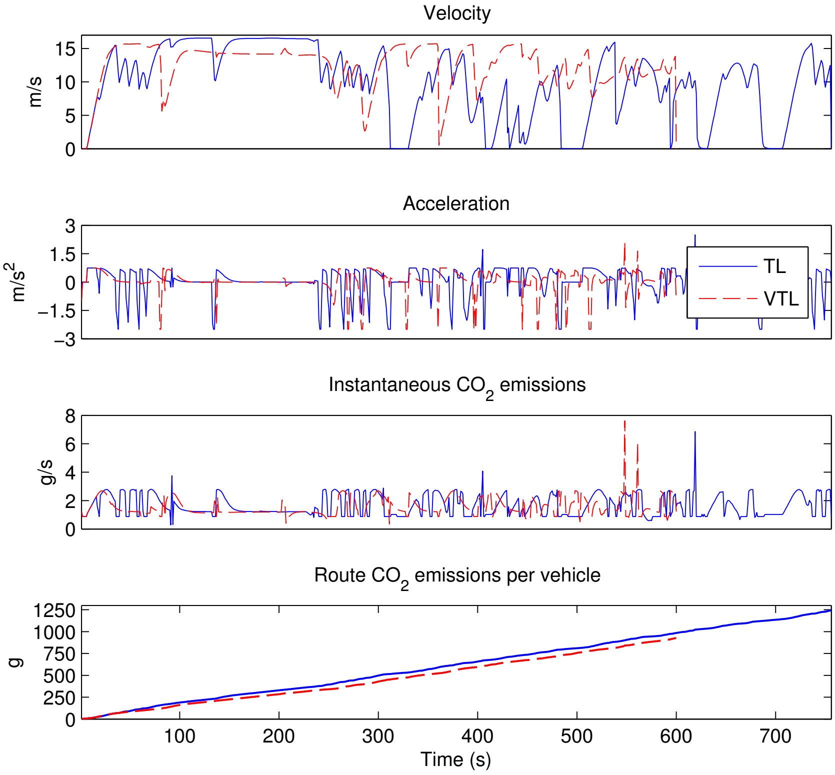
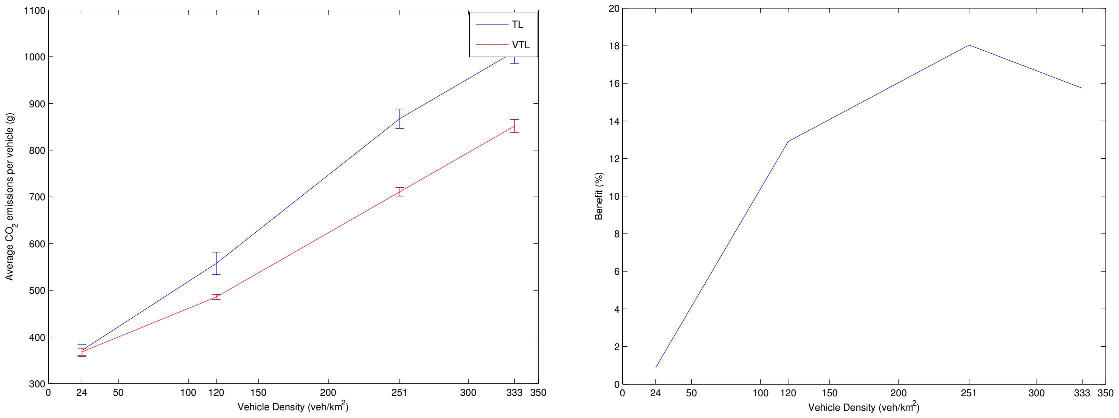


Figure 7.4: Individual vehicle metrics comparison (Velocity, Acceleration, Instantaneous CO_2 emissions and Cumulative CO_2 emissions for the traversed route (Medium vehicle density). The same vehicle traverses the exact same route with and without the VTL system. Differences in all metrics are evident. Also note that this particular vehicle takes less than half the time to complete its route with the VTL system.

directly between physical TL and VTL, as they happen in different locations of the route. The relevant comparison is the cumulative Route CO_2 emissions, which highlights the impact of the implementation of the VTLs. Observing this metric, it is clear that the overall number of stops during the route, as illustrated by the vehicle's acceleration and deceleration levels, does have a significant impact on vehicle emission rates [89]. For the example route, the cumulative fuel consumption is reduced by approximately 25% mainly due to the increased traffic flow and consequent less transportation congestion, and the ubiquity of the VTL solution, which can detect the existence or not of intersection conflicts.

7.5.4 Aggregated Results

Apart from investigating the benefits for individual vehicles, the performance of the VTL system was evaluated by considering all the vehicular interactions that take place in the complete transportation network. To perform this study the individual pollutant emissions values are aggregated for each simulation to determine the metric Average CO_2 emissions per vehicle. This metric is widely used to determine the environmental impact of ITS. Furthermore it is a referenced measure, which allows direction comparison of results in scenarios with different traffic flows.



(a) Absolute (b) Relative

Figure 7.5: Aggregated Vehicle metric for TL/VTL comparison given different vehicle densities. This graphic highlights the increased impact of VTL as traffic density becomes higher. Confidence intervals are depicted for each vehicle density and traffic control strategy (TL or VTL).

In order to make statistical inference, a number of observations of the system (8 simulation runs for each traffic density) was performed. This was followed by a statistical analysis to obtain an estimate of the selected performance metric. The mean of the metric *Average CO_2 emissions per vehicle* is the estimated parameter and 95% confidence intervals for the estimator are considered in the study.

Fig. 7.5a represents the selected metric in the TL and VTL scenarios, and considers vehicles densities ranging from low density to high density. In both scenarios with the increase of the vehicle density, the average CO_2 emissions per vehicle increase. As the density increases, intersection conflicts become more frequent, which causes increased congestion. Increased congestion leads to the stop-and-go phenomena that is associated to constant accelerations and decelerations that are one of the main causes of pollutant emissions. For all vehicle densities, the average CO_2 emissions per vehicle are lower for the VTL case.

Fig. 7.5b depicts the percent of improvement in terms of CO_2 emissions as a function of the vehicle density. The implementation of the VTL system is beneficial in terms of CO_2 emissions for all the traffic densities that were studied. In addition, as the car density increases the mitigation in terms of CO_2 becomes more evident. For the selected vehicle densities the benefit varies between 1% and 18%. Eventually, if we increase the densities to higher values (which are unrealistic for the capacity of the current traffic control system of the city), the benefit would start declining, as the theoretical capacity of the road network, independently of the intersection control scheme that is used, starts to be reached.

It should be noted that there is also a significant increase on the average vehicle velocity between 26% (low density) and 41% (high density). In urban scenarios, however, this does not lead to increased emissions as the optimal cruising speed is never reached. The mitigation of carbon emissions occurs due to self-organized and ubiquitous traffic control enabled by VTL. At high vehicle densities the absence of traffic signals at intersection exacerbates the congestion problem, which leads to increased emissions in the physical TL case. The herein presented results are in accordance to the results published in [95] where the vehicle traffic flow was studied.

7.6 Conclusions

The advent of wireless intervehicle communication, which should be available in the near future, opens a variety of opportunities to increase the safety and efficiency of road utilization. With regard to efficiency, an important aspect of its optimization will involve the mitigation of pollutants emission to fight global warming and climate change. In this chapter, we have addressed the evaluation of the environmental impact of a challenging application of intervehicle communication, called VTL. Such a system will have to overcome complex problems that are intrinsic to the critical control of the right of way of vehicles in an intersection through a distributed system based on wireless communications. In particular, VTLs face the hurdle of requiring 100% deployment in motorized vehicles to work. However, this penetration problem is a common issue for a variety of other V2V or V2I applications; safety-related applications are a main example that requires high penetration rates for effectiveness and are pushed forward for their evident advantages. Reaching this level of deployment requires governmental commitment to mandate the existing motorized vehicles to install VTLs as an after-market equipment[3]. To tackle this issue, studies must be performed to investigate whether changes can be made to the original VTL system to allow lower penetration rates and the coexistence with the current TL system.

In addition to the significant improvements in traffic flow that have been reported in the original paper on VTLs by Ferreira et al. [95] and to the increased safety of semaphore-controlled intersections, where accidents can be reduced by more than 30% [113], this work reported a reduction of 18% for the CO_2 emissions of a realistic number of vehicles that travel in a large-scale urban scenario when using the VTL system. Considering only the CO_2 component of the annual circulation tax that is in place in Germany, for example, 2 $€/g/km$, would justify the cost of an after-market VTL system for any car owner.

The present work has been performed for internal combustion-engine vehicles. As further work, we plan to investigate the energy savings that arise from the implementations of ITS measures for hybrid or electric vehicles, which currently have limited autonomy. Furthermore, the simulator should be extended to include alternative emissions-modeling approaches. Another interesting topic to study in more detail is pedestrian–vehicle interaction and human–computer interaction.

The inclusion of Urban Traffic Control (UTC)) systems in simulation can provide additional insights into the intersection control problem. More specifically, the benefit of the VTL approach compared to such centralized control systems will be studied. In the city of Porto, such UTC systems have been deployed to control part of the traffic signals. We are currently integrating in our simulation platform a replication of the functioning of this UTC based on simulated inputs

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[3] Electronic tolling systems and in-vehicle parking meters are examples of systems that have been the subject of legislation in some parts of the world.

that correspond to activations of virtual inductive-loop sensors. This line of research involves joint work with the company that develops the UTC system to have a virtual replication of the system that mimics the exact behavior of the traffic signals that are in place in the city of Porto.

Chapter 8

Dynamic and Distributed Taxi-sharing

8.1 Introduction

Modern societies rely on efficient transportation systems for sustainable mobility. The implementation of several ITS, such as adaptive traffic signal control [114] [95], bus control strategies [115], electronic ticketing infrastructure [116], on-demand transport [117], taxi queuing strategies [118] [119], can provide considerable improvements on the performance of various forms of public transport and consequently contribute to efficient urban mobility.

Collective transport is an important alternative transportation mode that can compete directly with private transport. One of the main goals of this type of transport is to reduce the number of vehicles in circulation and to promote efficiency in vehicle use. Car-sharing (decentralized car rental) [120] [121] and car-pooling (ride sharing using private vehicles) [122] initiatives have proven successful in many cities in the United States and in Europe as a complement to traditional transport modes. Taxi-sharing has the same philosophy as car-pooling/sharing but instead relies on taxis as a transportation resource and has a more flexible mode of operation. Recently, a number of local initiatives for this last system have emerged: e.g. London [123], NYC [124], Taipei [125].

In this work, we argue that more emphasis should be put on passenger requirements and better vehicle utilization, namely on route selection of public transport. More specifically, we focus on a collective transport form that can promote sustainable mobility and compete with the performance of private transport at the same time. Improved mobility can be attained by optimizing and sharing taxi routes among passengers using ITS.

This work focuses on a distributed and dynamic taxi-sharing system, which is an advanced, user-oriented form of public transportation characterized by flexible routing and scheduling of vehicles operating in shared-ride mode between distinct pickup and drop-off locations according to passenger needs [126], enabled by wireless communications and distributed computation. The service is designed to be dynamic (no reservations and immediate assignment), distributed (no central authority), automatic (no human intervention) and door-to-door, in order to be attractive, flexible and cost-effective for both passengers and taxi operators The main goal is then to provide concrete evidence in a realistic and large-scale scenario that significant improvements in several taxi operation metrics occur due to the deployment of this novel ITS technology. Furthermore, we aim to study the economical aspects of taxi-sharing, which we consider of major importance for the practical success of the system. To this end we also propose and evaluate a fare scheme for this new system.

The main contributions of this work can be summarized as:

- We propose a distributed and dynamic Taxi-sharing system enabled by wireless communications and distributed computing. Furthermore, we propose a pricing and charging scheme considering implementation details.
- We propose a realistic and large-scale simulation methodology using empirical taxi operation data, going beyond the level of detail of recent studies.
- We study in detail the performance of the system, including economic aspects, under varying demand conditions and varying system penetration rates. Results have shown that the deployment of the system can be advantageous for both passengers and taxi operators, and that a number of trade-off exists.

The remainder of this Chapter is organized as follows. In the next section we briefly present the related work in the broader area of Vehicle Capacity Sharing. Then, section 8.3 introduces the main characteristics and operation mode of a dynamic and distributed Taxi-Sharing System, including its two main components (Vehicle Algorithm and Passenger Algorithm) and the associated pricing/charging scheme. Section 8.4 presents a methodology for evaluating the operation of a taxi fleet using empirical data. Section 8.5 describes a realistic and large-scale simulation scenario and provides the main service and taxi operation results and corresponding discussion. Section 8.6 closes the Chapter with the main conclusions.

8.2 Related Work

The problematic of vehicle capacity sharing has attracted much attention from the research community over the last decades. Capacity sharing systems use several methods to make a more efficient usage of the installed capacity by sharing trips among passengers in a single vehicle (ride-sharing or taxi-sharing) or by sharing resources themselves (car-sharing). More specially, car-sharing [127–129] provides individuals access to private or company-owned vehicles without the burden of ownership, usually, for short-periods of time. For instance, in [130] the authors have concluded that car-sharing reduces the overall annual pollutant emissions and that the average distance travelled declined significantly, although more individuals have access to cars. The main goal of all these systems is to reduce the number of vehicles in circulation and to promote efficiency in vehicle usage.

Shared ride systems exist in a variety of forms, which differ in the operation mode and key enabler technologies. Ride-sharing establishes connections between users with similar routes and time windows. In [131] a generic peer-to-peer shared ride system composed of mobile nodes has been presented and the authors demonstrated that trips derived from local knowledge may not be optimal from a global view [131]. In [132] Agatz et al. proposed an optimization-based dynamic ride-sharing system that aims at minimizing total system-wide vehicle miles and users' individual travel costs. SmartRide [133] is an autonomous and opportunistic ride-sharing system enabled via short-range wireless communications. DC2S [134] is a dynamic car sharing system that makes use of the pervasive use of smartphones and a smart server to reduce the empty seats travelling problem.

Taxi-sharing has in essence the same operation mode as ride-sharing but instead relies on taxis as a transportation resource and has a more flexible mode of operation. Previous attempts to address the topic of shared taxis have mainly concentrated on pre-booking and/or the use of pre-defined routes, which clearly degrades the Quality of Service (QoS) offered by traditional taxis. More recently, dynamic approaches, where requests and assignments are performed in real-time, have been proposed (e.g. [125] [135]). Another common feature is the use of a central unit to perform all operations for taxi-sharing (e.g. [125] [136] [137]), which can have critical implications on the system scalability and performance. Regarding algorithmic aspects, in [137] Gidofalvi et. al. proposed a highly scalable trip grouping for cab-sharing. In [138] the authors presented initial ideas for a framework for taxi-sharing using GPS location, General Packet Radio Service (GPRS) for communications and a web service for ride matching. Additionally, in [139] the authors have show that economical factors are of major importance in the acceptance and implementations of taxi-riding services.

Car-sharing [120] [121] and car-pooling [122] initiatives have proven successful in many cities in the United States and in Europe as a complement to traditional transport modes. However, these services are not usually door-to-door and can have predetermined times, routes or service areas, which is less convenient than current private transportation. More recently, a number of local taxi-sharing initiatives have emerged in several cities throughout the world (e.g. London [123], NYC [124], Taipei [125]). However, in some cases the practical success has been limited since these implementations still suffer from the previously mentioned drawbacks. Another additional problem is the low process automation in current systems, which implies high human involvement.

8.3 Taxi-Sharing System

A dynamic taxi-sharing system is responsible for the efficient and real-time matching of user requests to available resources (taxi seats) and coordination between requests in such a way that resources are shared by users in real-time. In order to be attractive, flexible and cost-effective for both passengers and taxi operators the system that we propose was designed with the following characteristics:

- **automatic**: no human intervention is required in the decision making procedure. Users solely need to specify the requirements for the service.
- **constrainable**: customers can specify service degradation that they are willing to.

- **cost-effective**: in order to ensure early acceptance the pricing scheme should be attractive for passengers and taxi operators. Special emphasis should be put on the passenger side.
- **distributed**: no central authority is necessary to perform coordination between user requests. Computation tasks are performed in all nodes involved in the decision making process.
- **door-to-door**: the system allows passenger pickup and drop-off locations to be specified constituting an advantage over traditional public transport as well as a benefit for specific population groups.
- **dynamic**: a shared ride is established and assigned immediately. Consequently, there is no need for reservations or pre-booking of demand, which provides flexibility to the system. Furthermore, non-recurring trips are considered.

Before providing more details on the algorithm, we outline the main requirements for vehicles and passengers:

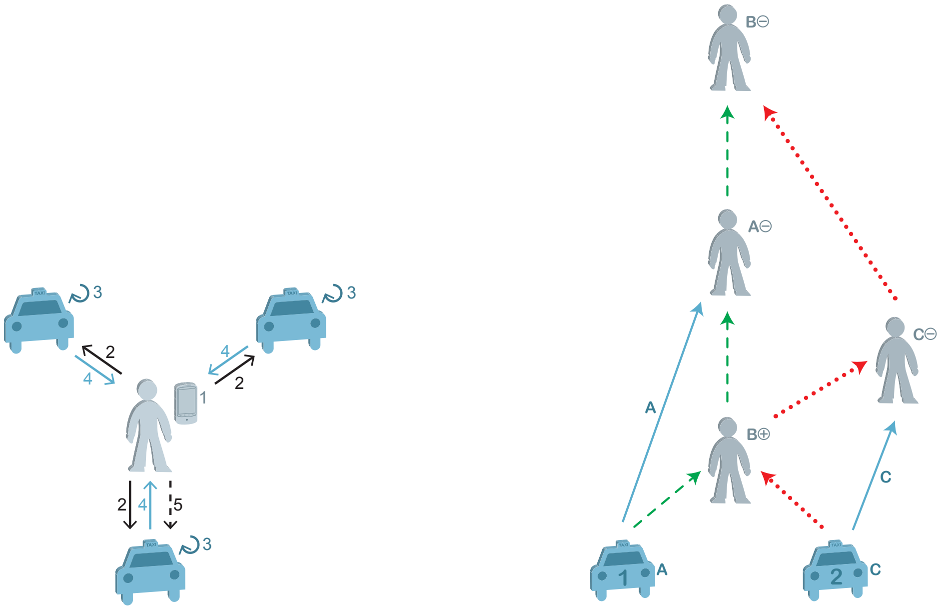
- passengers' and taxis' positions can be determined accurately from location sources;
- computation and wireless communication capabilities (e.g. on-board computer, smartphone) are available;
- vehicle routing and navigation functionality is installed in vehicles.

These requirements can be easily met since nowadays there is a widespread use of smartphones and modern taxi dispatching system include on-board computers with incorporated communication, vehicle routing and navigation capabilities, which is in favour of the deployment of the system. The proposed system could be based on conventional vehicles or advantageously on automatic, driverless vehicles [140] [141].

8.3.1 Algorithm

The general functioning of the proposed system is shown in Fig. 8.1a. Firstly, the client makes a pickup solicitation using an application on a smartphone; the request should include the client's current location, destination point, seat demand and allowed service degradation factor (1). The request is then received by all or a subset of moving taxis (2) that compute the distributed vehicle algorithm (3) [see Fig. 8.1b] and communicate the trip cost back to the user (4). This distributed algorithm is responsible for checking the route cost of associating a new request to the current service(s) for each taxi. The end user terminal receives the request responses, determines the least-cost admissible solution for taxi-sharing and selects a taxi for service (5). If there is no admissible sharing solution, the nearest available taxi is assigned (the closest vacant taxi or the taxi at the closest stand).

The nodes involved in problem solving (taxis and users) interact with each other using wireless communications and perform distributed computation tasks (e.g path cost calculation) to select a



(a) User perspective (b) Taxis perspective

Figure 8.1: Distributed and Dynamic Taxi-sharing System

taxi to serve a given client. Distributed computing implies that no central authority is needed for task coordination. Although computations are performed at both nodes, vehicles and user terminal, the implemented functionality varies substantially. Each of the algorithm's main components is explained in more detail in the following.

Vehicle Algorithm This block is executed at each taxi and has as main objective to calculate the best valid service sequence permutation , which can later be used to select the best vehicle for taxi-sharing. This is done based on newly received service requirements (O/D pair, seat demand and user constraints) and the current taxi state, such as current number of passengers and the remaining service sequence.

The first step in the algorithm consists on determining all possible permutations between O/D points after combining the points of the corresponding services. In order to minimize the total travel distance, the resulting set of service sequences is fed into a cost calculation function, which calculates the shortest path between all points in the sequence, and afterwards ranks the sequence. Yet, these permutations have to obey a number of constraints. Permutations are discarded whenever the following constraints are not met:

- *precedence*: origin precedes the destination;
- *capacity*: passenger number surpasses the taxi capacity;
- *service degradation*: exceeded degradation threshold for any of the passengers, either new or current.

TARIFF	FARE	EXTRAS	
1	4.50		
1	7.25	0.80	
1	2.50		

Figure 8.2: Proposed Taxi-sharing taximeter display.

Usually, constraint assessment results in a reduction of the number of valid routes. The last component selects the minimum-cost service sequence and communicates its cost back to the passenger (if applicable). The passenger request and resulting best service description (path and cost) are stored during a certain period of time for future use (e.g. in case the user is assigned to this vehicle). Similar operations are performed in other vehicles. The functionality distribution enables the problem to be solved in a small time interval and favors the system performance and scalability.

Passenger Algorithm The first task of the Passenger Algorithm is to issue a complaint service request (containing the parameters previously presented) to a subset of the taxi fleet. Next, within a certain time window, route permutation cost values are received from several vehicles. The best taxi for sharing is selected and informed by means of wireless communications. The present algorithm considers a simple technique where route permutation values are ranked and the highest value is selected. If taxi-sharing is not feasible the closest empty vehicle (at closest taxi stand or in the vacant state) is allocated to this service depending on the taxi distribution and its states.

8.3.2 Pricing & Charging

In order to be attractive and to ensure early acceptance, the system's pricing scheme should be designed to provide cost savings for all involved parties. At the moment we evidence low passenger adherence to this mode of transportation. Passengers can benefit from shared trip costs even when considering longer travel distances. Taxi drivers can substantially improve their profits by reducing operational costs related to traveling smaller distances (e.g. less fuel consumption, maintenance costs), which can substantially improve profitability.

The proposed tariff system for taxi-sharing is based on the current taxi pricing scheme existing in Portugal, where the customer pays a basic entry charge (fixed) and an amount proportional to distance and travel time (variable charge). Meter operation also depends on the time of the day (day or night tariff) and week day (week or weekend tariff). Similar taxi tariff models have been defined by governments or metropolitan areas in many parts of the world. The proposed pricing scheme for taxi-sharing works as follows:

- the passenger pays the normal taxi price whenever travelling alone;
- the passenger pays a proportion (e.g. 0.6) of the variable charge for the trip whenever sharing a ride with other passengers. The sharing proportion can be defined according to the number of on-board passengers;
- the passenger solely pays a proportion of the basic charge if any part of its path was shared with other passengers;
- whenever the taxi is stopped due to a passenger pickup or drop-off no charge is made to any passenger.

This scheme ensures that the longer the shared ride, the higher the savings for each passenger. The pricing scheme also ensures that the gains derived from sharing are higher than the cost of including new passengers.

Taxi-sharing implies a number of changes to the existing fare charging equipment. The majority of the current devices solely allow calculating and displaying a trip at a time. Regarding the display of the current trip cost, we foresee the replacement of taximeters by on-board units with displays that can show trip parameters (e.g. tariff, fare, extras) for each passenger (Fig. 8.2). Trip parameters can be associated to passengers by using a unique identification (e.g. photo, username) that can be obtained from passengers' accounts. In order to improve the system performance (e.g. passenger's travel times, fuel consumption) actions should be taken to speed up passenger disembark. One possible measure achieve this is to impose the usage of electronic payment means. Possible solutions would lead to the utilization of contactless payment systems, such as public transport smartcards, NFC-enabled smartphones, or contactless credit cards. These cashless payment solutions can also contribute to drivers' safety. which can improved the safety of taxi drivers.

8.3.3 Problem Formulation

This section presents the formalization of the taxi-sharing problem and solution. To model this transportation problem we start by describing the three main entities involved in the main system operations, namely passengers, service provider and road transportation network. Customers present to the system trip requests R with a rate λ. Each service requestR_i contains pickup (O_i)/delivery (D_i) locations, seat demand and a maximum service degradation factor SD_i. The distance between an origin-destination pair is d_{ij} and the number of pairs is n_{pairs}. On the other hand, the service provider (e.g. taxi union) possesses a fleet of n vehicles with a capacity of C

seats to fulfill trip requests. Usually, the fleet size will vary due to the changing customer demand and taxi-drivers shifts. The current set of requests being served by a given taxi n_i is denoted as $TR_i = \{R_i, R_j, ...\}$ and the current taxi occupancy is C_i. Finally, the road transportation network provides the infrastructure for vehicle movements with a time-dependent impedance with respect to the number of vehicles, intersection control strategies, etc. The network is represented by a graph G=(V,E) containing a set of vertices (v_j) connected by edges (e_j).

We consider a dynamic taxi-sharing system where the main decision is, for a given service request, to appropriately select an operating vehicle from the fleet to perform a subset of services in taxi-sharing mode that:

- fulfills the precedence, vehicle capacity and service degradation constraints for all passengers;
- minimizes the additional travel distance (time).

As explained previously the algorithm is computed in a distributed fashion at selected vehicles. From the perspective of each individual taxi, the problem can be formulated as a *Traveling Salesman Problem (TSP) with constrains* (i.e. vehicle capacity and service degradation constraints) considering the current position as the start point and the final position as the last customer drop-off. It is outside the scope of the algorithm to decide what the taxi driver does after dropping the last customer and what strategy is chosen (e.g. cruising or going to the closest taxi stand). Therefore, the problem can be formulated for each vehicle as follows:

$$
\begin{aligned}
\text{minimize} \quad & \sum_{n=0}^{n_{pairs}} d_{ij} \\
\text{subject to} \quad & t_{O_i} \leq t_{D_i},\ \forall_i. \in TR_i \\
& C_i \leq C,\ \forall_i. \in TR_i \\
& \frac{\sum d_{ij}^{TS} - d_{ij}^{CT}}{\sum d_{ij}^{CT}} \leq SD_i,\ \forall_i. \in TR_i
\end{aligned}
$$

The general taxi-sharing problem is resolved at the client by ordering the valid results of a subset of taxis. The objective that we have considered is the minimization of the total additional travel distance.

8.4 Methodology

To assess the feasibility and performance of the taxi-sharing system we have decided to conduct simulation-based studies since our main goal was a *realistic* and *large-scale* evaluation of the operation of a taxi fleet. The dynamism of the proposed algorithm and the complexity of implementing a complete and realistic field-trial made other options infeasible. Besides, system dynamism associated with the mobility of taxis makes development of analytical models complex. Furthermore,

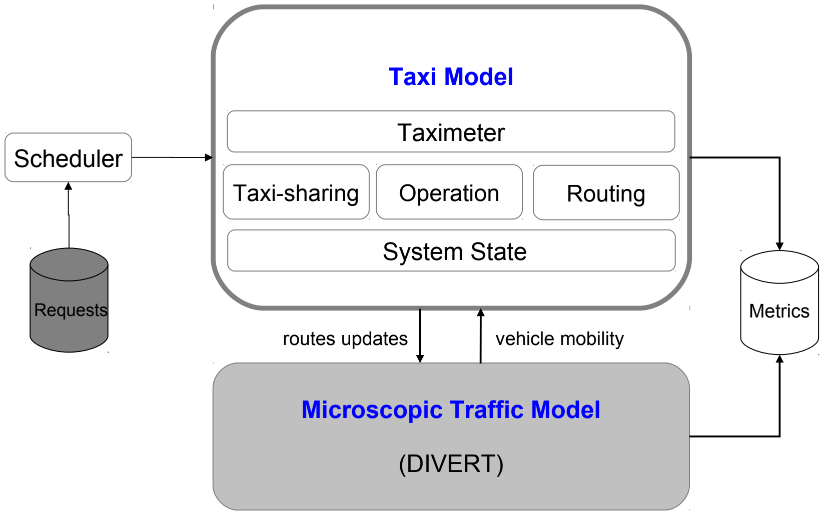


Figure 8.3: Simulation Platform for assessing the impact of the implementation of a taxi-sharing system.

using simulation has an additional advantage that different system configurations can be studied with little effort.

The main goal of this section is to present a methodology for evaluating different perspectives of the taxi-sharing system by means of simulation. More specifically, we study in great detail how different service assignment policies - with and without taxi-sharing - and parameters (e.g. varying penetration rates) influence the system performance. Each of the alternatives for taxi operation has identical settings in all possible static variables (e.g. fleet, vehicles, drivers, road scenario, service demand). Different service assignment policies will result in different mobility behaviour for each vehicle (e.g. routes) that is affected by dynamic aspects (e.g. varying service demand).

A conceptual representation of the simulation methodology is depicted in Fig. 8.3. The simulation platform is constituted by two main models that are closely interconnected: microscopic traffic model and taxi operation model. These two components were bi-directionally coupled since the operation of one influences the operation of the other. The taxi model provides the microscopic traffic model with new routes updates, which influences the mobility pattern of individual vehicles. On the other hand, the microscopic traffic model supplies vehicle mobility data to the taxi model (e.g. current taxi positions), which is used for service assignment and in the taxi-sharing algorithm.

Realistic input data is provided by the service scheduler, which emits service requests at the defined timestamp. Different service demands can be evaluated by modifying the service timestamp by a fixed value (e.g. 1.5, 2.0) for all services in the same simulation, which results in the concentration of services in a shorter period of time and consequently in an increased service request rate (services/s).

The system's basic underlying block is a microscopic traffic model where the individual behaviour of each vehicle is mimicked. The other model named *Taxi Operation* mimics the func-

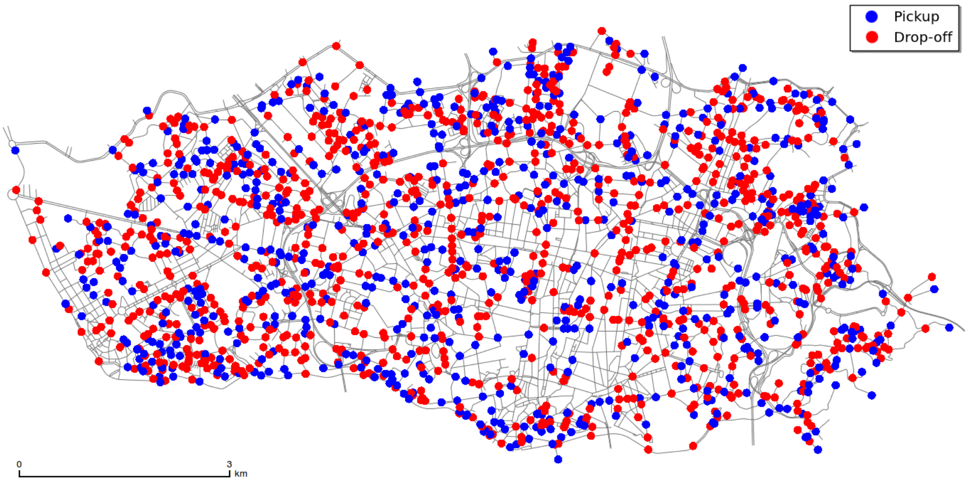


Figure 8.4: Road Network of the city of Porto. The blue and red points represent the service pickup and drop-off (O/D) points, respectively.

tioning of each vehicle in a taxi fleet. This model receives continuously updated information of the taxis' positions and other parameters from the microscopic traffic model and pre-timed service requests from the event scheduler. The Taxi model receives the event and starts the taxi-sharing algorithm described in section 8.3. In case there is no reasonable sharing alternative, the traditional taxi operation is replicated (solely one request is serviced at once). The Taxi Routing component is responsible for providing the shortest path and the associated cost to the remaining blocks. The Taximeter component replicates the functioning of a tariff system based on distance and time, and when performing taxi-sharing, the tariff system presented in section 8.3.2. The System State component stores relevant information for the algorithm functioning (e.g. current taxi state (e.g. busy), current position). Output data is continuously collected in logs for off-line processing to quantify the overall impact of the deployment of the taxi-sharing system.

8.5 Results & Discussion

The results and analysis presented here are based on the evaluation methodology presented in section 8.4 (see also framework depicted in Fig. 8.3). Different strategies (with or without taxi-sharing) are compared against each other making use of the realistic and large-scale simulation platform (see 8.5.1) and a number of performance metrics (see 8.5.2). The service demand presented in section 8.5.1 describes the base scenario; additionally, in this study we have also considered scenarios with higher service demands, namely 50% (1.5) and 100% (2.0) bigger.

To obtain an estimate for each metric, 20 simulation runs were performed for each varying parameter (e.g. taxi-sharing penetration rate) . Thus, a total of 360 simulations is considered in this study. The individual simulations were later on processed for statistical inference. More

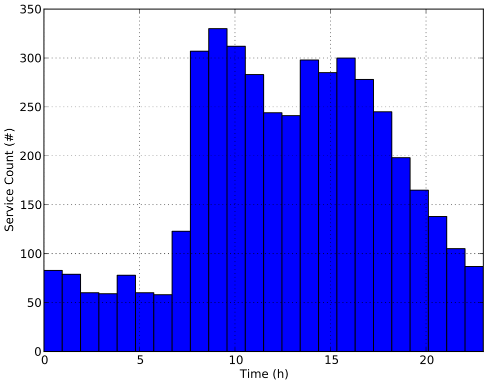


Figure 8.5: Taxi Service Demand. Hourly Service variation for a 24-hour period (weekday).

specifically, in this study we consider average values and Cumulative Distribution Function (CDF) for each variable.

8.5.1 Simulation scenario

The taxi operation in the city of Porto follows governmental and city regulations; all taxi operators need to comply with the predefined operation mode and pricing scheme. The market is also regulated which implies that new operators need to obtain licenses from the city council or to buy licenses from existing taxi owners. The last licenses in Porto have been given more than two decades ago. The taxi operation in the city of Porto has considerably changed over the last decades in technological terms. The underlying operating platform has evolved from the conventional radio-based system into a partly automated dispatching system enabled by wireless communications and positioning technology. The service demand has been decreasing slightly over the last decade due to the lower economic activity, due to the introduction of a mass transit system, among others.

The taxi-sharing system is assessed in a *realistic* and a *large-scale* scenario. To ensure that the simulations are realistic, we have replicated truthfully the current taxi operation in the city of Porto. More specifically, the city's operation mode (e.g. tariff system), vehicle characteristics (e.g. number of seats), the current taxi stand locations and passenger demand (e.g. O/D service points) have been instantiated. Regarding the operation mode, the tariff system and taxi union dispatching mode of Porto was replicated. It should be stressed that taxis usually return to the closest taxi stand after finishing a service where they wait for the next passenger. The exact location of the city's 63 taxi stands has been determined and used as input for the simulator. The main taxi union has a fleet of 441 vehicles. The capacity of the vehicle was set to 4 passengers since in Porto all taxis have 5 seats.

In addition, taxi operation is also studied using realistic passenger demand parameters. Since this union has recently installed a dispatching and fleet management system, which allows to constantly monitor taxi locations and taximeter information, real services' O/D points could be

Table 8.1: Passenger distribution per trip

Number of Passengers	Distribution (%)
1	82
2	13
3	4
4	1

extracted by combining relevant data (see Fig. 8.4). In the present analysis we resort to 24 hours of taxi operation, which corresponds to 4417 O/D locations, as input to the simulation request scheduler. The variation of the service demand with respect to the time of the day is depicted in Fig 8.5. Due to the higher passenger demand a weekday is considered in the study. Another important simulation parameter is the number of passengers per trip. Since these values cannot be obtained from the taxi management system, we conducted a survey in collaboration with taxi drivers to determine the average number of passengers per trip (see Table 8.1). A subset of taxi drivers was asked to record the number of passengers for each trip during a week. The records were then collected and processed to obtain the distribution presented previously.

To give scale to the analysis of the benefits of the system, selected metrics are analysed in a large-scale road scenario. The replicated scenario is the city of Porto, Portugal, which spans an area of 41.3 km^2 and has a road network size of 965 km. Porto is the central city in a metropolitan area with 1.3 million inhabitants. Fig. 8.4 represents the road network of the city, which has 328 (out of 1911) intersections managed by physical traffic signals.

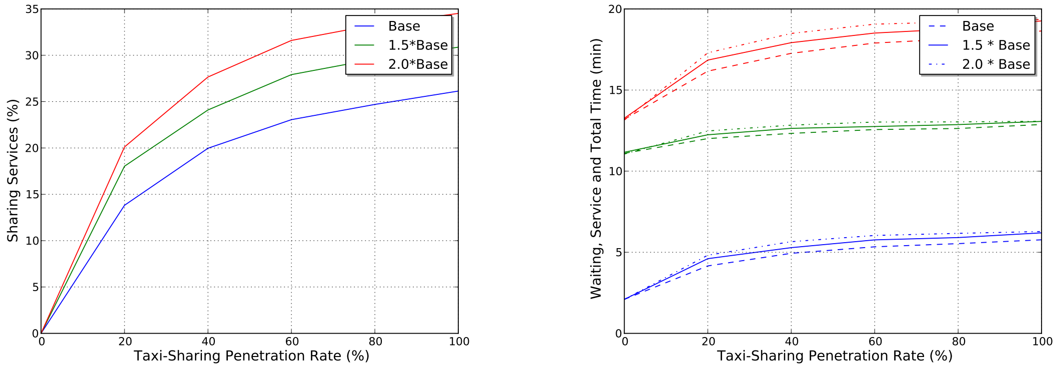
8.5.2 Performance Metrics

To study the benefits of the taxi-sharing system, a number of aggregate variables is analyzed. In the analysis two distinct perspectives are used to analyse the overall system performance, namely service and taxi perspectives.

The following set of metrics, and respective unit, demonstrates the passengers' performance in terms of time and cost for individual trips:

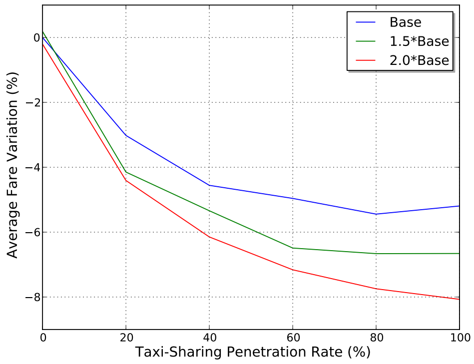
- Sharing Services (%): percentage of services made in taxi-sharing mode;
- Waiting Time (min.): time elapsed between passenger's request and vehicle arrival to client's origin point;
- Service Time (min): time elapsed between client's origin and destination points.
- Total Travel Time (min): time elapsed between passenger's request and vehicle arrival to client's destination. It is effectively the sum of waiting time plus service time;
- Trip Fare (€): total fare paid by the user in sharing and normal modes.

The following set of variables, and respective unit (if applicable), demonstrates taxis owners' performance in terms of operation mode and costs for all trips and analysed time :



(a) Sharing Services

(b) Waiting/Service/Total Travel Time



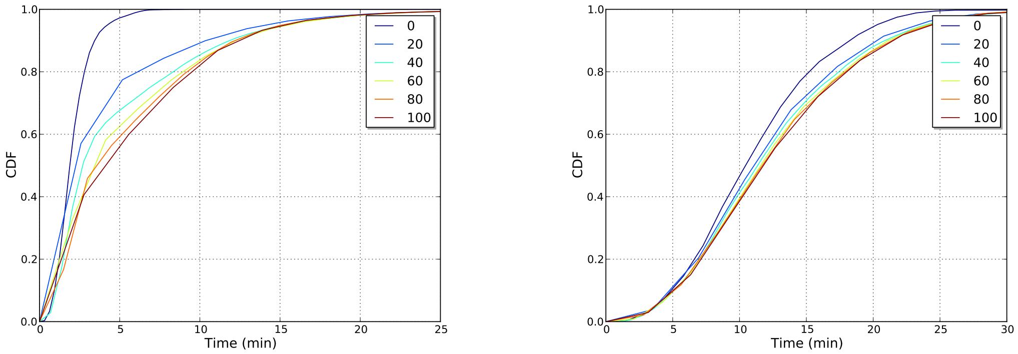
(c) Average Fare Variation

Figure 8.6: Service Operation Results with varying taxi-sharing penetration rates. Additionally to the base scenario, two scenarios with increased service demand by 50% (1.5) and 100% (2.0) are considered.

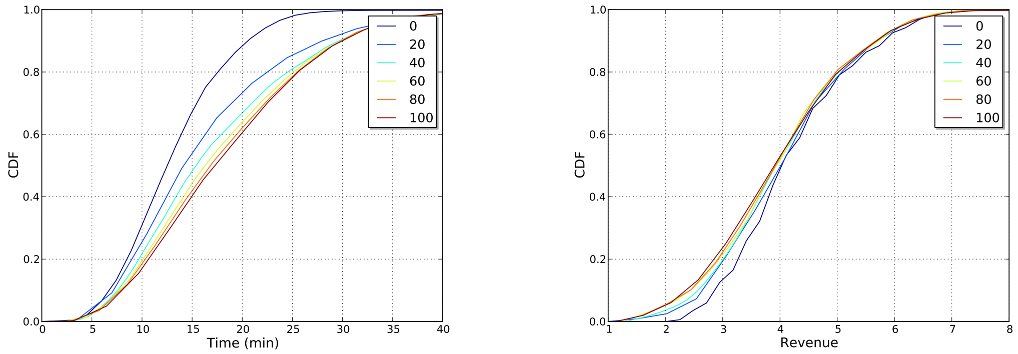
- Total Travel Distance (km): distance traveled by all taxis;
- Taxi Stand Departures (n/a): number of exits from all taxi stands;
- Revenue per Travel Distance (€/km): revenue per km earned by all vehicles.

8.5.3 Service Results

In this section selected metrics of the taxi-sharing algorithm are analysed from a passenger's perspective. Fig. 8.6a depicts the sharing services metric, which can be understood as the probability to match several services to one taxi and consequently to perform taxi-sharing. The sharing service metric reaches its maximum value (approximately 35%) for a 100% taxi-sharing penetration rate and for the scenario with the highest demand ($2.0 * Base$). We can observe that as the taxi-sharing penetration rate increases, more services are done in the taxi-sharing mode. For a given



(a) Waiting Time CDF (b) Service Time CDF



(c) Total Time CDF (d) Average Fare CDF

Figure 8.7: Detailed Service Operation Results (Base scenario).

taxi-sharing penetration rate, it can also be noticed that, as the service demand increases, the sharing service metric also increases. Both results were expected since the probability of matching services increases with increasing levels of deployment of the system.

Fig. 8.6b depicts average passenger waiting, service and total transit times. For the scenarios with no taxi-sharing, it should be firstly emphasized that all time metrics are in line with the actual taxi performance. For all settings, average waiting and service times are small since the closest free taxi to each passenger is assigned and real service distances are small. The results indicate that the average transit time increases with higher taxi-sharing penetration rates. More specifically, each passenger will spend a small additional amount of time to reach its destination since, usually, a detour will be made to serve other passengers. Yet, passengers can control this additional amount of time since they define the service degradation factor. The degradation of the QoS is especially clear for the average waiting time as this parameter is solely indirectly constrained. However, the average waiting time and service times are within acceptable limits for all demand scenarios. As expected, as service demand increases, there will be a increase in the time performance metrics since taxi-sharing it is more likely to happen. The service degradation due to an increasing service demand is considerably smaller than the one incurred due to the increase of system's penetration rate.

Fig. 8.7a-8.7c depict the CDF of passengers' waiting, service and total transit times obtained for the base scenario, respectively. The analysis of these plots confirms the observations made earlier on, namely that passenger waiting and transit times are degraded with the increasing introduction of taxi-sharing and that the service time is constrained due to the service degradation factor. Yet, most passengers (80 %) are picked up within 10 min and its service time is increased only by up to 3 min, which is clearly acceptable performance in terms of transit times. Another interesting fact is that further degradation in waiting and service times is almost negligible for taxi-sharing penetration rates above 60%.

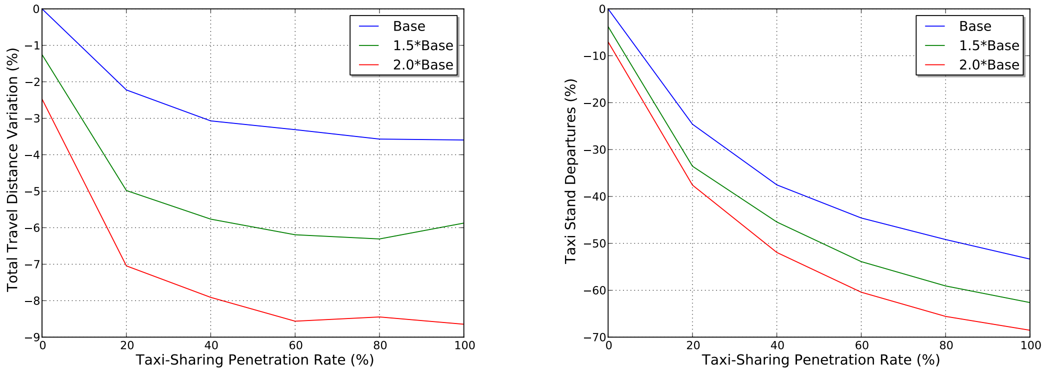
The economical aspect is one of the major factors that has limited the practical success of most taxi-sharing systems. Fig. 8.6c presents the average fare variation resulting from the implementation of the taxi-sharing system. The first fact we would like to point out is that average fares diminish considerably as the taxi-sharing penetration rate increases; average fares can decrease up to approximately 8% in higher demand scenarios. Secondly, for a given taxi-sharing penetration rate, the average fare decreases with increasing service demands. The same observations can be made observing the CDF of the average fare for the base scenario (Fig. 8.7d). Additionally, it can be concluded that fares below approximately 4.5 €show the biggest reductions in average fare variations.

8.5.4 Taxi Results

In this section selected metrics of the taxi-sharing algorithm are analyzed from taxi operators' perspective. Fig. 8.8a represents the total taxi travel distance for varying taxi-sharing penetration rates and varying service demands. We can observe that, as the percentage of taxi-sharing enabled taxis increases, the travel distance diminishes. This travel distance decrease can reach up to 9% in a 100% taxi-sharing penetration rate and in a higher demand scenario. Results also show that higher service demands lead to even bigger reductions in the total travel distance when comparing to the base scenario. Travel distance reductions are important for the taxi owner since operational savings can be reached due to the reduction of the total fuel consumption, maintenances cost, wages, among others. Citizens will also benefit from better air quality due to the reductions in pollutant emissions.

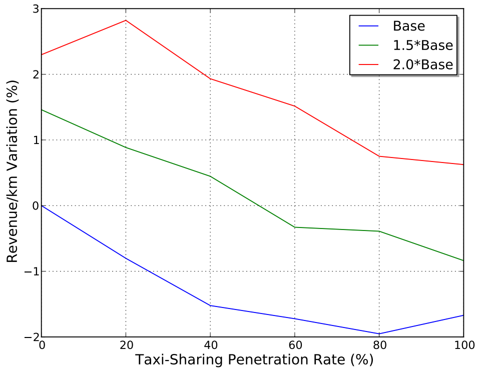
Fig. 8.8b depicts the number taxi stands departures to perform all services. In the opposite direction, this metric can be used to understand the number of moving taxis. As the percentage of taxi-sharing enabled taxis increases, the number of taxi stand exits diminishes. Furthermore, as the demand increases, the number of taxi stand departures will also considerably diminish (when considering the same system's penetration rate). These results indicate that a smaller number of vehicles is needed to fulfil a given service demand and that taxis should spend less time idling.

In the following, economical aspects for taxi owners are investigated. Fig. 8.8c represents the average revenue per travelled distance (€/km), which can be used as metric of profitability for taxi operators. It should be noted that in this study we did not take into consideration economical gains arising from lower travel distances (e.g. lower fuel consumption, less repairs). Observing this plot we can conclude as a general trend that the average revenue per travel distance decreases



(a) Total Travel Distance Variation

(b) Taxi Stand Departures Variation



(c) Average Revenue/km Variation

Figure 8.8: Taxi Operation Results with varying taxi-sharing penetration rates. Additionally to the base scenario, two scenarios with increased service demand by 50% (1.5) and 100% (2.0) are considered.

(even having negative variations) as the taxi-sharing penetration rate increases. The profitability variation decreases to negative values whenever the reductions in the average fare are bigger than the corresponding reductions in the travel distance. On the other hand, we can observe that the average revenue per travel distance variation metric improves in higher demand scenarios; for a scenario with maximum service demand this metric it is always better than the current base scenario. To conclude, there is a mixed result for the revenue per travel distance: i) it can decrease in some scenarios (e.g base scenario, $1.5 * Base$) with increasing system penetration rates; ii) it can improve in some scenarios (e.g. $1.5 * Base$, $2.0 * Base$) when comparing to the base scenario.

8.5.5 Discussion

The above presented results lead us to the conclusions that taxi-sharing can be beneficial for both passengers and taxi operators although trade-offs need to be considered. Besides, the performance of the system is closely related to the penetration ratio and service demand for this transportation service. Furthermore, it should be emphasized that as the taxi-sharing penetration rate and the service demand increases, the probability to perform taxi-sharing also increases, reaching almost 35% in the highest demand scenario considered in this study.

Sharing of resources is convenient for passengers mainly because it helps them to reduce their travel costs. The bigger the taxi-sharing penetration rate and the higher the service demand, the lower the average cost per passenger is. However, the passenger will also observe a degradation in the QoS of the traditional taxi system; this degradation will result in increased total transit time (waiting + service). In particular, passenger's preferential routes will not be followed since detours are made to serve other passengers. Yet, passengers can control this additional amount of time by defining the service degradation factor.

Taxi-sharing can also present added advantages for taxi operators. Results have shown that the travel distance can be reduced with increasing introduction of taxi-sharing. Furthermore, a higher demand scenario resulting from the implementation of taxi-sharing can also lead to reduced total travel distance. These results will impact positively operational costs (e.g. smaller fuel/repair costs) and capital expenditure (e.g. delayed purchase of new vehicles). Other important implication invokes revenue aspects. In this respect mixed results where presented if solely the average revenue per travel distance was considered. However, none of the cases provides a relevant effect (positive or negative) to taxi operators. We believe that, if the reductions of operational costs were to be added to the revenue per travel distance, taxi-sharing would be always advantageous for taxi operators for all penetration rates and all service demands. Thus, taxi unions should consider accepting this new mode of operation since it can lead to more efficient operation, to reduced operational expenditure and possibly to increased service demand.

From the results a number of trade-offs has been presented. To summarize, the following compromises need to be consider in the system design phase:

- service performance (e.g. average fare reduction, taxi matching probability) vs. passengers' allowed transit times;
- system's efforts (e.g. total travel distance) vs. passengers' service degradation;
- passenger fare gains vs. average revenue per travel distance for taxi operators.

Although the present study focus on a typical medium-sized European city (Porto, Portugal)[1] we consider that the results can be extrapolated to cities with similar characteristics in terms of demand, taxi operation mode and road network. By considering higher service demands we can effectively study the algorithm in different conditions, which increases the broadness of the results. Additionally, we argue that the presented system trade-offs can be broadly used for cities of any size.

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[1] In Europe a vast part of the urban population (44%) lives in medium-sized cities.

8.6 Conclusions

In this work, we have presented a distributed and dynamic taxi-sharing algorithm enabled by wireless communications and distributed computing capabilities. The algorithms have been implemented in a a realistic and large-scale simulation platform using empirical date from current taxi operation. The analysis of the taxi-sharing system has shown important benefits for both taxi operators (e.g reduced total travel distance) and passengers (e.g. reduced fares). Furthermore, it was concluded that the impact of varying the system penetration rate or the demand scenario is significant. However, when performing the deployment of the system or during its operation, a number of trade-offs needs to be considered carefully to ensure appropriate performance for all involved parties. More specifically, attention should be taken to the pricing scheme since in some situations taxi operators may perceive it as having a negative impact on their performance. Consequently, special focus should be placed on the advantages for taxi operators, such as reduced operational expenditure (e.g. less fuel consumption, maintenance costs) and delayed capital expenditure. Due to the benefits for customers, this type of transportation system can also lead to an increase in the overall service demand, which would clearly benefit taxi drivers.

Apart from the these advantages, the society as a whole will also benefit, namely from reduced pollutant emissions and decreased congestion. In [5] we have show that important reductions in CO_2 emissions can be attained with full deployment of a taxi-sharing system, reaching 9% under a higher demand scenario. However, in order for this type of disruptive technology to establish quickly, social and regulatory aspects need to be carefully considered; innovative strategies need to be devised to provide an incentive to people for sharing taxis. Additionally, institutional barriers (e.g. regulations for passenger transportation [2]) need to be removed or changed swiftly to encompass innovative services. Previous trials in different continents have also shown that taxi sharing can deployed with little or none regulation changes. Thus, we believe that by demonstrating to all involved parties the system advantages, legal changes could be made in a short period of time to allow the fast deployment of the system.

As future work, we intend to study and quantify the impact of the implementation of this type of transportation system in different scenarios. More specifically, we intend to understand how the network size and the geographical dispersion of requests' O/D affects the system performance. Further work is also necessary to study the most appropriate communication model for the taxi-sharing system. It should also be analyzed whether more sophisticated strategies for taxi stand selection (e.g. [142]) or pickup location selection would improve the performance of the taxi-sharing system.

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[2] The regulatory problems faced by UBER's (`http://www.uber.com`) innovative service in New York.

Chapter 9

Automated Parking System for Autonomous Vehicles

9.1 Introduction

Autonomously-driven cars are only a few years away from becoming a common feature on our roads [143, 144]. These self-driven vehicles hold the potential to significantly change urban transportation. One of the most important changes will not happen during the trip from origin to destination, but rather when these vehicles arrive at their destinations. An autonomous vehicle will leave its passengers at their destination and will then park by itself, waiting to be called to pick them up later on. This behaviour will have important implications on door-to-door trip time, traffic congestion and parking costs.

As pointed-out by Donald Shoup [145]: "*A surprising amount of traffic isn't caused by people who are on their way somewhere. Rather it is caused by people who have already arrived*". Shoup refers to this phenomena as *cruising for parking* and shows that, despite the short cruising distances per car, this results in significant traffic congestion, wasted fuel and high CO_2 emissions [146].

With autonomous vehicles, the door-to-door trip time of a passenger will not be aggravated by the cruise time needed to find a parking space, nor with the walking time needed to go from the parking space to the final destination. Furthermore, after leaving their passengers at their destinations, these autonomous vehicles can rapidly proceed to a parking lot that does not need to be at a reasonable walking distance, as happens with non-autonomous vehicles. Nevertheless, the parking of these autonomous vehicles will still face the same problems of non-autonomous vehicles, since parking space is scarce and expensive.

If we consider the average 150 square feet of a parking space, and we assume there are 250 million vehicles in the USA, then a parking lot to contain all these vehicles would measure 1,350 square miles, roughly 0.04% of the country's area. This does not seem much, but the problem is the concentration of vehicles in urban areas. As urban planners know, parking space is commonly allocated at a ratio of 1 space per 200 square feet of land use for a variety of businesses [147]. If we add an extra 30-50% of space for the access ways in typical parking lots, then we actually have ratios higher than 1:1 between the space allocated for parking and the space allocated for businesses such as supermarkets, shopping centres, office buildings, or restaurants. For example, in midtown Atlanta, in Georgia, USA, the percentage of land space that is 100% dedicated to parking reaches 21% [148]. This is one of the densest and most pedestrian-friendly area in the entire state of Georgia, USA. Parking is then often the biggest land uses in many cities.

In parallel with the paradigm of autonomous vehicles, electric propulsion is also starting to be applied to automobiles. Electric Vehicles (EVs) motors often achieve 90% energy conversion efficiency over the full range of power output and can be precisely controlled. This makes low-speed parking manoeuvres especially efficient with EV. Another technological innovation being proposed to automobiles is wireless ad hoc vehicular communication, in the form of V2V or V2I communication. The idea we present in this chapter is based on the combination of autonomous vehicles, electric propulsion and wireless vehicular communication to design a new paradigm of self-automated parking lot, which maximises the number of cars that can be fitted in the parking lot space, relying solely on in-vehicle systems.

The idea is relatively simple. An autonomously-driven EV equipped with vehicular communications (e.g. ITS-G5, 802.11p standard [79]) consults online for an available parking space in nearby self-automated parking lots. It reserves its parking space and proceeds to that location. Upon entering the parking lot, this vehicle uses V2I communication to exchange information with a computer managing the parking lot. The vehicle can give an estimate of its exit time, based on the self-learned routine of its passenger, or on an indication entered by this same passenger. The parking lot computer informs the vehicle of its parking space number, indicating the exact route to reach this parking space. As vehicles are parked in a manner that maximises space usage (no access ways), this path can require that other vehicles already parked in the parking lot are also moved. The parking lot computer also issues the wireless messages to move these vehicles, which are moved in platoon whenever possible, to minimise the parking time. The exit process is identical. Minimal buffer areas are designed in the parking lot to allow the entry/exit of any vehicle under all possible configurations. The managing computer is responsible for the design of parking strategies that minimise the miles travelled by parked vehicles on these manoeuvres.

The remainder of this chapter is organised as follows. In the next section we provide some background on parking lot technology. Following, we describe our system design issues. In the subsequent section we present the evaluation framework to compare our proposal with a conventional parking lot, leveraging on a dataset with entry and exit times of a real parking lot in the city of Porto, Portugal. We then evaluate a simple parking strategy for our self-automated parking lot proposal, based on this dataset, and compare the key metric of travelled distance in the parking lots, to show the feasibility of our proposal. We end with some conclusions.

9.2 Parking Technology

Traffic congestion has for some decades been one of the major transportation problems due to its many and related causes. In dense urban areas, the search for an empty parking place can create considerable congestion, which results in economical losses and serious environmental impact. Searching for parking often occurs due to the imbalance between on-road and off-road parking prices, and additionally the oversupply of free parking. A survey found that parking is free for 99% of all automobile trips in the United States [146]. In a historic study [145], Shoup reported that the average share of traffic cruising for parking amounts to 30% and the average search time is 8.1 minutes. In the same report, the author found that in a small business district in Los Angeles, cruising for parking leads to an additional 950,000 miles travelled, wastes 47,000 gallons of gasoline and produces 730 tons of CO_2 emissions. A comparable study [149] conducted in a district in Munich, Germany, shows a similar trend, i.e. wastes of 3.5 million euros on fuel and 150,000 hours, and 20 million euros in economical loss. Projected on larger cities in Germany, comprising multiple districts of similar sizes, a total economical damage of 2 to 5 billion Euros per year is estimated [149]. In [150], Ommeren et al. conclude that cruising time increases with travel duration as well as with parking duration, but falls with income.

9.2.1 Parking lot design

Parking also poses challenges to urban planners and architects. Considering that citizens often only use their cars to commute to and from work, the space occupied by these in urban areas is inefficiently used (e.g. currently the average car is parked 95 % of the time). Additionally, urban development has to consider local regulations that mandate parking space requirements depending on the construction capacity, which increases costs and limits buyers choices as demand surpasses parking space supply. A study in 2002 has estimated that parking requirements impose a public subsidy for off-street parking in the US between \$127 billion in 2002 and \$374 billion [146].

In recent years, there has been an increasing interest in the design of parking structures. Parking lots consist of four main zones, namely circulation areas for vehicles and pedestrians, parking spaces, access to the parking infrastructure and ramps in multi-floor structures. Parking structure design compromises the selection of a number of parameters, such as shape (usually rectangular), space dimensions, parking angle, traffic lanes (e.g. one or two-way), access type or ramping options, depending on site constraints, regulations, function (e.g. commercial or residential), budget and efficiency reasons. Due to a number of reasons (e.g. existence of pedestrian circulation areas) parking lots for human-driven vehicles are inefficient and costly (e.g. smaller soil occupancy ratio), which is critical in densely populated areas.

9.2.2 Parking Systems

Extensive research has been carried out in the area of parking systems enabled by ITS. This research field is commonly classified into two main categories, namely parking assistance and automatic parking. Parking assistance systems, which are enabled by sensing, information and communication technology, support drivers by finding available on-street and/or off-street parking places. In these systems, acquired parking information (supply or demand) is disseminated to drivers, or its support systems, for decision making, i.e. parking space/route selection and eventually parking reservation and price negotiation. Examples of assistance systems are parking information system [151, 152] (e.g. guidance, space reservation), parking space detection (e.g. using GPS [153], cameras or sensors [154]), or parking space selection (e.g. based on driver preferences [155]).

Special attention has also been dedicated to the broad area of automatic parking. An early mechanical parking system [156] used four jacks to lift the car from the ground and wheels in the jacks assisted on the lateral movement towards the final parking position. One of the major examples of this category is self-parking, where vehicles automatically calculate and perform parking maneuvers using sensor information (e.g. cameras, radar) and by controlling vehicle actuators (e.g. steering). An improvement to this system is *Valet Parking* [157,158] where besides self-parking, the vehicle autonomously drives until it finds an available parking place. It should be noted that the two previous systems can be used for on-road and off-road parking (e.g. parking lots).

To reduce the space necessary to park vehicles, automated robotic parking has been deployed in areas where available space is especially scarce and expensive. These parking lots use electric elevators, rolling and rotating platforms to park vehicles in multi-floor structures, maximizing the occupancy of space. The parking maneuvers are done automatically by the electric platforms, without any intervention from drivers or operators. Automated robotic solutions are readily available in the market by several manufacturers, such as Boomerang Systems [1] or Parkmatic [2]. However, due to their complexity, these systems require high capital investments and can have considerable operational costs (e.g. maintenance or energy costs), which can result in high costs for the end user. For instance, in many urban areas, the first hour of parking in such complex parking lots can reach $20. Another drawback of this solution is the absence of the Valet Parking feature since drivers need to bring vehicles into the closest parking place, which may not be the most appropriate (e.g. in terms of costs). Furthermore, the fixed size and small number of moving platforms limits the optimally of parking space allocation.

9.3 System Design

Our system design issues are described in this section. We address our assumptions regarding the self-driving capabilities of vehicles, the architecture and infrastructure of the parking lot, and a simple communication protocol which allows the parking lot controller to manage the mobility of the parked vehicles.

9.3.1 Parking Lot Architecture

The geometric design of the parking lot is an important issue in our proposal. As described in the previous section, in conventional parking lots there are a number of considerations that have to be taken into account when designing them. For instance, width of parking spaces and access

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[1] `http://boomerangsystems.com/`

[2] `http://www.parkmatic.com/`

ways, one-way or two-way use of the access ways, entry angle in the parking bays ($90°, 60°, 45°$), pedestrian paths, visibility to find an available parking space, etc.

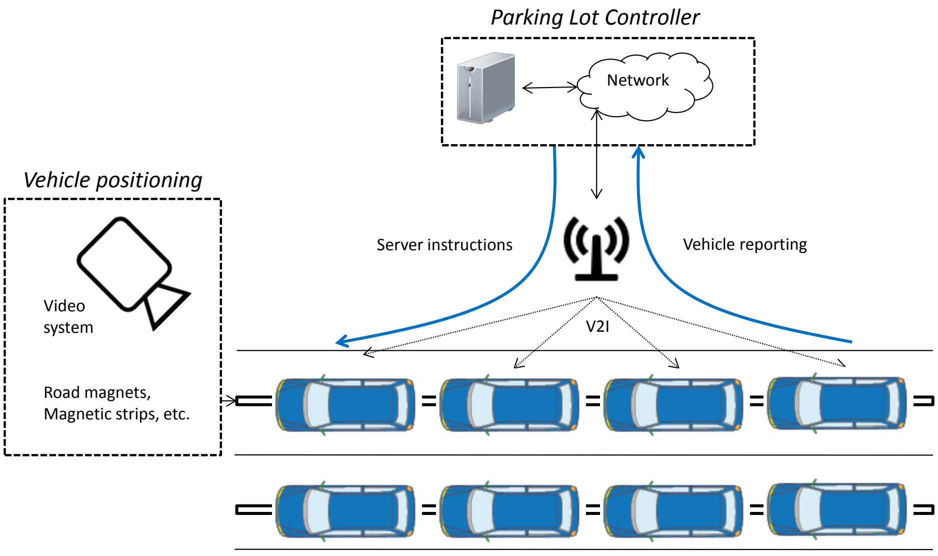
In our self-automated parking lot, many of these considerations do not apply. Manoeuvring is done autonomously by the car, pedestrian access is not allowed, and the assigned parking space is determined by the parking lot controller. The main design issue is defining a geometric layout that maximises parking space, leveraging on minimal buffer areas to make the necessary manoeuvres that allow the exit from any parking space under all occupancy configurations. This geometric design is ultimately determined by the shape of the space of the parking lot. The parking lot architecture also defines the trajectories and associated manoeuvres to enter and exit each parking space.

The parking lot has a V2I communication device which allows the communication between the vehicles and the parking lot controller. In theory, this infrastructure equipment could be replaced by a vehicle in the parking lot, which could assume the function of parking lot controller while parked there, handing over this function to another car upon exit, similarly to the envisioned functioning of a V2V VTL protocol [95]. Note, however, that the existence of the actual infrastructure, which could be complemented with a vehicle positioning determination system (e.g. video-camera offering an aerial perspective of the parking lot) to improve the controller perception of the location and orientation of vehicles, could simplify the protocol and improve reliability. Road magnets or industrial magnet strips could be two other alternatives for vehicle positioning inside closed parking lots. The system architecture of the self-automated parking lot is depicted in Figure 9.1.

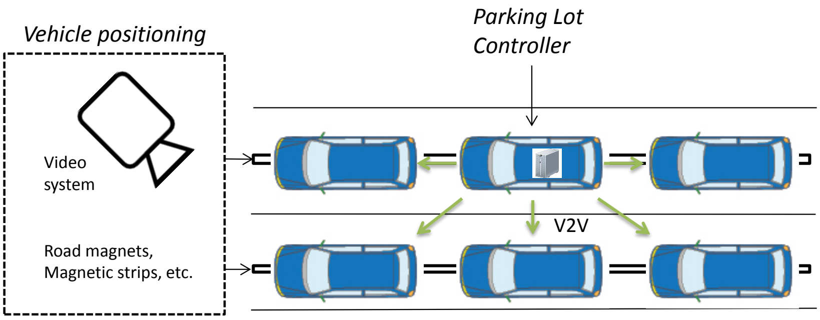
Reducing and simplifying such trajectories and manoeuvres is also an important design issue, as they affect the reliability of the system and allow faster storage and retrieval of cars. Note also that the parking lot architecture can take advantage of the fact that the passenger is not picking up the car at the parking lot, but it is rather the car that will pickup the passenger. This allows having different exits at the parking lot, which are selected based on the current location of the car. To optimise and simplify manoeuvres, these self-automated parking lots will require specific minimum turning radius values for vehicles. Only vehicles that meet the turning radius specified by each parking lot will be allowed to enter it.

The geometric layout of the parking lot and its buffer areas can assume very different configurations for the self-automated functioning. In particular, even parking areas which are not seen today as formal parking lots, such as double curb parking, could be managed by a similar parking lot controller.

As a proof-of-concept example, we provide the parking lot design illustrated in Fig. 9.2. This parking lot has a total of 10×10 parking spaces, and two buffer areas, one to the left of the parking spaces, and one to the right, measuring $6m \times 20m$. The size of the buffer area is determined by a minimum turning radius which was assumed to be $5m$ in this example, a typical value for midsize cars. As this parking lot is designed for autonomous vehicles, which enter it after leaving their passengers, it is not necessary to leave the inter-vehicle space that allows the doors to be opened. Thus, the width of the parking spaces can be significantly reduced ($\approx -20\%$). In this example, we



(a) Centralized



(b) Distributed

Figure 9.1: Self-automated parking lot system architecture.

use $2m \times 5m$ for each parking space.

This space-saving layout requires a specific strategy to guide the insertion and removal of vehicles. Ultimately, a layout is only feasible as long as the required movement by the vehicles does not have a significant cost. Next, we demonstrate a simple algorithm that exploits the exemplified layout. Later, in Section 9.4 we evaluate its performance.

9.3.2 Entry/Exit Algorithm

Consider Fig. 9.2. In this self-automated parking lot design, in order to simplify and standardise the manoeuvres, we use the buffer areas simply to allow the transfer of a vehicle from a given row to a new row which is 5 positions up or above (as dictated by the minimum turning radius of $5m$), as illustrated by the semi-circle trajectories depicted in Fig. 9.2. This transfer of a vehicle from one row r to another r' will eventually require that other vehicles are moved and re-inserted in r, in a carrousel fashion. This usage of the buffer areas is not particularly efficient from the point

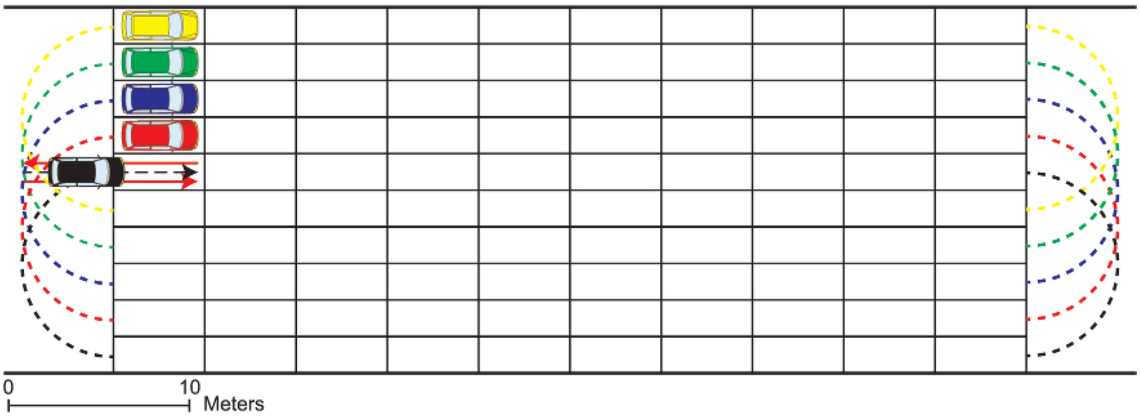


Figure 9.2: An example layout for a self-automated parking lot. Buffer areas are used to allow the transfer of a vehicle from one line to another line, 5 positions above or below, as illustrated by the dashed trajectory lines.

of view of space usage or mobility minimisation, but enables us to define a simple manoeuvring strategy of the parking lot that allows the exit of any vehicle. In this architecture we allow vehicles to enter/exit the parking lot through the left or right of the parking area.

A simple algorithm can then be defined as following:

- **On Vehicle Entry:** the vehicle is directed to the left-most row r with an empty space, such that the eventual movement by the vehicles already in r and r', to allow the entry of the vehicle, is minimised. The vehicle is placed in the furthest empty space in r.
- **On Vehicle Exit:** the exiting vehicle parked in row r is directed to exit from the front or back, such that the eventual movement by the vehicles in r and r', to create an open path, is minimised.

9.3.3 Self-Driving Capabilities

In the specific case of our self-automated parking lot proposal, the autonomous driving capabilities of vehicles involve much simpler tasks than in the case of driving on public roads. First of all, because the environment is fully managed by the parking lot controller and the only mobility that exists in the parking lot is determined by this controller. It is thus a fully robotised environment, where there is no interaction between autonomous vehicles and human-driven vehicles. In terms of technology and complexity, our setup is much more similar to Automated Storage and Retrieval Systems (AS/RSs), which have widely been used in distribution and production environments since its deployment in the 1950s [159], than to generic autonomous driving on public roads.

Given that the parking lot controller coordinates all mobility in the parking lot, it knows the current configuration of the parking lot at all times. Thus, all the sensing technology, which plays an important part in autonomous driving, is not necessary in this controlled environment. More than self-driving capabilities, the cars that use the self-automated parking lot need to have a system to enable their remote control (through Dedicated Short Range Communication (DSRC) radios) at slow speeds in this restricted environment. Drive-by-Wire (DbW) technology, where electrical systems are used for performing vehicle functions traditionally achieved by mechanical actuators, enable this remote control to be easily implemented. Throttle-by-wire is in widespread use in modern cars and the first steering-by-wire production cars are also already available [160]. EV will be an enabling factor for DbW systems because of the availability of electric power for the new electric actuators.

The precise localisation of vehicles is an important issue. In addition to global positioning systems, such as GPS, and to the aerial camera images, inertial systems from each car are also used to convey to the parking lot controller precise information about the displacement of each vehicle. This information can even report per wheel rotations, capturing the precise trajectories in turning manoeuvres.

Note that these limited requirements on the self-driving capabilities of the involved cars, would allow extending applicability of the self-automated parking lot to non-autonomous or semi-autonomous vehicles, which are left at the entrance of the parking lots by their drivers. While fully-autonomous production cars are still non-existent, automatic parking systems are already available in a number of production cars, based on research to control parallel parking manoeuvres of nonholonomic vehicles [161].

9.3.4 Communication Protocol

The communication protocol for the self-automated parking lot establishes communication between two parties: the Parking Lot Controller (PLC) and each vehicle.

A vehicle trying to enter the parking lot, first queries the PLC for its availability. The PLC has a complete view of the parking lot state, mapping a vehicle to a parking space, and responds affirmatively if it is not full. Upon entering the parking lot, the autonomous vehicle engages in PLC-mode. During the stay in the parking lot, the PLC is responsible for managing the mobility of the vehicle. To move a vehicle, the PLC sends movement instructions in the form of a sequence of commands, similar to the commands used in radio-controlled cars, that will lead to the desired parking space. For example, the carousel manoeuvre described in Section 9.3.1 corresponds to the following sequence: `forward` m_1, `steer` d°, `forward` m_2, `steer` $-d^\circ$, `forward` m_1. The commands depend on the vehicle attributes. These must be sent to the PLC when the vehicle enters the parking lot, i.e., width, length, turning radius, etc.

The protocol involves periodic reports sent by the vehicle to the PLC about the execution of each command (typically with the same periodicity of VANET beacons [79]). These periodic reports allow the PLC to manage several vehicles in the parking lot at the same time. Note that in order for a vehicle to be inserted in a parking space, other vehicles may need to be moved. Note also that concurrent parking can occur in different parking spaces in the parking lot. Based on the periodic reports, the PLC tries to move vehicles in a platoon fashion, whenever applicable, in order to minimise manoeuvring time.

A vehicle exit is triggered by a message sent to the PLC by the vehicle intending to exit (possibly after receiving a pickup request from its owner). The PLC then computes the movement sequence commands and sends these sequences to the involved vehicles.

Having an external controller managing the vehicles poses evident security issues. As explained in [162], vehicular network entities will be certified by Certification Authorities, e.g., governmental transportation authorities, involving the certification of the PLC communication device of each parking lot. Temper-proof devices may avoid or detect deviations from the correct behavior. In the ultimate case, certifications may be revoked and new vehicles will not enter the park. For the parked vehicles that will not be able to detect the certificate revocation, no high risks exist.

9.4 Evaluation Framework

In this section we describe a conventional parking lot layout and the layout used for our proposal of a self-automated parking lot. Our goal is to compare equivalent parking lots in terms of the number of vehicles that they can hold, using two important metrics: area per car; and total traveled distance in parking and exiting manoeuvres. The actual evaluation of this last metric using a real entry/exit dataset is done in the next section.

9.4.1 Conventional Parking Lot

For a comparative evaluation we use a conventional parking lot design, illustrated in Fig. 9.3. The design of this parking lot is based on a standard layout that tries to maximise parking space and minimise access way space, similar to the one seen in the dataset video, which we will discuss further ahead. We use the common measures of $5m \times 2.5m$ for a parking space and a width of $6m$ for the access way. Typically, two rows are placed facing each other, forcing cars to exit the parking space through a backup manoeuvre. The access way is based on a one-way lane, reducing its width and forcing cars to completely traverse the parking lot, in a standard sequence that consists of entering the parking lot, traversing it to find a parking space, parking, backing up to leave the parking space, and traversing the parking lot to proceed to the exit. This design allows us to discard variations in travelled distance when finding a vacant parking space is not deterministic.

This parking lot holds 100 cars and occupies an area of $72m \times 32m = 2,304m^2$. This yields an area per car of $23,04m^2$.

In this type of parking lot all vehicles traverse the same distance. The components of this distance are marked in Fig. 9.3. A represents the straight distances travelled in the access way, while B represents the curves. C denotes the entering and exiting manoeuvre in the parking space. Using a turning radius of $5m$, we obtain the following total traversing distance for a car: $A = 94,8m$, $B = 6 \times (2\pi \times 5m)/4$, $C = 2 \times (2\pi \times 5m)/4 + 2 \times 3m$. This yields a total of $\approx 164m$ traversed by each car. It is clear that the manoeuvring model to derive such distance is over-simplified, but it results in negligible differences in our problem.

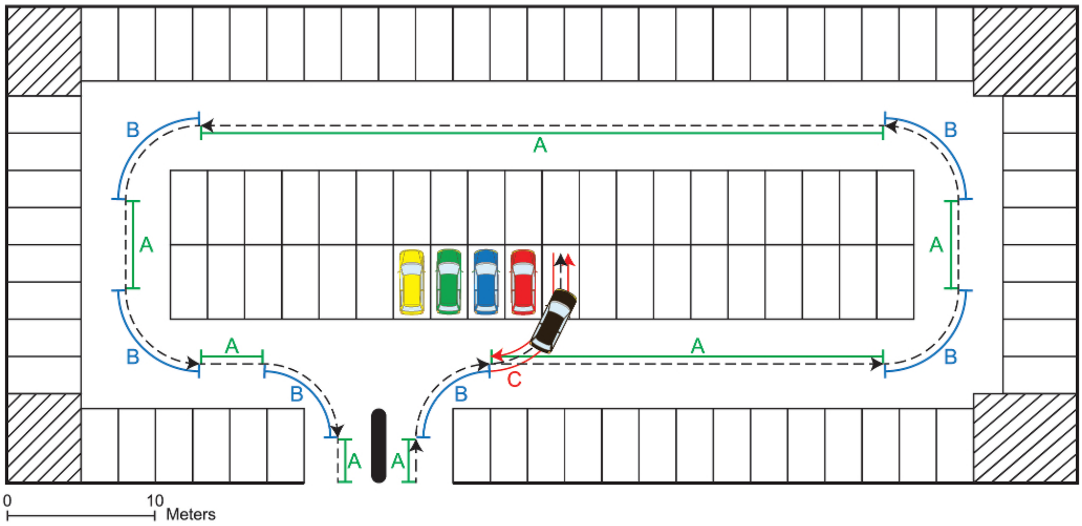


Figure 9.3: Layout and travel distance in a conventional parking lot.

9.4.2 Self-Automated Parking Lot

For the self-automated parking lot we use the layout described previously. To be as equivalent as possible to the parking lot in Fig. 9.3, we use the $N_c = 10$ columns and $N_r = 10$ rows, forming a 10×10 array, comprising parking spaces, illustrated in Fig. 9.2. Two buffer areas are also included, with a width of $6m$ each, as in the access way of the conventional parking lot. As this parking lot is designed for autonomous vehicles, which enter it after leaving their passengers, it is not necessary to leave the inter-vehicle space that allows the doors to be opened. Thus, the width of the parking spaces is reduced to $2m$. The length of each parking space is again of 5m. The total area of this parking lot is therefore $62 \times 20m = 1,240m^2$, yielding an area per car of $12.40m^2$. This represents a reduction of nearly 50% when compared to the area per car of the conventional parking lot.

In this self-automated parking lot the traveled distance can vary substantially from car to car, contrary to what happened in the conventional parking lot. As the autonomous vehicle leaves the parking lot to collect passengers at their location, we allow it to leave the parking lot either through the left or right buffer areas. It can also exit through a backup manoeuvre. Instead of deriving a single total distance traveled by each car, as in the conventional parking lot, we can try to derive the average distance that is travelled by each vehicle under special configurations of the parking lot. Note that vehicles will not be stopped in a fixed parking space, as the managing algorithm will move them to create the access ways during entries and exits of other vehicles.

To have an idea of the magnitude of the travelling distance in this self-automated parking lot, we can compute the entry and park distance for a special case where the parking lot fills completely in a monotonic process (i.e. no exits are observed). Let $\beta = 6m$ be the length of the entry buffer, and $\gamma = 5m$ the length of a parking space.Assume vehicles enter through the left buffer area of the parking lot. The first N_c vehicles fill the furthest column, travelling a total of $N_c(\beta + N_c\gamma) = 560m$. The next N_c vehicles fill the previous column, travelling a total of $10(\beta + 9\gamma) = 510m$. Iteratively,

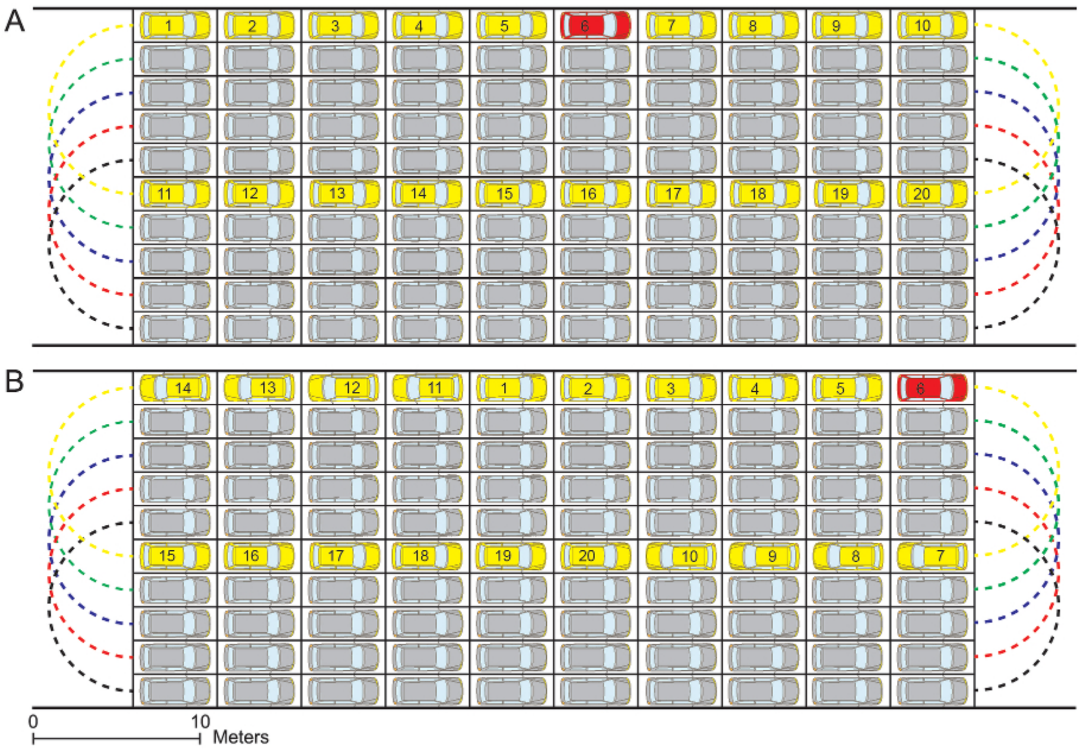


Figure 9.4: Completely full parking lot. In this architecture, vehicles use the buffer areas to implement carrousels between lines 1-6, 2-7, 3-8, 4-9 and 5-10. Rotation can be clockwise or counter-clockwise.

the total distance in meters to fill the parking lot is thus:

$$\sum_{i=1}^{10} 10(\beta + i\gamma) \tag{9.1}$$

which gives $3,350m$, or an average of $33.5m$ per vehicle. This value is exactly the same that would be obtained if vehicles would park at the first available column, moving forward as necessary to accommodate entering vehicles, as described in Section 9.3.2.

With a completely filled parking lot, the average travelled distance for the exit of each vehicle depends on the algorithm that creates exit ways by using the buffer areas. One possible alternative is to use the buffer areas as described previously, allowing vehicles to execute semi-circle trajectories based on their turning radius. If we use a turning radius of $5m$, as in the conventional parking lot, then these semi-circle trajectories join line 1 to line 6, line 2 to line 7, etc, as illustrated in Fig. 9.4. If the red vehicle shown in frame A of Fig. 9.4 wants to exit, then all vehicles in lines 1 and 6 have to rotate clockwise using the semi-circle trajectories where necessary, until the red vehicle has no vehicles blocking it, as illustrated in frame B of Fig. 9.4. Note that the rotation can be counter-clockwise, as would be the case if the vehicle that wants to exit is vehicle number 5 in frame A of Fig. 9.4. These semi-circular trajectories can cause vehicles to be in different directions in the same row, but this is completely irrelevant in terms of the functioning of the parking lot.

This usage of the buffer areas is not particularly efficient in terms of minimisation of travelling distance, but allows a simultaneous, platoon-based, mobility of vehicles, thus improving the overall exit time. As the manoeuvres are simple and standard, it also allows the derivation of an analytic expression that represents the average travelled distance for exiting vehicles under the full parking lot configuration. We consider c_i to represent a vehicle that wants to exit from the i^{th} column ($i-1$ vehicles in front). It varies from 1 to $\frac{N_c}{2}=5$, as we consider the symmetry on clockwise and anti-clockwise rotations. Thus the average travelling distance for exiting vehicles is:

$$\frac{\sum_{c_i=1}^{\frac{N_c}{2}} 2\left(\sum_{j=1}^{c_i-1} j\gamma+\gamma\pi\right)+(N_c-c_i-1)\gamma+c_i\gamma+\beta}{\frac{N_c}{2}} \tag{9.2}$$

This gives approximately $143.85m$. Adding the average entry and park distance of $33.5m$, we obtain a total per vehicle of $177.35m$, which is similar to the $164m$ in the conventional parking lot. Note that in the conventional parking lot the $164m$ distance is fixed under all occupancy configurations of the parking lot, including nearly empty configurations. In the self-automated parking lot, the distance travelled in nearly empty configurations will be much smaller. Note also that a good parking strategy can minimise the exits of middle column vehicles, with important implications on the overall travelled distance.

9.4.3 The Entry/Exit Dataset

To realistically evaluate the travelled distance in our proposal of a self-automated parking lot we have to resort to a dataset with the observed entries and exits of an existing parking lot. The type of parking lot in terms of its usage can significantly affect the performance of the algorithm managing the mobility of the cars. For instance, a shopping mall parking lot will have a higher rotation of vehicles, with shorter parking times per vehicle, when compared to a parking lot used by commuters during their working hours. An important parameter to the algorithm optimising the mobility of the cars in the parking lot is the expected exit time of each vehicle, given at entry time. This time can be inserted by the passenger or automatically predicted by the car, based on a self-learning process that captures the typical mobility pattern of its passenger [163].

Our dataset is constructed based on the video-recording of the activity of a parking lot during a continuous period of 24 hours. The parking lot in question is cost-free, which affects the parking pattern. It serves commute workers, as well as a nearby primary school, causing some shorter stops of parents who park their cars and walk their children to the school. This parking lot has a total of 104 parking spaces, which we reduced to 100 in order to match our 10×10 layout, by ignoring the entries and exits related with four specific parking spaces. This parking lot is continuously open. It only has one entry point and we thus only allow vehicles to enter our self-automated parking lot through the left side entrance. We start with an empty configuration of the parking lot, ending 24 hours later, with some vehicles still in the parking lot. Table 9.1 summarises the key facts in

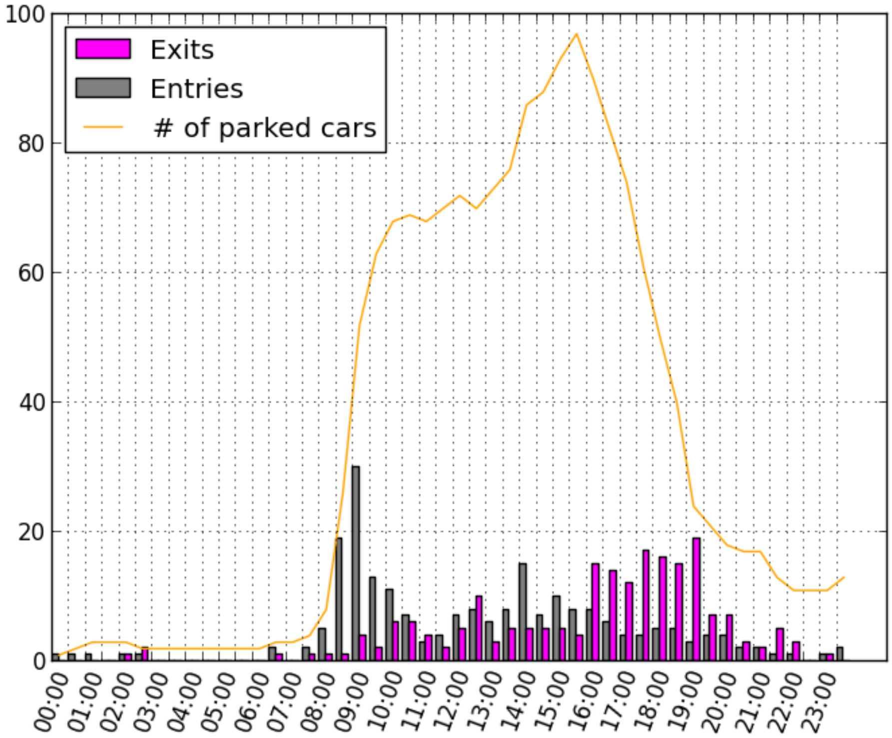


Figure 9.5: A histogram presenting the number of entries and exits of cars per hour. We also plot the total number of cars in the parking lot. Full occupancy is almost reached at 16h05.

this dataset [3]. A histogram with the distribution of entries and exits per 30 minutes intervals is provided in Fig. 9.5.

Table 9.1: Key facts in the entry/exit dataset

Parking lot location	(41.162745, -8.596255)
Start time	Dec 11th, 2013, 00:00
Duration	24 hours
Parking spaces	100
Total entries	222
Total exits	209
Average parking duration	3h38m25s
Average occupancy (0-24h)	34.76%
Average occupancy (9-17h)	74.59%

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[3] The dataset is available at `http://www.dcc.fc.up.pt/~michel/parking.csv`

9.5 Results

We implement a simple strategy to park cars, ignoring the estimated exit time that would be given by each entering car. Our strategy is simply to place the car in the parking space that requires a minimal travel distance of the cars in the parking lot. No optimisation based on the estimated exit time is used. Our goal is to show that even with such non-optimised strategy the total travelled distance is significantly less than in a conventional parking lot. Clearly, an optimisation strategy that uses the estimated exit times to order the vehicles in monotonic sequences would be able to give better results. Such optimisation strategy is however out of the scope of this thesis.

The key metric that we evaluate is the total travelled distance of each vehicle, from entry time to exit time. Another possible metric would be the manoeuvring time. However, in our carrousel architecture vehicles are moved in platoon and thus total time is not affected by the number of vehicles in the platoon, but only by the distance travelled by the leading vehicle.

To measure this distance and to have a visual perspective of the functioning of the system, we implemented the self-automated parking lot architecture and mobility model using the Vehicular Networks Simulator (VNS) framework [56]. VNS was extended to model the specific features of our problem, namely the platoon-based mobility of vehicles. A video of this simulation under the dataset input is publicly available [4]. The animation steps are based on the discrete entry and exit events, rather than on the continuous time, to eliminate dead periods.

9.5.1 Total Travelled Distance

A plot with the total travelled distance during the 24 hours we analysed is presented in Fig. 9.6, with two series representing the conventional parking lot (dashed red line), and the self-automated parking lot (solid blue line).

As can be seen, the reduction observed in total travelled distance is very significant. In the self-automated parking lot, we obtained a total travelled distance of $23,957.64m$, for the 222 vehicles entering the parking lot (note that 13 vehicles remain in the parking lot after we end the simulation at 23:59:59). Using the fixed value of $\approx 164m$ for the conventional parking lot with the same number of entering and exiting vehicles, we obtain a total of $34,261.24m$ travelled distance, which translates into a reduction of 30%. Note that this reduction is obtained with a non-optimised strategy for parking vehicles. The non-optimised strategy affects primarily the performance during the period where the parking lot is nearly full (from 14h00 to 17h00), as the exits of middle-parked vehicles generates significant mobility of other parked vehicles, as can be seen in Fig. 9.6.

In Table 9.2 we present values for maximum travelled distance by a vehicle, average travelled distance and standard deviation. Fig. 9.7 shows the cumulative distribution function of distance per vehicle, where the linear behaviour is clear. Even the maximum value of $404m$ travelled by a vehicle translates into less than \$0.05 according to the average operating costs of a fuel-powered sedan in the USA [164]. Note that the vehicle that travelled $404m$ stayed in the parking

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[4] `http://www.dcc.fc.up.pt/~rjf/animation.avi`

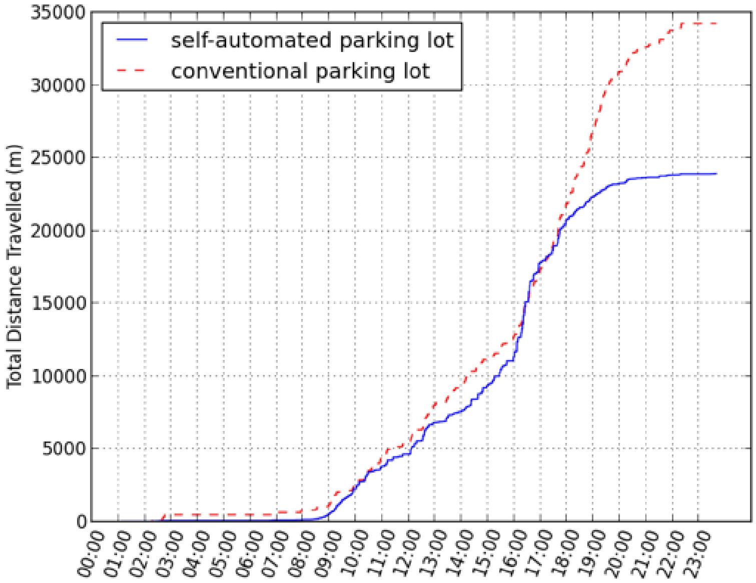

Figure 9.6: These plots present the evolution of the total distance travelled throughout the 24h analysed, both for the conventional parking lot and for the self-automated parking lot. Note how the non-optimised strategy causes a rapid increase on the curve for the self-automated parking lot around 16h00, when the parking lot is full and exits peak.

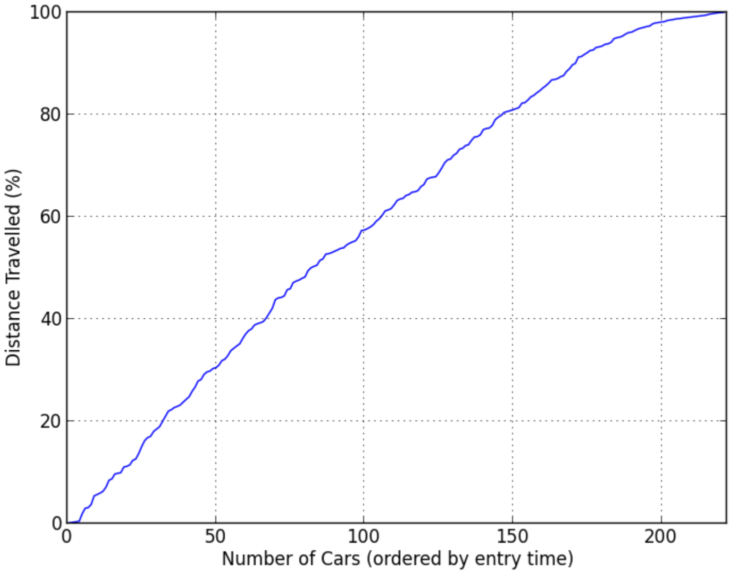

Figure 9.7: Cumulative distribution function of distance per vehicle.

lot for approximately 16h, resulting in an average travel of 25m per hour, which translates into an operating cost of less than \$0.003 per hour.

Table 9.2: Travelled distance statistics per vehicle

Maximum travelled distance	$404m$
Average travelled distance	$112m$
Standard deviation	$87m$

9.6 Conclusions

In this thesis we have presented a new concept of a self-automated parking lot, where autonomous cars use vehicular ad hoc networking to collaboratively move in order to accommodate entering vehicles and to allow the exit of blocked vehicles. Using this collaborative paradigm, the space needed to park each car can be reduced to nearly half the space needed in a conventional parking lot. This novel paradigm for the design of parking lots can have a profound impact on urban landscape, where the current area allocated to car parking can sometimes surpass 20%. Our proposal is particularly effective with the emergent paradigm of EV, where very high energy conversion efficiency is obtained at the low speeds observed in parking lot mobility.

Our proposal, however, needed to show that the overall collaborative mobility generated in such a self-automated parking lot is not prohibitively high, compared to the mobility in conventional parking lots. Using a real dataset of entries and exits in a parking lot during a 24 hour period, we have shown that even using a simple and non-optimised strategy to park vehicles, we are able to obtain a total travelled distance that can be 30% lower than in a conventional parking lot. This non-intuitive result further strengths the potential of our idea in re-designing the future of car parking.

Although out-of-the-scope of this thesis, we have no doubt that the interesting optimisation problem that uses estimated exit times to determine the original placement for each car will be able to further improve the results reported here. Another more general topic that should be addressed is vehicle localization in challenged environments (e.g. dense urban, close parking garage) where the parking system will operate. To assess the feasibility of the solution in a real world scenario, the proposed system should be prototyped and thoroughly evaluated. A complete assessment of energy consumption aspects, either for electric vehicles or fuel powered vehicles, is also of prime importance.

Chapter 10

Conclusion

In this chapter the main concluding remarks are presented. A summary of the main thesis contributions emphasizing the core results and broader thesis conclusions are presented and discussed in Section 10.1. To finalize possible future work and open research directions are given in Section 10.2.

10.1 Conclusions

The aim of this thesis were twofold: a) to evaluate vehicular networks in realistic conditions and large-scale scenarios and b) to propose three systems enabled by vehicular communications and to evaluate its traffic and environmental performance, which correspond to the two main parts of the thesis. The main challenges closely associated with these goals that have been identified are the following, respectively,: a1) to create a simulation platform where network, traffic and environmental aspects are accurately modeled and tightly integrated; a2) to study how the performance of Cooperative Awareness in vehicular networks is influenced by real-world constraints and b1) to understand how the performance of a traffic light system influences the pollutant emissions from vehicles; b2) to build a distributed, dynamic and scalable ride-sharing system and to understand traffic, economic and environmental performance by simulation; b3) to design and to assess an automated parking system for (semi-) autonomous vehicles enabled by vehicular communications.

Part I of the thesis was devoted to the realistic and large-scale assessment of vehicular communications. The two main assessment methods that were presented and discussed were computer-based simulations and field operation trials, which have clear distinct features and consequently different advantages and drawbacks. In this section, we have presented an integrate simulation platform that combines traffic, network and energy & emissions models in combination with empirical data to realistic assess vehicular applications in large-scale scenarios. Additionally, we have presented how to accurately replicate the functioning of a taxi fleet also using empirical data. The presented platform is generic and thus can be easily adapted or extended to study a wide range of other ITS related applications. For instance, to study a novel application it would be only necessary to adapt (e.g. taxi model) or create a new application model. Regarding field operational trials, we have resorted to empirical data from the DRIVE-C2X project to study the performance of Cooperative Awareness of Vehicular Awareness in realistic scenarios and settings. By using novel metrics the advantages and disadvantages from the periodic broadcast of neighborhood awareness messages have been studied. In this study we concluded that that link layer and neighborhood awareness criterion can be fulfilled for safety applications at the cost of increased interference to distance vehicles for which the information might not be relevant. This result supports the feasibility of VTL enabled by the neighborhood awareness concept of VANET protocols.

In the second part of this thesis, we proposed and studied in detail three intelligent transportation systems enabled by short-range V2V communications (Virtual Traffic Lights, automated parking system) or by cellular communications (dynamic, distributed taxi-sharing). VTL is decentralized, self-organized and ubiquitous traffic control system with acyclic operation and where the traffic signal information is individually presented in each vehicle. In this thesis, we evaluated the impact of VTLs on Carbon Emissions Mitigation in a complex simulation framework, involving microscopic traffic, wireless communication and emission models. Compared with an approximation of the physical traffic light system in the city of Porto, our results have shown a significant reduction on CO_2 emissions when using VTLs, reaching nearly 20% under high-density traffic. The implementation of this system results in reduced congestion levels due to the optimized management of intersections and due to the maximization of the network throughput of the complete road network. Improved and smoother traffic flow lead to reduced stop-and-go phenomena that is associated with constant accelerations and deceleration that is one of the main causes of pollutant emissions. To conclude, the VTL system conducts to improved efficiency on road network utilization through a improved and smoother traffic flow, which results in improved environmental performance.

Further, in Part II of this thesis, we propounded a dynamic and distributed taxi-sharing system enabled by cellular communications. This system relies on positioning information, communication and distributed processing to achieve cooperation between vehicles and passengers, which results in shared trips for passengers with similar routes. In this thesis, we have also made a realistic and large-scale evaluation of the taxi-sharing system using an integrated simulation platform (application, microscopic traffic and emission models), including a realistic and accurate replication of the taxi operation in the city of Porto using empirical data. The assessment of this system has shown advantages for both passengers an taxi drivers mainly in terms of reduced fares, reduced travel total travel distance and improved operation costs. The study also demonstrated that the system performance improves with increasing system penetration rate and demand level. To conclude, the taxi-sharing system leads to more efficient and sustainable vehicle usage through increased vehicle occupancy and decreased total travel distance, which results in improved environmental performance.

Additionally, in Part II of this thesis, we proposed an automated parking systems for (semi-) autonomous vehicles enabled by V2V or V2I communications. This fully automated parking system relies on the cooperative movement of vehicles to create space for cars entering or exiting the parking lot. A controller, either a vehicle or a centralized node, gathers information on the current parking infrastructure state and calculates vehicles movements that allows access or exit of vehicles from densely occupied parking areas. The system assessment has shown advantages in terms of reduced parking area per vehicle and reduced total traveled distance for vehicles (up to 30% less) in this new parking lot paradigm when comparing with conventional parking lots.

10.2 Future Work

In each of the previous chapter we have already presented a number of future research directions. However, the open research directions there presented were closely related to the system under being proposed and evaluated. In this section we provide broader scope research directions in two main areas, namely application and system aspects.

ITS applications

- *Specific design for Greener Mobility:* The majority of related work provide environmental benefits solely as an indirect impact of the implementation of a given system. We argue that more emphasis should be given to the *specific* design of ITS fro green mobility. Thus, ITS should optimize directly environmental parameters or at least that these should have a key role in algorithm design.

- *Collaboration*: Several of the presented systems rely on cooperation for achieving their goals. As future work we foresee a shift to collaborative mobility where all actors (e.g. people, vehicles and infrastructure) build cooperative and participatory systems that rely on interaction to address common issues and goals.

- *Application integration*: With very few exceptions, ITS applications work in isolation and therefore interactions with other applications are not considered. We argue that the interaction or integration of multiple applications can create synergies that can then lead to improved performance, scalability and cost savings.

- *Macroscopic management*: Apart from considering microscopic ITS we argue that more emphasis should be put on studying macroscopic measures. Macroscopic measures, where the operation of the main players in vehicular mobility is coordinated by traffic management entities, can lead to improved performance in environmental terms but also better mobility and increased network throughput. By promoting a network approach, the overall system would improve since coordination could be achieved between participants. However, the design should also to find a balance between network performance and the performance of individuals.

System

- *Partial Deployment*: Several of the presented systems rely on high or full penetration rates for correct functioning, which is not a realistic scenario in a near future. Thus, strategies should be devised for applications to function in low/partial deployment scenarios. Furthermore, frequently it should be studied the impact of partial deployment on the overall system performance.

- *Fundamental limits*: A great number of papers in this area focus on the evaluation of use cases or study a limited part of the solution range. Due to this we argue that more importance should be given to understanding the system's or algorithms fundamental limits. Furthermore, the main bottlenecks or limitations ought to be studied in detail. For instance, it has not been fully demonstrated that the available or proposed technologies can meet the requirements of applications (e.g. intersection control management at dense urban areas).
- *Induced Demand*: This thesis has shown that significant mobility and environmental improvements can be attained through the deployment of several ITS. As mobility is improved more people can decide to use motorized transport who would not otherwise have done it. This induced mobility can lead to degraded performance in mobility and environmental terms under certain conditions. The relationship between between system improvements and induced performance needs to be carefully investigated in future research works (e.g. [165]).
- *Standardization*: Although the standardization of network aspects is well advanced there are still many opportunities for standardization in the higher layers of the protocol stack. Standardization of architectures, application requirements, interfaces, functions, messages and protocols creates compatibility, interoperability and quality assurance.
- *Network Heterogeneity*: In this thesis we have considered the use of short-range communications (e.g. 802.11p) or alternatively long-range communications (e.g. cellular). The combined usage of several networks can bring advantages to all parties. For instance, information dissemination mechanisms can be optimized when considering heterogeneous networks. In addition, intelligent selection or combined use of several communication technologies increases the reliability and can improve the QoS offered to applications.

Appendix A

List of Publications

A.1 Published Papers

A.1.1 Journal Papers [1–3]

In the following the list of peer-reviewed journal papers related to this thesis are given:

[1] Michel Ferreira and Pedro M. d'Orey. On the Impact of Virtual Traffic Lights on Carbon Emissions Mitigation. IEEE Transactions on Intelligent Transportation Systems, 13(1):284–295, Mar. 2012.
Abstract: Considering that the transport sector is responsible for an increasingly important share of current environmental problems, we look at Intelligent Transportation Systems (ITS) as a feasible means of helping in solving this issue. In particular, we evaluate the impact in terms of Carbon Dioxide (CO_2)emissions of Virtual Traffic Light (VTL), which is a recently proposed infrastructureless traffic control system solely based on Vehicle-to-Vehicle (V2V) communication. Our evaluation uses a real-city scenario in a complex simulation framework, involving microscopic traffic, wireless communication, and emission models. Compared with an approximation of the physical traffic light system deployed in the city, our results show a significant reduction on CO_2 emissions when using VTLs, reaching nearly 20% under high-density traffic.

[2] P. M. d'Orey and M. Ferreira. ITS for Sustainable Mobility: A Survey on Applications and Impact Assessment Tools. IEEE Transactions on Intelligent Transportation Systems, Dec. 2013.
Abstract: Road transportation is one of the main sources of greenhouse gas emissions, which lead to global warming and climate change. Promoting the decarbonization of this sector through more efficient and greener mobility is a challenging task that can be achieved by intelligent transportation systems (ITS) enabled by vehicular communications. In this paper, we briefly present how mobility players and enablers (driver, vehicle, and road network) influence energy consumption and pollutant emissions. Furthermore, this survey paper details how different ITS, ranging from eco-routing to intelligent intersection management, can lead to sustainable mobility by promoting a more efficient vehicle usage and enhanced efficiency on road network utilization. Results

shown that ITS has the potential to considerably reduce fuel consumption and pollutant emissions, namely, by smoothing the traffic flow, reducing the number of start–stops, and reducing the total travel distance. In addition, we present and analyze two main methods for evaluating green transportation systems: 1) field operational tests; and 2) simulation-based evaluations. We give special emphasis to simulation-based assessment of Green ITS measures by detailing the necessary models and their interactions. Finally, we propose a number of recommendations and future research directions in the area of Green ITS.

[3] P. M. d'Orey and M. Ferreira. Can Ride-Sharing become Attractive? A Case Study of Taxi- Sharing Employing a Simulation Modelling Approach. IET Intelligent Transport Systems, 2014. In Press.
Abstract: Improved urban mobility can be attained through more efficient vehicle usage and better road network utilization, namely through increased vehicle occupancy and new operation modes. In this paper we focus on a dynamic and distributed taxi-sharing system that takes advantage of nowadays widespread availability of communication and distributed computation to provide a cost-efficient, door-to-door and flexible service, offering a quality of service similar to conventional taxis. This system has been evaluated following a Simulation Modelling Approach, including a realistic and accurate replication of the taxi operation in the city of Porto using empirical data (real origin/destination data and average occupancy rates). Simulation results show improved performance in terms of reduced fares (up to 8%), reduced total travel distance (up to 9%) and smaller operation costs. Furthermore, we proposed that several trade-offs (e.g. service performance versus passengers' transit times) should be considered during the system deployment and operation. In the study it was also shown that increased system penetration rate and demand level can even further improve the system performance.

A.1.2 Conference Papers [4–8]

In the following the list of peer-reviewed conference papers related to this thesis are given:

[4] Pedro M. d'Orey, Ricardo Fernandes, and Michel Ferreira. Empirical Evaluation of a Dynamic and Distributed Taxi-Sharing System. In Proc. of IEEE Intelligent Transportation Systems Conference, Anchorage, AK, USA, Sep. 2012.
Abstract: Modern societies rely on efficient transportation systems for sustainable mobility. In this paper, we perform a large-scale and empirical evaluation of a dynamic and distributed taxi-sharing system. The novel system takes advantage of nowadays widespread availability of communication and computation to convey a cost-efficient, door-to-door and flexible system, offering a quality of service similar to traditional taxis. The shared taxi service is assessed in a real-city scenario using a highly realistic simulation platform. Simulation results have shown the system's advantages for both passengers and taxi drivers, and that trade-offs need to be considered. Compared with the

current taxi operation model, results show a increase of 48% on the average occupancy per traveled kilometer with a full deployment of the taxi-sharing system.

[5] Pedro M. d'Orey, Ricardo Fernandes, and Michel Ferreira. Reducing the Environmental Impact of Taxi Operation: the Taxi-sharing Use Case. In Proc. of 12th International Conference on ITS Telecommunications, Taipei, Taiwan, Nov. 2012.
Abstract: Considering the fast development of urban areas and the increasing environmental awareness, we focus in this paper on a taxi-sharing system for improving the efficiency of public transport. In particular, we present a realistic and large-scale evaluation of the environmental impact of this system. The proposed method improves the efficiency of this form of public transport by determining, on the fly, the best match between taxi user requests, which leads to a reduction of the total and vacant travel distance. Our results show important reductions of CO_2 emissions with full deployment of the system, reaching 9% under a higher demand scenario.

[6] Ricardo Fernandes, Pedro M. d'Orey, and Michel Ferreira. DIVERT for Realistic Simulation of Heterogeneous Vehicular Networks. In Proc. IEEE International Workshop on Intelligent Vehicular Networks, San Francisco, USA, 2010.
Abstract: Simulation of vehicular networks has been extensively studied in the last few years. In order to have an holistic view of the network functioning, communications and vehicle mobility aspects should be modeled in detail and fully integrated. This article presents a tool for simulating heterogeneous vehicular networks. The existing microscopic traffic simulator, DIVERT, has been extended by adding NS-3 support resulting in a very tightly integrated simulator. The feasibility of the approach has been tested by means of an application example: in-vehicle traffic lights. The provided results demonstrate the superior performance and the scalability of this novel simulator.

[7] Pedro M. d'Orey and Mate Boban. Empirical Evaluation of Cooperative Awareness in Vehicular Communications. In Proc. of IEEE Vehicular Technology Conference (VTC Fall), 2014.

Award: Best Paper Award

Abstract: Vehicular networks will enable a number of active safety and traffic efficiency applications. At the core of many of those applications is cooperative awareness: the ability to detect location, speed, and heading of surrounding vehicles. We empirically analyze three key metrics that shed light on the communication performance available to applications: 1) Packet Delivery Ratio: link quality in terms of the proportion of received messages over distance; 2) Neighborhood Awareness Ratio: the proportion of detected neighbors within a given distance, which serves as an indicator of the effectiveness of cooperative awareness message exchange; and 3) Neighborhood Interference Ratio: the proportion of neighbors above the desired range of interest, which can provide insight into the interference levels of fully deployed systems. By analyzing the measurement data collected within the scope of the DRIVE-C2X project, we conclude that the link layer delivery and neighborhood awareness criterion can be fulfilled for safety applications: in the analyzed datasets, the cooperative awareness ratio is close to 100% up to 100 meters. Depending on the desired region of interest, the interference from far-away vehicles can be considerable, thus requiring effective congestion control to balance between neighborhood awareness and interference.

[8] Michel Ferreira, Luıs Damas, Hugo Conceicao, Pedro M. d'Orey, Ricardo Fernandes, Peter Steenkiste, and Pedro Gomes. Self-Automated Parking Lots for Autonomous Vehicles based on Vehicular Ad Hoc Networking. In Proc. of the IEEE Intelligent Vehicles Symposium, Jun. 2014. In press.
Abstract: Parking is a major problem of car transportation, with important implications in traffic congestion and urban landscape. Reducing the space needed to park cars has led to the development of fully automated and mechanical parking systems. These systems are, however, limitedly deployed because of their construction and maintenance costs. Leveraging on semi and fully-autonomous vehicular technology, as well as on the electric propulsion paradigm and in vehicular ad hoc networking, we propose a new parking concept where the mobility of parked vehicles is managed by a parking lot controller to create space for cars entering or exiting the parking lot, in a collaborative manner. We show that the space needed to park such vehicles can be reduced to half the space needed with conventional parking lot designs. We also show that the total travelled distance of vehicles in this new parking lot paradigm can be 30% less than in conventional parking lots. Our proposal can have important consequences in parking costs and in urban landscape.

A.2 Pending Publications [9]

The following journal paper is currently being finalized :

[9] Pedro M. d'Orey and Mate Boban. Cooperative Awareness in Vehicular Networks. IEEE Transactions on Vehicular Technology, 2014.

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[1] Michel Ferreira and Pedro M. d'Orey. On the Impact of Virtual Traffic Lights on Carbon Emissions Mitigation. *IEEE Transactions on Intelligent Transportation Systems*, 13(1):284–295, Mar. 2012.

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[3] P. M. d'Orey and M. Ferreira. Can Ride-Sharing become Attractive? A Case Study of Taxi-Sharing Employing a Simulation Modelling Approach. *IET Intelligent Transport Systems*, 2014. In Press.

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[6] Ricardo Fernandes, Pedro M. d'Orey, and Michel Ferreira. DIVERT for Realistic Simulation of Heterogeneous Vehicular Networks. In *Proc. IEEE International Workshop on Intelligent Vehicular Networks*, San Francisco, USA, 2010.

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