UNIVERSIDADE FEDERAL DE SÃO JOÃO DEL-REI

Thiago da Silva Gomides

An Adaptive and Distributed Traffic Management System for Vehicular ad-hoc Networks

São João del-Rei

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Dissertação apresentada como requisito para obtenção do título de mestre em Ciências no Curso de Mestrado do Programa de Pós Graduação em Ciência da Computação da UFSJ.

Orientador: Daniel Ludovico Guidoni

Universidade Federal de São João del Rei – UFSJ

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This work is dedicated to everyone
who contributed in some way to making
that dream come true. Thank you very much!

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"Somewhere, something incredible
is waiting to be known"
(Carl Sagan)

Resumo

A capacidade da infraestrutura rodoviária e as interrupções temporárias nas viagens consistem nas principais razões por trás do fenômeno do engarrafamento. A urbanização e o crescimento das cidades intensificam ainda mais essas duas razões, por meio do aumento das áreas de trabalho e da demanda por mobilidade. Nesse cenário, vários problemas podem surgir, como altos custo de mobilidade, congestionamentos mais frequentes, danos ambientais significativos, prejuízos à qualidade de vida e aumento da poluição urbana. Assim, soluções tecnológicas para o congestionamento do tráfego, como *Traffic Management System (TMS)*, surgem como aplicações alternativas e fáceis de usar. Portanto, este trabalho apresenta o *ON*-DEMAND: An adaptive and Distributed Traffic Management System for VANETS. A solução proposta é baseada na comunicação V2V e na visão local do congestionamento do tráfego. Durante o deslocamento em uma estrada, o veículo monitora a distância percorrida e a esperada, considerando uma condição de tráfego de fluxo livre. A diferença entre essas medições é usada para classificar um fator de contenção, ou seja, a percepção do veículo nas condições de tráfego na estrada. Cada veículo usa o fator de contenção para classificar o nível geral de congestionamento e essas informações são disseminadas proativamente nas proximidades, considerando uma abordagem adaptativa. No caso de um veículo não possuir as informações de trânsito necessárias para estimar rotas alternativas, ele executa uma descoberta reativa de conhecimento de informações de trânsito. A solução proposta é comparada com três soluções da literatura, denominadas DIVERT, PANDORA e s-NRR. Nossos resultados mostraram que *ON*-DEMAND apresenta melhores resultados em relação às métricas de congestionamento de rede e tráfego.

Palavras-chaves: redes veiculares. sistemas de gerenciamento de tráfego. sistemas distribuidos.

Abstract

Road capacity infrastructure and temporary interruptions in trips consist of the main reasons behind the traffic jam phenomenon. City urbanization and growth further intensify these two reasons through the increase of work area and the demand for mobility. In such a scenario, several issues can emerge, such as higher mobility costs, more frequent traffic jams, more significant environmental damage, reduced quality of life, and more pollution. Thus, technological solutions for traffic congestion as Traffic Management Systems rise as alternative and easy-to-use applications. Therefore, this work presents a *ON*-DEMAND: An adaptive and Distributed Traffic Management System for VANETS. The proposed solution is based on V2V communication and the local view of traffic congestion. During its displacement in a road, the vehicle monitors its travelled distance and the expected one considering a free-flow traffic condition. The difference between these measurements is used to classify a contention factor, i.e., the vehicle perception on the road traffic condition. Each vehicle uses the contention factor to classify the overall congestion level and this information is proactively disseminated to its vicinity considering an adaptive approach. In the case a vehicle does not have the necessary traffic information to estimate alternative routes, it executes a reactive traffic information knowledge discovery. The proposed solution is compared with three literature solutions, named DIVERT, PANDORA and s-NRR. The performance evaluation shows that *ON*-DEMAND presents better results regarding network and traffic congestion metrics.

Key words: vehicular networks. vehicular traffic management systems. distributed systems

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List of abbreviations and acronyms

TMS	Traffic Management Systems
ATMS	Advanced Traffic Management Systems
VANETs	Vehicular Ad-hoc NETworks
ITS	Intelligent Transportation System
ACEA	European Automobile Manufacturers' Association
RSU	Road-Side Units
OBU	On-Board Unit
UN	United Nations
IEEE	Institute of Electrical and Electronics Engineers
DSRC	Dedicated Short-Range Communication
CALM	Communications access for land mobiles
ARIB	Association of Radio Industries and Businesses
ATIS	Advanced Traveller Information Systems
AVCS	Advanced Vehicle Control Systems
CVO	Commercial Vehicle Operations
APTS	Advanced Public Transportation Systems
ARTS	Advanced Rural Transportation Systems
ISO	International Organization for Standardization
I2I	Infrastructure-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-Everything
WAVE	Wireless Access in Vehicular Environments

LTE	Long-Term Evolution
3G	3rd generation of broadband cellular network
4G	4th generation of broadband cellular network
5G	5th generation of broadband cellular network
FCC	Federal Communications Commission
ETSI	European Telecommunications Standards Institute
CCH	Control Channel
SCH	Service Channel
Mbps	Megabits per second
BPSK	Binary Phase Shift Keying
QPSK	Quadrature Phase Shift Keying
QAM	Quadrature Amplitude Modulation
RM	Resource Manager
RCP	Resource Command Processor
WSMP	WAVE Short Message Protocol
IPv6	Internet Protocol version 6
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
POI	Points Of Interest
AU	Application Unity
VNS	Vehicular Navigation Systems
DSP	Dynamic Shortest Path
RKSP	Random K Shortest Paths
EBkSP	Entropy Based K Shortest Paths
DIVERT	A Distributed Vehicular Traffic Re-Routing
s-NRR	Static Next Road Rerouting

a-NRR	Adaptive Next Road Rerouting
RCs	Regional Computers
TOCs	Traffic Operation Centres
Re-Route	Vehicular Traffic Management Service based on Traffic Engineering for VANETs
ANN	Artificial Neural Network
INCIDEnt	INtelligent protocol of CongestIon DETection
PANDORA	Preventing trAffic congestioN through a fully-Distributed Rerouting Algorithm
HCM	Highway Capacity Manual
LOS	Level-of-Service
IMOB	Intelligent urban MOBility management
GPS	Global Positioning System
CO2	Carbon dioxide
SUMO	Simulation of Urban MObility
TD	Traveled Distance
ED	Expected Distance
ΔED	Variation of Expected Distance
ED_L	Lower limit for free-flow conditions
CF	Contention Factor
CL	Congestion Level
NCL	Number of Congestion Level
TTL	Time-to-live
IRR	Information Request-Response
OVMT	Original Vehicle Mobility Traffic
CO_2	Carbon dioxide
HBEFA	Handbook Emission Factors for Road Transport

LLTTL	Lower Limit Time-to-live
NTTL	Number of Time-to-live
NRD	ON-DEMAND Next Road Decision

List of symbols

$G = (V, E)$	Graph G composed by V and E.
V	Vertex set
E	Edges set
W	Weight set
v_i	Vertex i
e_{ij}	Edge between vertex i and j
w_{ij}	Cost to travel in e_{ij}
$\mathbb{R}_+^*$	Set of positive real numbers
ϕ	Ratio between distances $(\frac{Travelled\_Distance}{Expected\_Distance})$
t_i	Time in moment i
β	Maintenance threshold
$\in$	Is an element of
$\ni$	Is not an element of
$V_{max_{ij}}$	Maximum allowed velocity considering the edge e_{ij}
T	Maintenance timeout
$D_{max_{ij}}$	Road size considering the edge e_{ij}

Contents

1 Introduction

1.1 Introduction

Managing urban mobility is a major and recurring challenge in large cities (ACEA, 2016; DJAHEL, 2015; Xia, 2018). The United Nations (UN) classifies this challenge as one of 17 Goals to Transform Our World which, by 2030, will make cities more inclusive, safe, resilient and sustainable. However, the lack of investment in transport infrastructure distances urban centres from these ideal conditions. According to *The Future of Urban Mobility 2.0* study, 53% of the world's population was concentrated in urban centres in 2014 and, by 2050, a growth of 14% is expected. The study describes that this concentration is attributed mainly to the essential activities such as work, education, the search for better opportunities and quality of life (MABOGUNJE, 1970). The lack of an efficient urban planning accentuates the problems of mobility and contributes to the emergence of vehicular traffic congestion. The INRIX Research evaluates the direct and indirect cost of congestion in Europe, where the direct cost considers the fuel consumption and wasted time in traffic, and the indirect cost considers the cost of business. The study revealed that congestion cost in Europe will exceed 183 billion euros (COOKSON; PISHUE, 2016). Traffic congestion impact's people quality of life (COOKSON; PISHUE, 2018), making cities more stressful and less productive environments (EKBLAD, 1993).

The US Federal Highway Administration (SYSTEMATICS, 2005) considers a number of main sources for traffic congestion: traffic control devices, physical road capacity, traffic incidents, working and industrial zones, weather and traffic demand. The industrialization of countries increases the industrial zones, which has a impact on traffic incident and traffic demand. Changes in road infrastructure demand a complex urban mobility study, time and costs. To reduce these impacts, technological solutions rise as an easy to use solution with lower implementation costs and influence on people's lives.

An example of these solutions is the vehicular Traffic Management Systems (TMS) (SOUZA, 2017) (or Advanced Traffic Management Systems (ATMS)), which consider road and user characteristics for the creation of mechanisms capable of improving the utilization of the available road infrastructure. In general, a TMS assess vehicle movement conditions for traffic monitoring, performs congestion detection and suggests new routes to minimize congestion impacts (SHAHGHOLIAN; GHARAVIAN, 2018; Wang, 2018; SOUZA ALLAN M.; MAIA, 2018). A TMS may be implemented using Vehicular Ad-hoc Newtorks (VANETs) by using the capacity of a vehicle to monitor its displacement, perform computing and disseminate traffic information using vehicular communication (AHMED; GHARAVI, 2018). The TMS solutions can be divided in terms of communication infrastructure, where some solutions use a central server in order to have a global view of the traffic congestion (WANG, 2015; WANG, 2016; WANG, 2014; PAN, 2017), a decentralized Road Side Unit infrastructure (BRENNAND, 2017; LOURENçO, 2018) using Vehicle-to-Infrastructure (V2I) communication or a fully distributed solution using only Vehicle-to-Vehicle (V2V) communication (SOUZA, 2017; MENEGUETTE, 2016).

Considering the costs related to implement an infrastructure-based vehicular traffic management solution, this work proposes a fully distributed solution to perform traffic management in vehicular networks, named ON-DEMAND. The proposed TMS is based on vehicle's local observation in order to estimate the traffic condition. When a vehicle verifies signs of congestion during its route, it disseminates the observed traffic information using a V2V pro-active and adaptive information dissemination protocol. The vehicle considers the received traffic information and, when necessary, the vehicle verifies alternative routes with lower traffic congestion. If the vehicle does not have traffic information of neighbouring roads, it executes the reactive traffic information discovery protocol. As the proposed TMS is completely distributed and, due to the highly dynamic vehicular scenario, the pro-active information dissemination protocol has a communication module to preserve the road traffic estimation, named Knowledge maintenance. ON-DEMAND was compared to literature solutions, presenting better results related to network and traffic efficiency metrics.

1.2 Background

Improving the urban mobility of people is a key challenge faced by several countries. Usually, people choose individual transport rather than public ones, especially in cities where the public transport is not sufficient or widely distributed. This situation causes many reflections considering environmental and economic aspects. For instance, the congestion cost in the USA will exceed US$ 192 billion in 2020 (SCORECARD, 2015). Moreover, according to the World Health Organization (WHO), pollution caused by fossil fuels leads to the increase of diseases, such as lung cancer, heart disease, the number of strokes and the intensification of respiratory diseases (ORGANIZATION, 2006).

In order to reduce the traffic congestion and its impact, social changes are proposed due to the lower cost of implementation. However, alternatives such as plate rotation and the incentive to use public transport, specially in developing countries, are inefficient (LIU, 2019). In this context, the use of VNS (Vehicle Navigation System) has popularized in large urban centres, where a faster route is recommended without prior evaluation of the displacement context. Thus, VNS applications such as WAZE, Google Maps, INRIX, or Apple Maps are based on statistics predictions limited to the analysis of a set of characteristics in the reorganization of the vehicles, which may create a new congestion in other region or secondary path (THAI, 2016). In addition, these services depend on information collected in social networks, which may not represent the actual state of the road traffic conditions (SOUZA, 2017).

With the advancement of mobile communication, especially wireless technologies and on-board processing of vehicles, it is possible to develop an Intelligent Transport System (ITS) with the purpose of using inter-vehicle communication to solve various problems in traditional urban centres, such as reducing traffic jams, reducing vehicle travel time, reducing accidents and increasing road flow capacity (LANA, 2018). In order to implement an ITS, the Vehicle Ad-Hoc Networks define a set of communication services where a wireless ad-hoc network is created between vehicles (AHMED; GHARAVI, 2018; WU, 2015; DIETZEL, 2014). A distributed traffic management system can be created under the physical communication infrastructure of vehicles, where each vehicle monitors its perception of the condition of road traffic (average vehicle speed, number of cars within its communication range etc.) and disseminates this set of information to other vehicles (PISA, 2018; SOUZA, 2017). The purpose of this dissemination is the creation of a distributed knowledge about the road traffic conditions of a certain region. In this way, vehicles can find alternative routes to reduce congestion and, consequently, vehicles are able to reduce their travel time. The main challenge of traffic management is to modify vehicle routes without causing congestion in other regions of the city (SOUZA, 2017).

1.3 Objectives

The main objective of this thesis is to investigate characteristics, behaviours, and patterns adopted by vehicles in the urban scenario for designing and implementing a new TMS based on VANETs. Thereunto, the solution must face three common challenges in TMS development: traffic flow analysis, information sharing, and rerouting process. These processes allow reducing traffic jams by increasing the flow in urban centres. Moreover, the propose TMS must be able to work in a real-time way with low communication overhead. Besides, the specific objectives of this thesis are:

Objective 1 - Traffic flow analysis: Design a mechanism capable of measuring traffic flow in a vehicular network, considering the characteristics of each road segment, such as distance, maximum allowed speed and cost of travel in free-flow conditions. Thus, each vehicle can independently classify the quality of the flow during its journey. The flow classification must efficiently identify changes in displacement quality with a low response time.

Objective 2 - Information sharing Whenever traffic on road segment changes, vehicles need to share this knowledge with the neighbourhood to create a distributed database of traffic information. Thus, the second specific objective is to implement an efficient and reliable mechanism for sharing information that can provide sufficient knowledge with less communication overhead.

Objective 3 - Rerouting process Finally, implement a distributed algorithm to redirect vehicles to new routes with less congestion. Thus, each vehicle must consider the flow change information received and stored in its database to calculate a new route.

1.4 Contributions of this Thesis

This thesis is an evolutionary process that aims to cover all the proposed objectives. Initially, we investigated how to establish a mechanism to make efficient traffic measurements. The work (Gomides, 2019) published on *15th International Conference on Distributed Computing in Sensor Systems (DCOSS '19)*, introduces the Traffic flow analysis that consists of a novel technique to classify traffic based on the relation between the travelled and expected distances. Moreover, we introduce the study of how the size of knowledge affects route suggestions. At that time, we considered the knowledge on the first neighbourhood information sharing in (Gomides, 2019) on *XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - (SBRC '19)* and Next Road decisions (Gomides, 2019). These two solutions (Gomides, 2019; Gomides, 2019) share the same central idea, thus, the vehicles share their local street information to provide knowledge about traffic conditions, vehicles moving on adjacent streets receive such information to be used for the re-routing decision. The Traffic flow analysis keeps the same from the beginning and each paper introduces new concepts/models. The main improvement is the Information sharing module. Therefore, in (Gomides, 2020a; Gomides, 2020b; GOMIDES, 2020) the focus is to introduce multi-hop communication, a novel mechanism to manage the communication overhead and the proactive and reactive behaviours. Note that these improvements are part of this thesis and it will be described better on the follows chapters. In addition, the list of contributions is described below.

List of Contributions

The contributions and results of this Master's thesis were published at the following conferences:

- **1. GOMIDES, THIAGO. S.**; GUIDONI, DANIEL L. Protocolo de Roteamento de Veículos Fundamentado na Taxa de Ocupação da Via para Redes Veiculares. In: XXXVI Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2018, Campos do Jordão - SP. I Workshop for Scientific Initiation and Undergraduate Students.

- **2. GOMIDES, THIAGO S.**; FERNANDES, MASSILON L.; SUMIKA HOJO DE SOUZA, FERNANDA; VILLAS, LEANDRO; GUIDONI, DANIEL L.. FIRE-NRD: A Fully-Distributed and VANETs-based Traffic Management System for Next Road Decision. In: 2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS), 2019, Santorini Island. p. 554.

- **3. GOMIDES, THIAGO S.**; LOURENÇO, MASSILON; SOUZA, PEDRO; GUIDONI, DANIEL L.. SGTD: Sistema de Gerenciamento de Tráfego Distribuído para Redes Veiculares, In: XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2019, Gramado - RS.

- **4. GOMIDES, THIAGO S.**; DE GRANDE, ROBSON E.; SOUZA, FERNANDA S. H.; GUIDONI, DANIEL L.. Um Sistema Adaptativo e Colaborativo para Minimizar Congestionamentos utilizando Comunicação entre Veículos, In: XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2020.

- **5. GOMIDES, THIAGO S.**; DE GRANDE, ROBSON E.; SOUZA, FERNANDA S. H.; GUIDONI, DANIEL L.. RIDER: Proactive and Reactive Approach for Urban Traffic Management in Vehicular Networks, In: 2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS), 2020.

- **6. GOMIDES, THIAGO S.**; DE GRANDE, ROBSON E.; SOUZA, FERNANDA S. H.; GUIDONI, DANIEL L.. A Traffic Management System to Minimize Vehicle Congestion in Smart Cities, In: 2020 IEEE International Conference on Systems, Man, AND Cybernetics (IEEE SMC), 2020. **Submitted**

In parallel, the student has been participating as a co-author in other works as follows:

- **1.** LOURENÇO, MASSILON; **GOMIDES, THIAGO S.**; DE SOUZA, FERNANDA S. H.; MENEGUETTE, RODOLFO I.; GUIDONI, DANIEL L.. A Traffic Management Service Based on V2I Communication for Vehicular Ad-hoc Networks. In: the 10th Latin America Networking Conference, 2018, São Paulo.

- **2.** LOURENÇO, MASSILON; **GOMIDES, THIAGO S.**; DE SOUZA, Pedro; SILVA, CRISTIANO; Guidoni, Daniel L . Uma Solução Baseada em Infraestrutura

Auxiliar para o Problema de Gerenciamento de Tráfego em VANETs. In: XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2019, Gramado - RS.

- **3.** DE SOUZA, Pedro; LOURENÇO, MASSILON; **GOMIDES, THIAGO S.** ; DE SOUZA, FERNANDA S. H. ; SILVA, CRISTIANO ; GUIDONI, DANIEL L.. HyPER: Heurística de deposição de infraestruturas auxiliares para Redes Veiculares. In: XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2019, Gramado - RS. I Workshop for Scientific Initiation and Undergraduate Students.

- **4.** RESENDE, Júlio C. M.; SANTOS, André Felipe ; **GOMIDES, THIAGO S.**; LOURENÇO, MASSILON ; SCHIAVONI, F. L. ; LAIA, M. A. M. . O impacto das fragilidades da comunicação 802.11 em competições de robótica. In: XXXVII Brazilian Symposium on Computer Networks and Distributed Systems - SBRC, 2019, Gramado - RS. Connected Devices Cybersecurity Workshop. **(Extended abstract)**

- **5.** SOUZA, PEDRO ; LOURENÇO, MASSILON ; **GOMIDES, THIAGO S.** ; COSTA, G. ; DE SOUZA, FERNANDA S. H. ; SILVA, CRISTIANO ; GUIDONI, DANIEL L. . Planning the Deployment of QoS-based Communication Infrastructures for Connected Vehicles using GRASP and Path Relinking. In: IEEE LATINCOM (Latin-American Conference on Communications), 2019, Salvador. Proceedings of the IEEE LATINCOM, 2019.

In addition, this work was accepted to Elsevier Computer Communications (COMCOM) journal.

- **1. GOMIDES, T. S.** ;DE GRANDE. R. E. ;SOUZA A. M.; SOUZA, F. S. H.; VILLAS L. A.; GUIDONI D. L. An Adaptive and Distributed Traffic Management System for Vehicular ad-hoc Networks. Journal ELSEVIER Computer Communications (COMCOM).

1.5 Work organization

This thesis is organized into six chapters as follows. Chapter 2 shows the background used to develop this work, including ITS and VANETs overview, the communication features, challenges, characteristics and others. Chapter 3 introduces literature solutions for Traffic Management Systems, highlighting the difference between our solution and literature solutions. Chapter 4 presents the proposed solution including its System Overview and Design Principles in Section 4.1, and, the ON-DEMAND description in Section 4.2. ON-DEMAND has been divided into 4 sections as follows. The first section presents the Road Traffic Analysis, where vehicles can verify their displacement based on the relation between the distances. The next section shows the Proactive Information Dissemination mechanism used to share information when flow changes are detected. Section 4.2.3 presents the Reactive Knowledge Discovery that allows the vehicles to request information when necessary. Finally, Section 4.2.4 describes how vehicles should calculate their new routes after receiving/requesting traffic knowledge. Chapter 5 shows the experimental results used, including scenario description, simulation parameters and performance analysis, and finally, conclusions and future work are presented in Chapter 6.

2 Background

This chapter provides an overview of Intelligent Transportation System and VANETs, including basic concepts, architecture, aspects such as nodes mobility, the 802.11p communication standards, challenges and applications. Also, this chapter comprises two sections: ITS and VANETS, that is, from general to specific perspectives. In other words, the analysis begins with an explanation of the ITS systems that pass through the Advanced Traffic Management System to the Vehicular Networks. This process is a timeline that helps to understand how to implements technological solutions for traffic management.

2.1 Intelligent Transportation System

Intelligent Traffic Systems are a set of advanced applications that aim to provide innovative and sustainable systems to improve road safety, efficiency, comfort, and security for the transit in urban centres. ITS integrates users and road data, communication, sensors, advanced mathematical methods and computing to create high technology solutions and improvements (SUSSMAN, 2005). Figure 1[1] presents an example of some of the possible applications in the ITS field. It stands out that each application can work together or independently. Considers the goals of ITS, road safety applications can include Collision warning system, Lane-keeping assistance and Curve speed warning. Sustainable vehicles and traffic management can help to reduce environmental damage. The Navigation system, Cruise and traffic lights control can minimize the travel time. The next sections show a discussion of ITS with components, architecture and applications.

2.1.1 Architecture

Each country has different challenges to contemplate when designing ITS systems where culture, road structure, policies and other factors directly affect the definition of ITS architecture. Therefore, standardization defines the correct way of interaction between devices and components. The main proposed architectures include American, European and Japanese. American ITS Architecture (BOARD, 2004), defined by the U.S. Department of Transportation, describes a division into four classes that show how to established communication and roles between ITS elements and 22

[1] Retrieved from: www.iso.org/news/2015/06/Ref1976.html Accessed <19 March 2020>

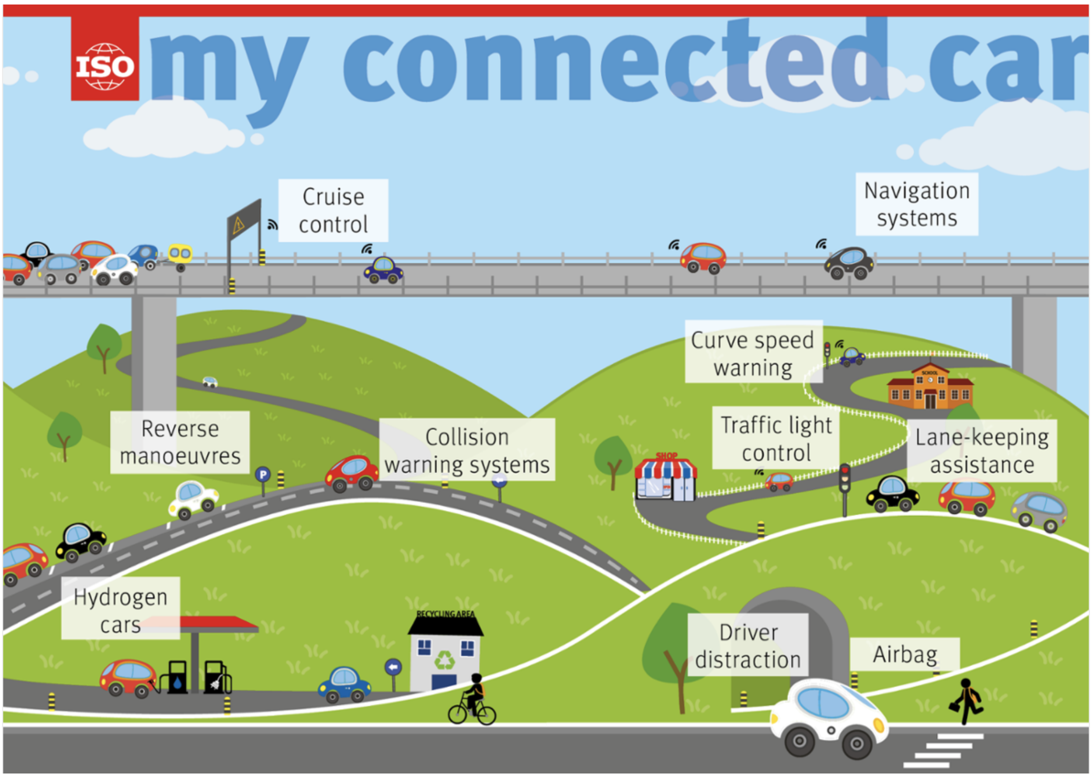


Figure 1 – ITS environment. ISO - MY CONNECTED CAR

subsystems. Figure 2 shows the division into four classes: Centers, Fields, Vehicles and Travellers. Centers define the control and management centres of the entire system and how to perform these services; Field that incorporates all the infrastructure part of the environment (RSU, monitoring sensors, cameras); Vehicle including vehicles and sensors; and the Travelers via devices used by people during the trip.

The project Smartway (LORCH, 2006) proposes the ITS architecture in Japan. The main characteristics incorporate communication between vehicles and between vehicles and the entire intelligent infrastructure of the roads (sensors, RSU, traffic lights) and use as the communication standard the Dedicated Short-Range Communication (DSRC) (Jiang, 2006), together with the proposed standard Association of Radio Industries and Businesses (ARIB) (similar to the WAVE protocol). European architecture (ITS ISO CALM) has similar characteristics with American and Japanese architectures with the use of RSU and DSRC communication implementations (ISO/TC 204 Intelligent transport systems, 2010). However, the major exception is the use of the communication protocol Communications access for land mobiles (CALM) that provides a communication interface between transmission technologies such as 3G/4G, WIFI, infrared, among others.

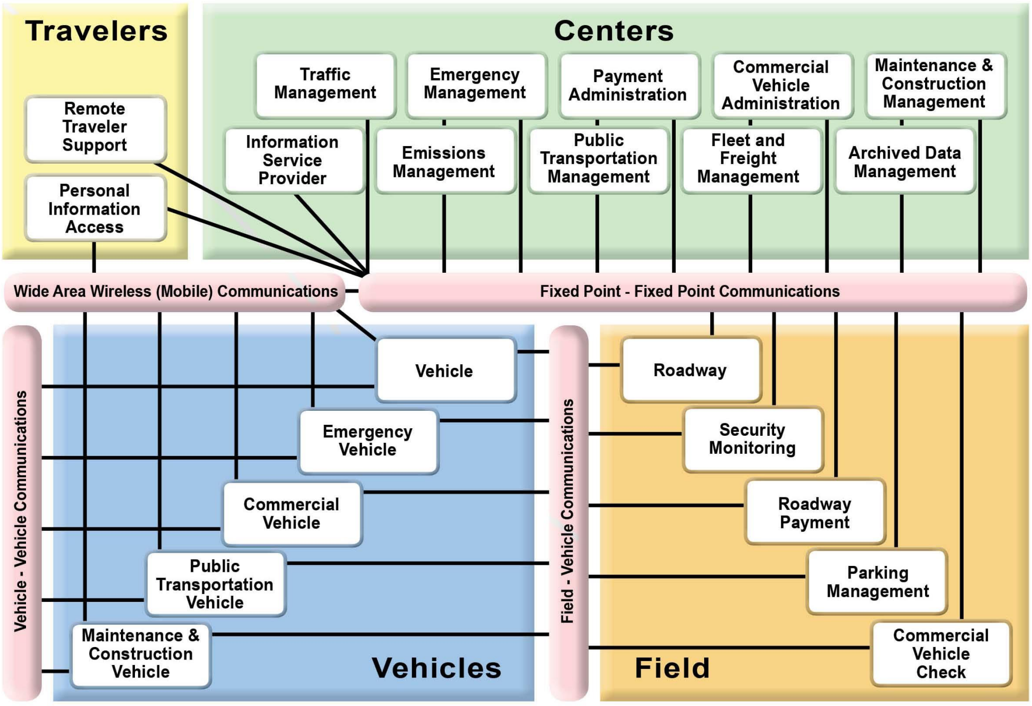


Figure 2 – USA National ITS Architecture (BOARD, 2004)

2.1.2 Components

The components of an ITS system consider two perspectives (SUSSMAN, 2000): Internal and External components. In this thesis, the Internal components refer to the system itself and External when the system works with the external environment.

Internal components

The internal components of an ITS assume three categories depending on their functionality. Thus, (i) the **Physical components** that make up the system, (ii) the **Operators** that make the system working and (iii) the **Operation plans** that allow managing the operation of the system.

Physical components includes city Infrastructure (including roads, terminals and stations), nodes as vehicles, equipment (including system accessories), the drive systems, fuels and location, control and communication systems.

Operators Work (performed by people); organized work (unions); system management (information and knowledge management); competition between transport and communications (evolution of communications that allow new ways of working and doing business while people travel); strategic planning (capital planning and investments in the transport area); operations management (system operation management); the tension between operations and marketing (customer/cost orientation); maintenance management (infrastructure and vehicles); operational research (analytical quantification of the system) and management of the transport system (similar to the management of a company).

Operation plans Scheduling plans (arrivals and departures); crew selection (for transport vehicles); flow distribution (traffic balancing); connection patterns (of roads and means of transport); negotiation of cost/service level (from the company's point of view); contingency planning (forecasting failures and ways to overcome them).

External components

The external components of a Transport System function represent the connection of the Transport System and the environment. This component includes the government (as the first entity promoting the transport system); competition (as a factor in the evolution of companies linked to the sector); the financial community (as a source of finance); the supplying industry (of infrastructure, vehicles and equipment); the shareholders; the general public and, finally, the customer.

2.1.3 Functional Areas in ITS

Due to the scope and possibility of developing solutions, ITS assumes different categories/areas. In (Nasim; Kassler, 2012) and (SUSSMAN, 2005) perspective it is useful to consider ITS systems in terms of six areas: Advanced Traffic Management Systems (ATMS), Advanced Traveller Information Systems (ATIS), Advanced Vehicle Control Systems (AVCS), Commercial Vehicle Operations (CVO), Advanced Public Transportation Systems (APTS) and Advanced Rural Transportation Systems (ARTS). These six categories derive from the ISO (International Organization for Standardization) taxonomy established for the referred applications or services to the ITS users (TRANSPORT, 1999).

Advanced Traffic Management Systems The ATMS aims to ensure the capacity of the road network is used to the maximum, i.e, to improve traffic conditions and thus provide a better quality of service. Thus, ATMS provides mechanisms capable of identifying traffic congestion and ways of calculating alternative routes for vehicles in regional areas in order to improve the efficiency of the road network and maintain priorities for public transportation. For this, real-time data is collected, used and disseminated by ATMS to alert transit operators about alternative routes. ATMS will respond in real-time to changed conditions in different domains (that is, traffic jams and accidents).

Advanced Traveller Information Systems ATIS systems aim to provide travellers with real-time information services on urban traffic conditions. In this way, it is possible to influence decision making, providing greater efficiency to the road network and transportation systems, achieving an ideal flow of vehicles and, reducing congestion and pollution levels. Some systems may provide guidance and assistance services in choosing alternative or ideal routes. ATISs form the basis for the transmission of traffic information between monitoring systems and the common traveller. With use, travellers can decide, at home, at work or anywhere else they are, on which road, mode of transport, route or even the most suitable time to reach their destination.

Advanced Vehicle Control Systems AVCS combines sensors, computers and controllers, both in vehicles and in road infrastructure, to alert and assist drivers (or possibly intervene) in driving the vehicle (DIRECTOR, 1995). The objectives of AVCS include improving driving safety, reducing congestion on urban roads, increasing the performance of the road network and creating new concepts for transportation services.

Commercial Vehicle Operations At CVO technologies, logistics companies such as private operators of trucks, vans and taxis adopt ITS technologies to improve the productivity of their routes and the efficiency of their operations.

Advanced Public Transportation Systems APTS applies new technologies for the operation of vehicles with a high occupancy rate. These technologies try to improve the accessibility of information to users of public transport and organize the scheduling of public transport vehicles and the use of bus fleets. Through the APTS, it is possible to provide a more flexible, efficient and secure service to guarantee customer satisfaction and control travel costs.

Advanced Rural Transportation Systems ARTS system aims to work on environments with less population density, hence with a smaller number of vehicles in circulation. ARTS reflects the rural areas as communities or areas with less than 50,000 inhabitants. Thus, the rural areas present particularities such as narrow roads, tight curves without visibility, reduced traffic signs, the mix of users (i.e., different types), fewer alternative routes and ways to establish communication compared to urban centres.

2.2 Vehicular Networks

Vehicular Ad Hoc Networks is defined as a branch of Mobile Ad Hoc Networks (MANETs) that has as the main objective the improvement of the safety and comfort for the passengers and drivers in traffic. Recently, many researchers emphasize their studies in VANETs (Pan, 2012; PAN, 2017; WANG, 2015; LOURENçO, 2018; BRENNAND, 2017; MENEGUETTE, 2016; WANG, 2015), mainly due to the correlation with recent and hot topics such as Smart Cities, Internet of Things, Mobile Cloud Computer, 5G, and others. However, in the 1980s, the VANETs potential was already the subject of discussions (HARTENSTEIN; LABERTEAUX, 2008). Thus, VANETs present several and specific characteristics compared to MANETs, e.g, its architecture, challenges, resources, and applications. The following sections present a brief discussion of VANETs, highlighting the main features of this technology.

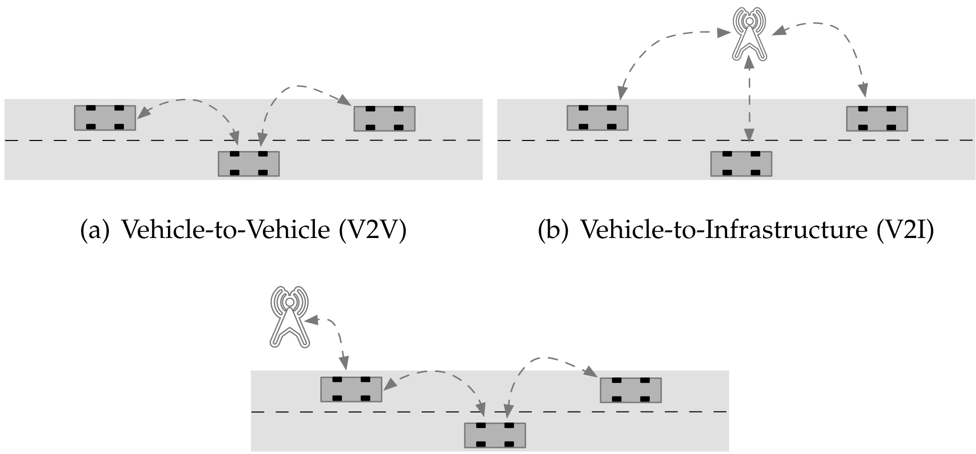
2.2.1 Components

VANET environment can be implemented from three main components, as described in (AL-SULTAN, 2014), these being: Application Unit - AU, On-board Unit - OBU and Road Side Unit - RSU.

On-board Unit The OBU device consists of a Resource Command Processor (RCP) whose main functions are to store and retrieve information, allow access from a user interface and a specific interface that allows connection to other OBUs and RSUs. The network interface present in each OBU is developed by IEEE WAVE 802.11p standards and technologies. Also, vehicles have a vast set of sensors that, when connected to the OBU, increase their ability to produce information.

Road Side Unit The RSU is a device connected to the side of roads, highways or streets. RSU, like OBU, implements IEEE WAVE 802.11p technology. Other technologies can be added, such as 802.11a/b/g/n, LTE and 5G wireless technologies or long-distance communication technologies, such as fiber optics. The role of RSU is to expand the communication range of VANETs and can serve as an access point or information distributor.

Application Unit AU is a device that interacts directly with vehicle drivers and passengers. AU uses the capabilities and resources offered by OBU to establish communication from one vehicle to another and to establish a connection with the resource provider, internet or RSU. The connection between the AU and the OBU can be established over a wired or wireless connection. In addition, AU can be a dedicated device for safety applications



(a) Vehicle-to-Vehicle (V2V) (b) Vehicle-to-Infrastructure (V2I)

(c) Hybrid

Figure 3 – VANET architectures

2.2.2 Architecture

The VANET architecture defines how each node can be organized considering the communication model. Thus, based on the architecture, the VANET environment can be described in three different models (AHMED; GHARAVI, 2018), namely: Vehicle-to-Vehicle, Vehicle-to-Infrastructure and Hybrid, shown in Figure 3 and described below:

Vehicle-to-Vehicle Illustrated in Figure 3(a), the V2V architecture, is defined by ad hoc aspects in which communication is performed only between vehicles without the need for auxiliary infrastructure (Karagiannis, 2011). Therefore, each vehicle has the responsibility to analyze, process and share the information with the network. Thus, to build a V2V network, only vehicles equipped with On-Board Unit are required, which reduces the cost of deploying the technology, however, due to high node mobility and low vehicle density in remote areas, disconnects can often occur.

Vehicle-to-Infrastructure V2I communication, presented in Figure 3(b), consists of vehicles and infrastructures called Road Side Unit, located along highways or city intersections. RSUs can centralize network traffic as intermediate communication nodes, or they can act as a gateway, allowing communication between 802.11p and the Internet (LI; WANG, 2007) or 5G (Ge, 2017), for example. Also, RSU can provide more processing and communication capability to the environment, helping to reduce network disconnections but increasing costs.

Hybrid The hybrid architecture combines V2I, V2V features to provide higher connection availability than V2V and lower cost compared to V2I, shown in Figure 3(c).

In addition, hybrid architecture can work in conjunction with cellular network technologies, e.g. LTE and 5G (Karagiannis, 2011). Thus, may communicate with the RSU considering one or more hops, for example, the RSU may provide 1-hop storage and processing capacity or a mechanism for establishing a connection between vehicles.

2.2.3 IEEE 802.11p standard

The IEEE 802.11p standard denominated Wireless Access in a Vehicular Environment (WAVE) is an IEEE 802.11 derived standard that defines how to establish communication in vehicular networks, adjusted for low overhead DSRC spectrum operations (Karagiannis, 2011). Dedicated Short-Range Communication is designed as a division of wireless communication channels that work between a short-range and medium-range communication spectrum for Intelligent Transportation System proposals. The DSRC is divided into 7 channels, each with a 10 MHz band allocated within the 75 MHz range of the 5.9 GHz frequency spectrum, as proposed by the United States Federal Communications Commission (FCC) in 1999. Besides, in Europe, the frequency used ranges from 5725 to 5875 MHz allocated by European Telecommunications Standards Institute (ETSI) and in Japan, it is being used in the 5.8 GHz band (SAHOO, 2014).

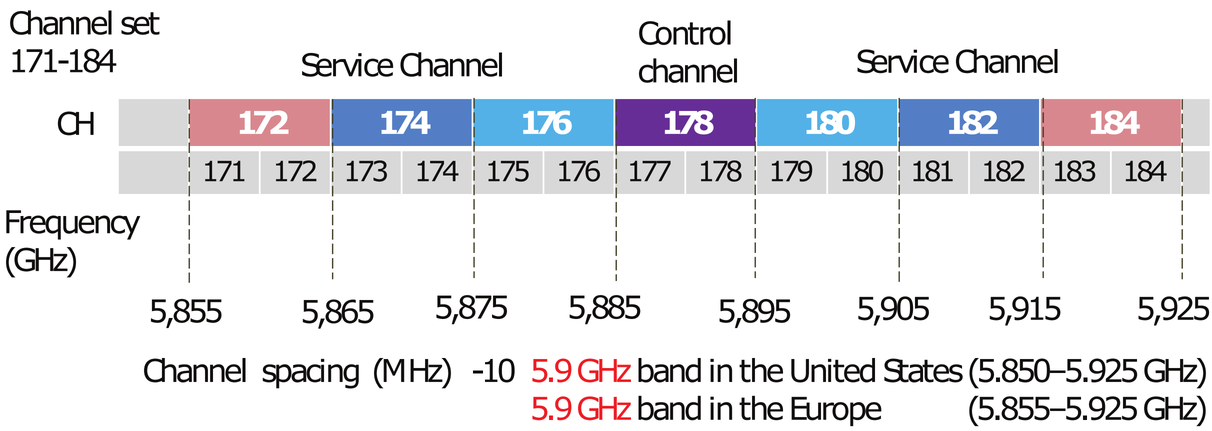


Figure 4 – Channels and frequencies available for IEEE 802.11p (SAHOO, 2014)

Each channel is defined to support different applications, as shown in Figure 4. The fourth channel of the DSRC band, channel 178, is reserved for the Control Channel (CCH), i.e, it is reserved for network management and control messages only. The first and seventh channels are used for special purposes and higher performance applications such as emergency on channel 172 and public safety channel 184. The rest of the channels are Service Channels (SCH) available for security and user applications.

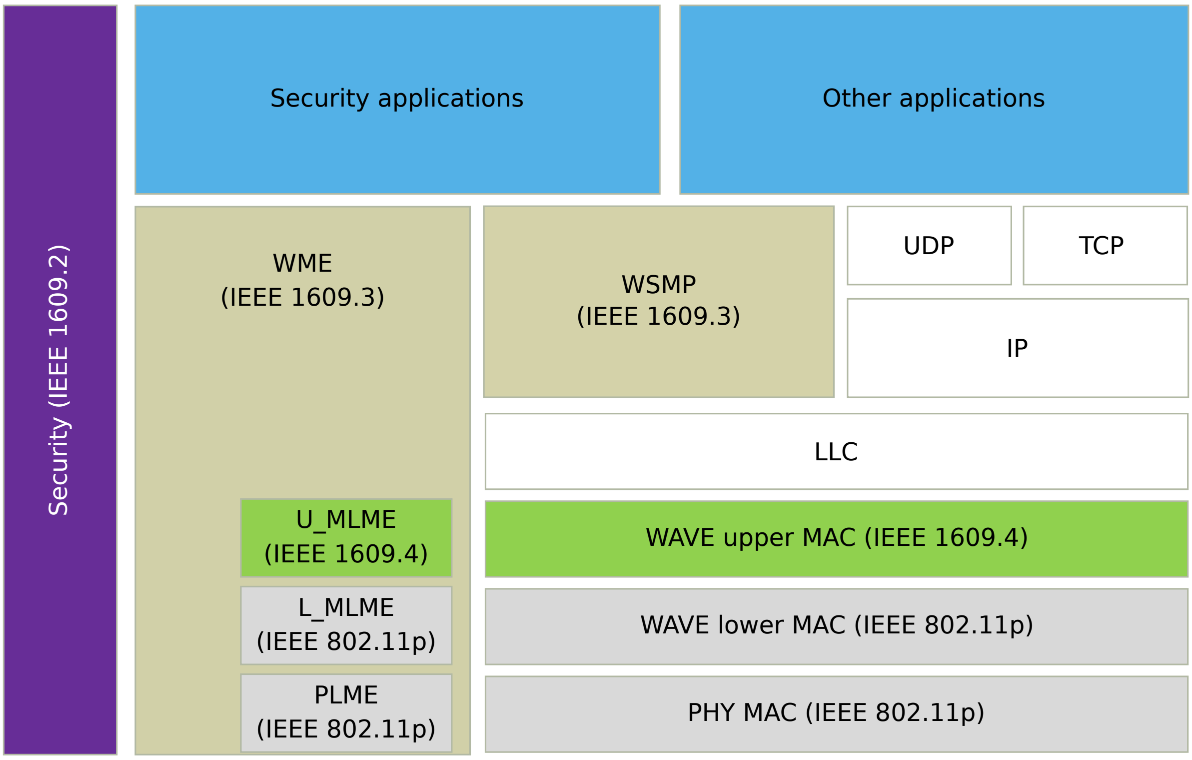


Figure 5 – WAVE Protocol Stack (ALVES, 2009) - **Adapted**

Therefore, the IEEE 802.11p standard defines improvements to the 802.11 standards required for Intelligent Transport System (ITS) applications. For example, WAVE communication enables information exchange between high-speed vehicles and the Road Side Unit. Thus, two physical layer adaptations were made to the IEEE 802.11 standard to support vehicular communication, being these: allows adjustments in (i) data transfers and, (ii) different modulations. Data transfers can assume the values: 3, 4.5, 6, 9, 12, 18, 24 e 27 Mbps (Megabits per second). The modulations can be Binary Phase Shift Keying (BPSK), Quadrature Phase Shift Keying (QPSK), 16 e 64 Quadrature Amplitude Modulation (QAM). At the data link layer, the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol is used as an access method (Jiang; Delgrossi, 2008).

2.2.4 WAVE architecture

The WAVE architecture is defined by the IEEE 1609 family standards in conjunction with IEEE 802.11 in six documents: IEEE P1609.1, IEEE P1609.2, IEEE P1609.3, IEEE P1609.4, IEEE 802.11, and IEEE 802.11p. These documents describe all layers of the WAVE protocol stack and its purpose. The key feature of the WAVE architecture is to facility V2V and V2I communications. Figure 5 introduces the WAVE protocol stack. As follows, we showed a brief description of the WAVE protocol documents.

IEEE P1609.0 IEEE 1609.0 is a WAVE architecture guide, i.e. ITS overview, its components, and operations. This document defines as IEEE 1609 standards and how multi-channel works together (IEEE-SA, 2019).

IEEE P1609.1 IEEE P1609.1 describes the Resource Manager (RM) capable of multiplexing communication between various vehicular network applications. The RM application runs on an RSU while the application Resource Command Processor (RCP), on an OBU. In addition, in IEEE 1609.1 some features of an OBU are specified (IEEE-SA, 2006).

IEEE P1609.2 IEEE 1609.2 (IEEE-SA, 2017) defines standards and security operations for vehicular networks, such as definitions of public key structures and certification authorities. In addition, the document defines formats of safety messages, Public Safety On-board units (PSOBUs) and Security Management, whose function is managing the certificate revocation list the root certificate.

IEEE P1609.3 IEEE P1609.3 proposes how network services work. The WAVE Short Message Protocol (WSMP) communication protocol is proposed as an alternative to the IPv6 protocol and can work with UDP and TCP. Due to low latency and for not being connection-oriented, WSMP is more efficient for the WAVE environment compared to UDP and TCP. IEEE P1609.3 is also responsible for defining how nodes are addressed and identified, and information sharing considering WAVE channels. More information about the pattern are available in (IEEE-SA, 2016).

IEEE P1609.4 The IEEE P1609.4 describes the multi-channel operations and synchronization on radio interfaces. Devices with radio interface only can monitor the control channel while using service channels by the synchronization module. Also, IEEE P1609.4 described as a layer enhancement MAC specified in the IEEE 802.11 standard (Chen, 2009).

IEEE P1609.5 (Draft) The IEEE 1609.5 standard describes switching between V2V communication and V2I communication services. Note that the default IEEE 1609.5 is under development being a draft (MEJRI, 2014).

IEEE P1609.11 The IEEE 1609.11 standard or Over-the-Air Data Exchange Standard Protocol for Intelligent Transportation Systems (ITS) defines secure services and messaging for the implementation of electronic payment services for DSRC (IEEE-SA, 2011).

2.2.5 Features

Vehicular networks share some characteristics of traditional mobile wireless networks, e.g, frequent changes in network topology, especially because of the mobility of nodes. However, the dynamics of the VANET nodes is particularly about the other branches of MANETs, a discussion about will be presented (OLARIU; WEIGLE, 2009). Table 1 highlights and compares the differences between the main features between MANETs and VANETs standards.

Mobility In traditional mobile ad hoc networks, nodes are not limited by topology and can move at random, i.e, which makes mobility unpredictable. However, in vehicular networks, the topology of the scenario is static and includes some elements such as streets, roads, traffic signs, and traffic lights, resulting in predictable mobility (LI; WANG, 2007; OLARIU; WEIGLE, 2009).

Density the density of the network in VANETs varies according to traffic, which can be very high during congestion or peak hours and very low in traffic in suburban areas (LI; WANG, 2007);

Power restrictions In MANETs, the power limitation is evident. However, vehicles equipped with long-life battery can supply continuous power for processing, storing, and communication (LI; WANG, 2007).

Dynamic topology The topology in VANETs undergoes rapid changes resulting from the high mobility of nodes. In addition, the connection time between vehicles is related to their positioning, such as the direction of travel and the power of the communication interfaces present in each vehicle.

Memory, Computing power and Communication capacity Nodes in VANETs can be equipped with an expressive number of sensors and computational resources, such as: processors, memories with large capacities, GPS. These resources increase the computational capacity of the node, which helps to obtain reliable communication and collect information regarding the current position, speed, and direction.

2.2.6 Applications

The process of integrating different technologies in auto-vehicles has been receiving incentives in recent years. This process results mainly from the development of Intelligent Transportation Systems (BAZZAN; KLÜGL, 2007). In this sense, the applications in VANETs can be divided into two different aspects (Jakubiak; Koucheryavy, 2008), namely: (i) Safety-related and (ii) Comfort-related (**commercial**).

Vehicular Ad-hoc Networks	vs.	Mobile Ad-hoc Networks
Costly	**The Production Cost**	Inexpensive
Frequent and very fast	**Network Topology Change**	Sluggish/Slow
High	**Mobility**	Low
Frequent Variable and Dense	**Density in Node**	Sparse
Thousands kps	**Bandwidth**	Hundred ops
Up to 600m	**Range**	Up to 100m
It is Depended on Vehicle Life Time	**Node Lifetime**	It is Depended on Power Source
High	**Reliability**	Medium
Regular	**Nodes Moving Pattern**	Random

Table 1 – VANETs *versus* MANETs (LOO, 2011) - **Adapted**

Safety-related

Safety-related applications can be grouped into **Assistance** (navigation, cooperative collision prevention, and lane change), **Information** (speed limit or work zone information) and **Warning** (post-accident, obstacle or road condition warnings) (Jakubiak; Koucheryavy, 2008). Usually, when emergencies happen the Safety-related applications must send notification packet which should be broadcasted to all vehicles on the highway.

Anti-collision system The main objective of this system is the management of crossroads. These systems can generally be implemented with V2V and V2I communications and induction loop sensors. Induction loops have the role of collecting flow data in each direction of the crossroads. This data is sent to traffic lights or road side units to check the probability of collisions. When the collision situations are detected, a collision message must be sent.

Public safety This type of system is developed to assists emergency service, i.e, police, fire-fighters or ambulances, to improve their services. Thus, applications in public safety can focus on minimizing the travel time of rescue teams to the accident site. Also, other applications are related to preventing secondary accidents through traffic management when an accident happens.

Navigation Assistance The purpose of this type of system is to keep the driver focused on traffic. Nowadays, with the evolution of the smartphone, wearable, and car's entertainment technologies, many drivers shift their attention to the devices while they are driving.

Diagnosis and maintenance of vehicles Application intended to alert the vehicle owners about a possible defect that could compromise his safety. For example, a recall from the concessionaire to exchange a defective part. In this application category, an infrastructure can send messages to vehicles that need to perform the repair.

Vehicles Information This category of application most often uses only communication between vehicles. Applications have the objective to alert neighbouring vehicles about events, for example, lane change, warning about the condition of the road and accidents.

Comfort-related

Comfort-related is considered applications that may improve user experience, e.g, Points Of Interest (POI) localization, current traffic or weather information, and interactive communication. In addition, online games, instant messaging and, applications which may run on top of TCP/IP stack (MARINESCU, 2018; Jakubiak; Koucheryavy, 2008). Some of the vehicle network applications in this category can be developed about P2P (Peer-to-peer) models (ALVES, 2009).

Data producer Vehicles are the only data sources in this type of application. Through OBU devices, vehicles can detect or collect data, this data can be images of traffic on streets, avenues and highways. Besides, with the data collected, the vehicles perform the processing and forward the extracted information, alerting to possible congestion and/or accidents.

Data consumer In this application category, vehicles are only data consumers. Content can range from multimedia files to information about road conditions. In this type of application, streaming movies, music applications and navigation stand out.

Data Producer/Consumer In this type of application, vehicles are producers and consumers of content. In this category, interactive applications such as online games and videoconferencing standout.

Vehicles as intermediaries All categories of applications need to use intermediate vehicles to carry out communication or forward messages. Therefore, the vehicles that provide communication support for other vehicles are the intermediate nodes.

2.3 Summary of the Chapter 2

Chapter 2 includes an overview of Intelligent Transportation System and Vehicular Networks technologies and features. Section 2.2 presents a VANETs introduction and, Section 2.2.1 and 2.2.2 introduces the architectures of the vehicular environment (V2V, V2I and, Hybrid). Section 2.2.3 exposes the communication standards, definitions of IEEE 802.11p and Section 2.2.4 shows a brief explanation about the WAVE protocol stack. Also, Sections 2.2.5 presents VANETs main features and a comparison with MANETs. Finally, Section 2.2.6 gives the division of application and VANETs characteristics.

3 Related Work

Considering the communication infrastructure, the vehicular traffic management systems can be divided into three approaches: (i) centralized, (ii) infrastructure based and (iii) distributed. In *centralized* solutions, vehicles receive alternative routes with lower traffic congestion, from a central server with a global traffic information view. These solutions demand a high communication cost (PAN, 2017; WANG, 2015). Vehicular Navigation Systems (VNS), such as Google Maps, INRIX, Waze and Apple Maps are also examples of centralized solutions. On the other hand, in *decentralized* solutions, Roadside Units (RSU) are deployed on the road in order to receive, process and disseminate traffic information and alternative routes. However, the use of RSU introduce an extra cost for the TMS (LOURENçO, 2018; BRENNAND, 2017; Lourenço, 2019). Finally, *distributed* solutions are based only on V2V communication. The vehicles, while moving, disseminate and receive traffic information in order to locally estimate alternative routes (SOUZA, 2017).

3.1 Centralized

VNS solutions are turn-by-turn and Global Positioning System (GPS) based applications developed for smartphones, car multimedia centres and, navigation systems. These applications became popular in the past few years with the popularization of GPS receiver and smartphones. Usually, the common features of VNS solutions are voice turn-by-turn navigation, real-time traffic information and safety alerts such as accident reports, traffic jams, road maintenance, and others. Some applications are collect information such as speed and geographical position and, periodically and anonymously, share this information to improve vehicle routes. However, as discussed before, these approaches can move the traffic jam for other regions or secondary path (THAI, 2016). Besides, some of the most common problems and complications of VNS include limited routing distance, calculation of the route based only on distance, limitations in supporting the smartphone model, navigation problems, and program failures in some physical locations[1,2,3].

In (Pan, 2012), the authors present a solution named Random k Shortest Path, which consists of a centralized TMS that uses the travel time of each road segment to calculate new routes. Periodically, the central server requests the travel time of each

[1] https://support.google.com/maps/threads?hl=en&thread_filter=(category:maps_directions)
[2] https://support.apple.com/kb/index?page=search&type=organic&src=support_searchbox_main
[3] https://discussions.tomtom.com/en

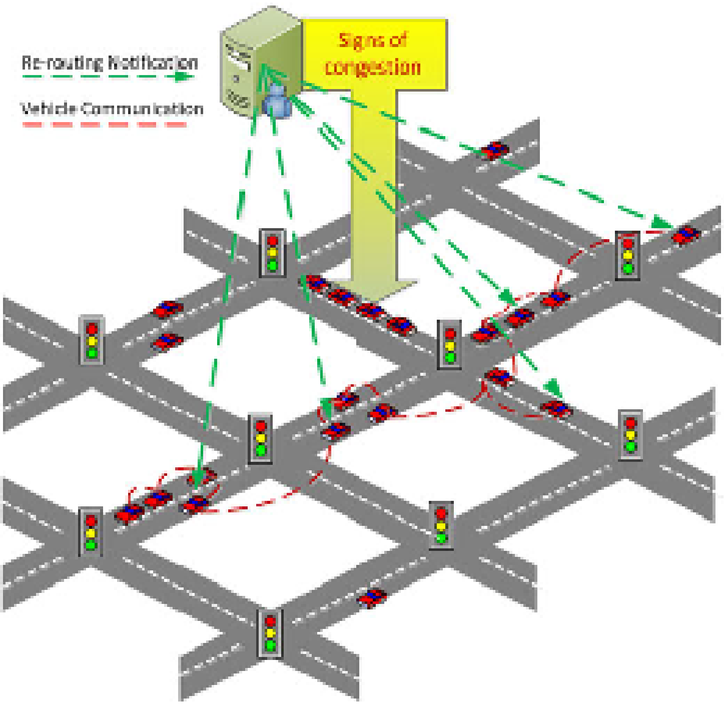


Figure 6 – DIVERT (PAN, 2017) overview

road segment for vehicles. The server analyzes the global traffic flow and forwards new lower-cost routes to the vehicles. For each vehicle, k alternative paths are calculated to achieve a more distributed flow of vehicles. When receiving the k paths, the vehicle chooses one of them at random. Moreover, the difference between the k-fastest routes and the k-slowest routes must not be higher than 20% to prevent a significant increase in travel time. The authors evolved R*k*SP to present DIVERT: A Distributed Vehicular Traffic Re-Routing System for Congestion Avoidance (PAN, 2017). DIVERT is a complete TMS with traffic analysis and data dissemination protocols, which is based on cellular communication between vehicles and the central server. Figure 6 shows the DIVERT overview. The data contains lane densities shares via a cellular network. The central server detects traffic jams with vehicle information and calculates new lower-cost routes. The central server supports the decisions in the DIVERT which makes the solution dependent. In case of server failure or overload, the protocol will have less efficiency. Besides, measure the overload of the cellular network is difficult due to different applications that can use it.

In (WANG, 2014; WANG, 2015; WANG, 2016), two architectures named (*Static - Next Road Rerouting*) and *a*-NRR (*Adaptive - Next Road Rerouting*) are presented as a re-routing service set based on heuristic strategies to choose the next most appropriate route. Aiming to obtain enough information to rearrange vehicular flows, in both proposals traffic conditions are frequently monitored by Traffic Operation Centres (TOCs), composed by: traffic lights (*s*-NRR) or Road-Side Unit (*a*-NRR). In this way, after detecting congestions or blocked roads, Regional Computers (RCs) are notified by TOCs about the observed events such that RCs can communicate to vehicles and define new routes when needed. In *s*-NRR architecture, when loop sensors detect traffic events, vehicles are notified by the server and request the best next road to the RSU, which considers its destination and the current traffic conditions. However, due to its static centralized processing, the reorganization is performed individually without any mechanism for load balancing. This strategy favours a shifting of the existing congestion to another point of the network. To overcome this limitation and provide a better distribution of the flows, the *a*-NRR architecture is able to analyze vehicular flows through V2I communication. By detecting congestion, the decision making is complemented with load balancing strategies for the new routes. Therefore, according to (WANG, 2015), the proposed solutions are able to reduce congestion with similar travel time results, which were also observed in our simulations. However, the flow detection mechanism works when the road is already blocked, which requires time for the solution to react. In other words, the system does not detect the evolution of traffic, only the obstruction. Also, the message exchange process is extensive.

In (Guidoni, 2020), the authors present a novel central-server vehicular traffic management system based on flow-density macroscopic traffic engineering methods. The proposed solution, named Re-RouTE, is divided into four modules: Location Information, Network Representation, Network Classification and Route Suggestion. Firstly, the Location Information module receives the speed and positions of all vehicles in the network. The Network Representation uses the collected data to create a weighted graph representing the city map. The Network Classification module applies traffic engineering theory and concepts in order to verify traffic congestion. The result of this process is a knowledge that describes if the road segments have traffic jams and its intensity. Periodically and using the Route Suggestion module, the system sends lower-costs routes for each vehicle.

3.2 Infrastructure based

Infrastructure/decentralized solutions deploy RSUs to decentralize the possible tasks of a central server. Thus, the tasks of receiving and processing data, classifying congestion and others can be performed by the RSU. Also, RSU can increase the connection of vehicle networks and can be used to keep data close to the required location.

In (BRENNAND, 2017), the authors propose a fog computing approach to decentralize processing and storage of traffic information. Named FOg Route VEhiculaR – FOREVER, this solution uses a publish-subscribe method for information dissemination between infrastructures and vehicles. Figure 7 illustrates an overview of the FOREVER approach. In orange, the communication radius of the infrastructure is shown and, in yellow, the knowledge area. Therefore, each infrastructure controls a coverage region within its communication radius, orange region . However, FOREVER implements a mechanism that allows RSU to share pieces of information between them, yellow region. Finally, the protocols implement a turn-by-turn rerouting, i.e., when necessary, vehicles ask RSU new lower-cost routes.

A decentralized routing protocol called *Fast Offset Xpath* (FOX) is implemented in (BRENNAND, 2019) on a fog computing environment for information storage and processing tasks. This model is based on the geographical distribution of *Road-Side Unit* (RSU) with wireless communication and processing capabilities. In order to deploy the RSUs, the city is divided into regions of the same size, providing full communication coverage by locating one RSU in each region. FOX considers each vehicle constantly notifies its corresponding RSU about traffic conditions observed inside its region as well as periodically requests alternative routes with lower travel times. Thereby, each RSU, provided with information regarding its area of knowledge, analyzes the existence of less congested routes through the k-shortest path algorithm with the probabilistic Boltzmann distribution, later, notifies the vehicles with the best options. According to the authors, FOX provides an approximation of resources to end-users, reducing the response time and the complexity of the information maintenance of the routes. In this solution, the information is stored and processed by the RSU and the cars must calculate new routes. Besides, RSU stores information only from the first neighbourhood. It is noteworthy that due to the cost and processing power of each RSU, information storage could consider larger regions, which does not happen.

The authors in (Barba, 2012) propose a decentralized smart city framework based on Intelligent Traffic Lights (ITLs) management. The ITL framework uses warning messages composed of traffic density and weather conditions in order to help drivers to make better and safer decisions. The goal of the traffic density information is to collect traffic statistics from the vehicle during their displacement, thus, providing local and global traffic knowledge. The weather conditions information is used in the central server in order to detect and send alerts when accidents happen. The vehicles notify their positions to the system every 2 seconds, where the system is able to calculate the density of each road segment.

In (ZAMBRANO-MARTINEZ, 2019), the authors proposed an approach for traffic flow prediction based on the integration of a central server with autonomous vehicles. The goal of this work is to create a planning system that can provide time-dependent route recommendations inspired by traffic congestion history. Thus, the system executing in a central server collects and processes the traffic data and, when necessary, sends to each vehicle a route recommendation considering a traffic balancing.

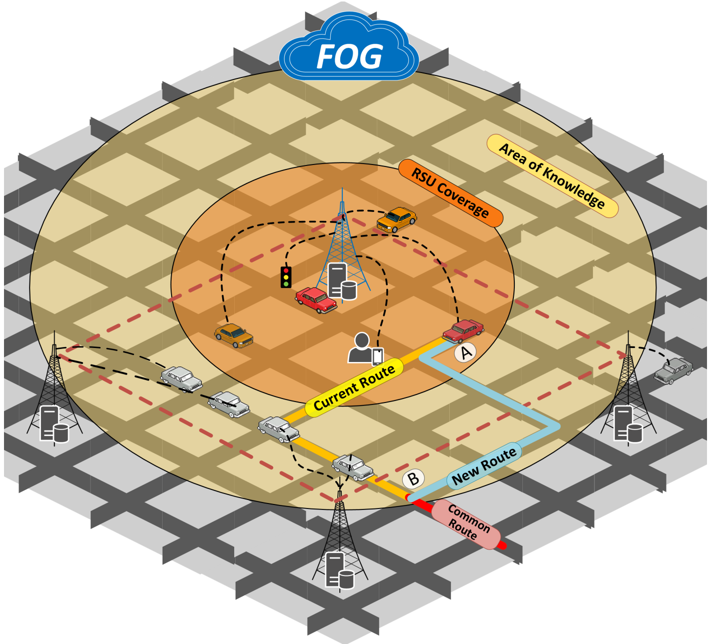


Figure 7 – FOX (BRENNAND, 2019) and FOREVER (BRENNAND, 2017) overview

The system uses real-time feedback from the traffic data collected from the induction loops deployed on the streets of Valencia, Spain. The used induction loops allow the system to be more reliable regarding possible inaccurate of GPS measurements. The proposed framework works with dynamic information of traffic congestion or unexpected events, which does not happen in conventional VNS.

In (Lourenço, 2019), the authors propose DESTINy – DEcentralized System for Traffic Management, a TMS based in V2V and V2I communication models. In DESTINy, the traffic knowledge id stored by the RSUs. Differently from FOX or FOREVER (in which alternative routes are calculated by the RSUs), vehicles executing DESTINy are able to estimate their own routes. To simulate real-world features, the deployment of RSUs does not follow a specific pattern with the same area of coverage. Moreover, the vehicles use V2V communication to exchange messages aiming to reach the RSU and update its traffic knowledge database. The database contains the travel time information of all neighbouring roads and, when necessary, the vehicles execute an Information Request-Response protocol to receive the road travel time. After receiving the travel time information, the vehicle uses a shortest travel-time path algorithm to find alternative routes. To minimize the number of information requests, when a vehicle forwards an Information Request-Response message, it can update its knowledge. For that, it verifies if the message contains travel time information of neighbouring roads and, in this case, it can suppress new requests.

3.3 Distributed

In (SOUZA, 2017), a fully distributed TMS called PANDORA – Preventing trAffic congestioN through a fully-Distributed Rerouting Algorithm, is proposed. PANDORA considers the opportunistic knowledge dissemination using Vehicle-to-Vehicle communication (V2V), and is able to minimize the communication overload due to a model of floating content and Geo-located traffic information in critical areas. The critical area defines the region where the TMS should be execute to decrease traffic congestion. For that, the critical area is divided into sub-regions, and vehicles moving in a specific sub-region receive the travel time of all roads within it. The system uses critical regions where each region consists of a central point and a radius r_a that that area occupies. Initially, the algorithm creates a floating content over a critical region. This content is a graph that covers this entire region. When a vehicle verifies that it is leaving a critical region, it maintains the message that is the area of the pass r_f being $r_f > r_a$. The vehicle can pass a message when it hears a periodic message from another vehicle within the critical area or the forwarding area. Using a one-second beacon interval, vehicles share their geographic locations and speeds to all vehicles inside the sub-region in order to classify the vehicular displacement. Considering the received information and based on Level-of-Service (LOS) proposed in Highway Capacity Manual (HCM) (TRB, 2010; SCHROEDER, 2016), vehicles estimate alternative routes with lower travel time. An important parameter of PANDORA is the definition of the critical area, due to its impact on the number of transmitted messages to execute the vehicular traffic management solution.

Based on Artificial Neural Network (ANN) classification, a solution named INtelligent protocol of CongestIon DETection (INCIDEnt) is proposed in (MENEGUETTE, 2016). In this approach, ANN is responsible for detecting and classifying traffic jams on the road segments. The ANN core has two types of neurons, two inputs and one output. Thus, for the congestion classification, the ANN considers in the input neuron the speed and road segment density of vehicles, while the output neuron is the traffic classification which may assume values between 0 and 1. Value 0 represents free-flow conditions and 1 is an extreme traffic jam condition. Periodically, vehicles classify the traffic contention of the current and next segment roads and share this information with their neighbours. Thereafter, vehicles request and calculate routes with lower traffic contention using the received information.

The Intelligent urban MOBility management (IMOB) (Akabane, 2018) is a TMS for traffic improvement in urban centres multi-layer and based on vehicle social networks. Thus, divided into three layers, the first layer is responsible for participatory sensing, which uses a periodic message approach. The information into the first layer carries vehicle data such as current speed, geolocation, timestamp and the classification of each vehicle. Two factors are considering the use of the influence of the node in diffusing information and the second the quality of the transmission link. In other words, a formula classifies vehicles by influence level on the network and the communication interference. Thus, the best-rated vehicle is responsible for sending data to its neighbourhood. Upon receiving the data, the vehicle stores and broadcasts the measured information. The nodes most adjacent to the traffic jams calculate first a new route in a collaborative process.

The authors in (LI, 2018) present a region-based communication framework for vehicular networks. The proposed solution, also, can reduce intersections traffic jams. Voronoi diagram determines each region on the system and, the V2V architecture establishes protocol communication. Thus, traffic management uses a Saturation Degree of Lanes (SDL) solution to measure the conditions of the flow in each lane with granulated information based on POV. The scenario presents vehicles without OBU resources, which cannot share data and, the Vague set theory tries to minimize the lack of information. This work can effectively improve the ability to detect and avoiding traffic congestions. The performance of the proposed framework shows better results with common approaches adopted in existing maps and routing protocols.

3.4 Summary of the Chapter 3

Chapter 3 presented a literature overview classified into three groups, being these, centralized, decentralized and, distributed solutions. Section 3.1 highlights the centralized solutions, especially, a brief explanation about VNS, the more diffused systems, for traffic management. Section 3.2 focus on the decentralized solutions which use a combination of cars and RSUs to storage and process information. Section 3.3 exposes the closest solutions with ON-DEMAND, distributed solutions. The presented solutions in this chapter can minimize traffic jams with the process of classification, dissemination and reroute guidance. Table 2 illustrates a detailed comparison among literature vehicular Traffic Management Solutions. The quantitative analysis considers the communication architecture, challenges, behaviour, traffic view and, vehicle rerouting. Communication architecture divides the literature review in centralized, infrastructure-based and distributed. Network challenges consider aspects as the capacity to reduce broadcast storm problems, protocol ability to detect lack of information and, control of information overload. Also, the behaviour means the way as the Traffic Management System performs the knowledge dissemination, i.e., if the TMS only shares knowledge or is able further to request when necessary. Traffic View determines the considered area of knowledge to calculate new routes. Finally, the features section compares some aspects as request-response methods, real-time versus periodical decisions and, if the protocol works in a region-based way.

	Architecture			Network Challenges			Behavior		Traffic View			Features			
Relative Work	**Centralized**	**Distributed**	**Infrastructure based**	**Broadcast storm**	**Knowledge insufficiency**	**Overload control**	**Proactive**	**Reactive**	**Local**	**Global**	**Adaptive**	**Information Request-Response**	**Real-time decisions**	**Periodical decisions**	**Region-based**
VNS	✓						✓			✓					
RkSP (Pan, 2012)	✓						✓			✓				✓	
DIVERT (PAN, 2017)	✓						✓			✓				✓	
s-NRR (WANG, 2014)	✓							✓		✓			✓		
a-NRR (WANG, 2015)	✓							✓		✓			✓		
Re-RouTE (Guidoni, 2020)	✓							✓		✓			✓		
FOX (BRENNAND, 2019)			✓	✓			✓		✓					✓	✓
FOREVER (BRENNAND, 2017)			✓	✓			✓				✓			✓	✓
Barba et. al (Barba, 2012)			✓					✓			✓		✓		✓
ABATIS (ZAMBRANO-MARTINEZ, 2019)			✓					✓			✓		✓		✓
DESTINy (LOURENçO, 2018)			✓	✓	✓	✓		✓	✓			✓		✓	✓
INCIDEnt (MENEGUETTE, 2016)		✓		✓		✓	✓		✓				✓		
iMOB (Akabane, 2018)		✓		✓		✓	✓				✓			✓	
LI et. al (LI, 2018)		✓		✓		✓	✓				✓			✓	✓
PANDORA (SOUZA, 2017)		✓		✓		✓	✓				✓			✓	✓
ON-DEMAND		✓		✓	✓	✓	✓	✓			✓	✓	✓		

Table 2 – Quantitative analysis of literature TMS solutions

4 ON-DEMAND – An Adaptive and Distributed Traffic Management System for Vehicular adhoc Networks

4.1 System Overview

The proposed system establishes minimum synchronization overhead through distributed decision-making and assumes independent computing-capable vehicles.

4.1.1 Design Principles

Two main principles define the *ON*-DEMAND vehicular traffic management system. First, the system should allow vehicles to compute their paths/routes independently and using just local information. In this case, there is no need for a central entity that provides a global view of the traffic conditions in a whole urban region. Vehicles using only neighbourhood information should be able to find alternative paths collaboratively to achieve a better re-routing process. Second, local V2V should be the primary communication methodology for generating a distributed database of traffic information. Thus, in addition to a central-serverless feature, there is no requirement for Road Side Units to manage the local and distributed information about traffic conditions.

Figure 8 – *ON*-DEMAND system

In this work, the proposed underlying system consists of a series of mechanisms, protocols and modules to implement fully-distributed vehicular traffic management. The system should allow vehicles to evaluate their routes, also named paths in this work, to share their local perception of the traffic in a collaborative way, and to find alternative routes using their local information. Figure 8 shows the system overview and fundamental design principles. Vehicles share their local traffic observations using V2V communication. The blue vehicle, when receiving a new traffic information message, can find an alternative path without a traffic jam, which is represented by the green line. Besides our solution being able to find new routes, it also prevents vehicles from becoming congested when possible. In our work, vehicle displacement, or travelled distance, asserts local observations in a road segment.

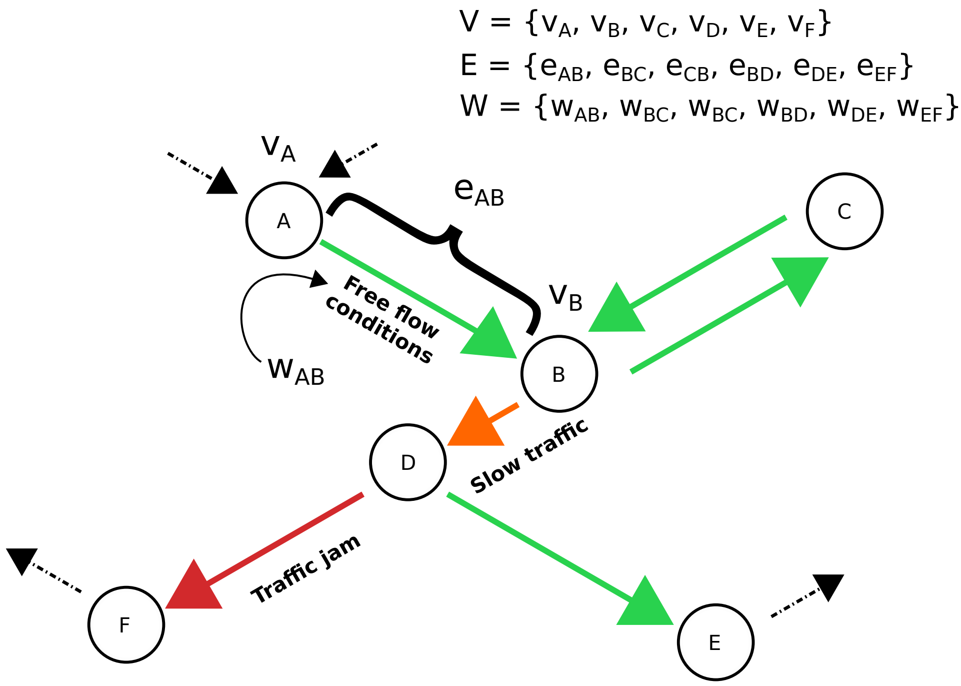


Figure 9 – City (Figure 8) represented as a graph G = (V, E). The colours red and green represent traffic jams and free flow conditions, respectively.

4.1.2 System Architecture

The operation of our proposed TMS considers the dynamic characteristics of an urban traffic environment as described below:

Definition 4.1.1. *Let the VANET environment be defined as a directed and weighted graph* $G = (V, E)$, *where* $V = \{v_0, v_1, \ldots, v_n\}$ *is the set of vertices and* $E \subseteq \{e_{ij} = (v_i, v_j) \mid (v_i, v_j) \in V^2 \land v_i \neq v_j\}$ *is the set of edges (also called directed edges, directed links, directed lines, arrows or arcs) which are ordered pairs of distinct vertices. The set of edges represents the road segments (road between two intersections) and the set of vertices represents the city map intersections. Thus, each edge* $e_{ij} = (v_i, v_j)$ *represents the road segment* e_{ij} *connecting the*

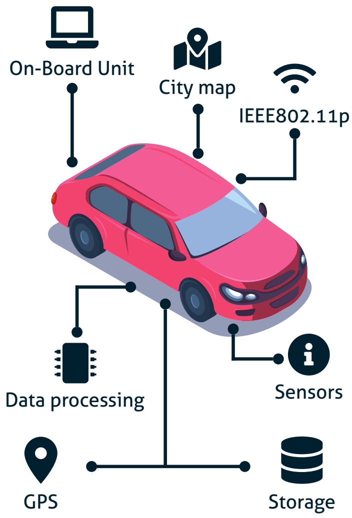


Figure 10 – Vehicle features

intersection i and j with an associated cost w_{ij}, which represents the cost of traversing it in travel time terms. The set of weight can be represent by $W = \{w_{ij}, i \neq j\}$ and $w_{ij} \to \mathbb{R}^*_+$.

Each vehicle in our VANET environment is capable of processing, analyzing, communicating and making distributed decisions. For this, as shown in the Figure 10, all vehicles are equipped with: On-Board Unit, IEEE 802.11p communication interface, several sensors types, Global Position System receiver and the road map with the city characteristics. The city map in the vehicles is represented by $G = (V, E)$, and Figure 9 illustrates an example related to roads in Figure 8. In addition, the map contains some roads segment definitions, such as dimensions, number of lanes, traffic lights positions, and maximum allowed speed.

4.2 Proposed Traffic Management System

The proposed Vehicular Traffic Management System, named ***ON*-DEMAND**, is divided into three steps. The first step comprises the (i) Road Traffic Analysis, where each vehicle determines the level of contention/congestion of all roads of its path. The second step consists of a (ii) Communication Model, where each vehicle verifies if the estimated level of contention should be disseminated to its neighbours. The communication model also contains a module of traffic information discovery, which is executed when the vehicle does not have traffic information related to its vicinity. The third step refers to (iii) Rerouting, where each vehicle calculates alternative routes considering the received traffic information.

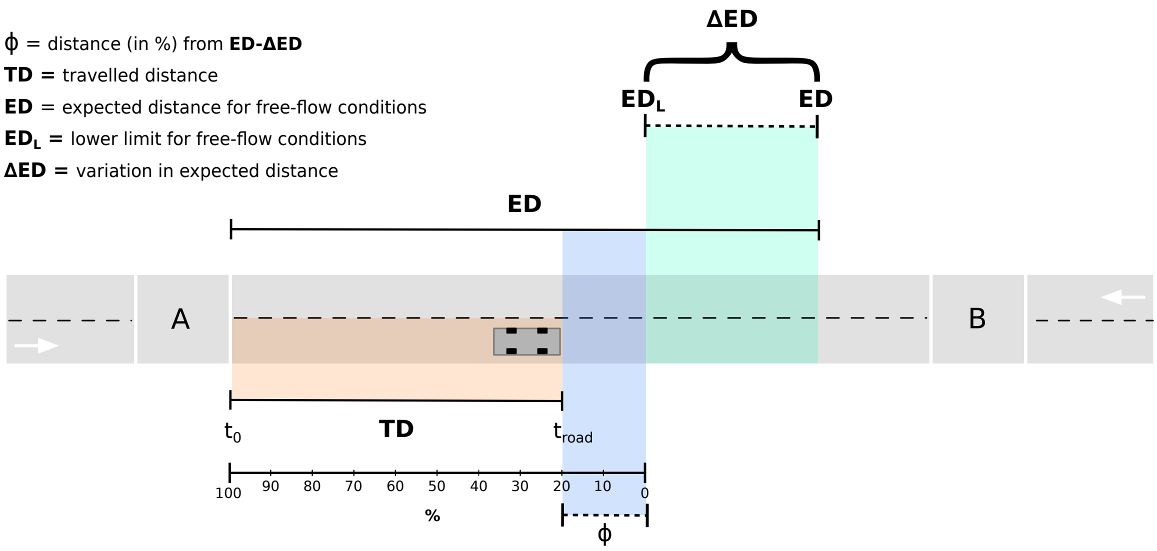


Figure 11 – Displacement analysis within a road segment

4.2.1 Road Traffic Analysis

The road traffic analysis is used to verify the condition of a road, more particularly its traffic congestion. During its route, each vehicle evaluates its displacement in terms of **Travelled Distance (TD)** considering the road segment the vehicle travels and the related time spent to achieve the spatial progress. These values are compared to the expected displacement considering a free-flow condition. Our model considers the **Expected Distance (ED)** traversed following the maximum allowed road speed. This analysis is estimated according to Equation 4.1:

$$\phi = 1 - \frac{TD}{ED_L} = 1 - \frac{TD}{(v_{road_L} \times t_{road})} \tag{4.1}$$

where v_{road_L} is the lower limit for allowed road speed, t_{road} is the elapsed time for the verified displacement, and ϕ is the relation between the distances. ϕ may take positive and negative values. The positive values of ϕ measures the difference between the evaluated distances as percentages and ranges between $[0, 1]$, where $0 \rightarrow 0\%$ and $1 \rightarrow 100\%$. On the other hand, the negative values of ϕ originate from having TD larger than ED. The negative ϕ represents when the vehicle displacement demonstrates a free-flow movement, where the vehicle speed exceeds the allowed road speed. Note that the greater the positive difference between TD and ED, the worse the conditions of the displacement is. This relation is defined since the vehicle is far from the expected distance in the ideal conditions. These situations represent traffic congestion at different levels. Figure 11 shows how the displacement study is performed considering a vehicle moving from v_A to v_B, representing the travelling on road e_{AB}. If we consider the travelled time on $e_{AB} \rightarrow t_{e_{AB}}$ in the free-flow condition, the vehicle is expected to travel

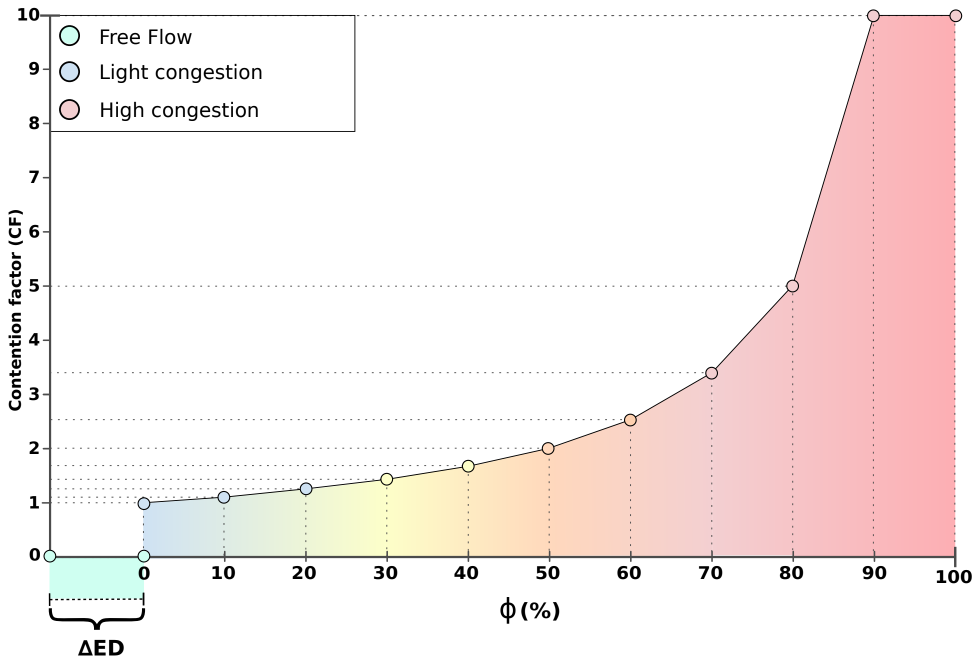


Figure 12 – Momentary Contention Factor

the distance ED. However, traffic real-world conditions and environments involve a high diversity and complexity of factors, such as crosswalk, traffic light, or different driver behaviour that involves different acceleration, breaking interval, and travel speed. Thus, to better express such real-world conditions, we propose the use of ΔED to represent a range of free-flow conditions. ΔED is also introduced to consider small variations of traffic contention, which represent the dynamism of the environment and do not characterize real traffic congestion. Thus, vehicles with the travelled distance $TD \in \Delta ED$ experience free-flow conditions. On the other side, vehicles with $TD \notin \Delta ED$ undergo a congested environment and, consequently, an increase in the distance ratio defined by ϕ. For instance, the vehicle in Figure 11, under ideal conditions, should have travelled at least the free-flow range ΔED, green region in Figure 11; however, due to real-world traffic conditions, its travelled distance is $\phi = 20\%$, which is lower than ΔED – the orange region in Figure 11. In this case, the vehicle identifies signs of congestion.

The estimated value of ϕ allows us to define the contention factor, which is the quantification of the observed traffic contention. Figure 12 shows the Contention Factor (CF) function considering the momentary value of ϕ. When $TD > ED$, demonstrating negative values of ϕ, or when $TD \in \Delta ED$, the vehicle is moving at free-flow and, consequently, the contention factor is 0. For values of $TD \notin \Delta ED$, the contention factor growth is proportional to $CF = \frac{ED}{TD}$, considering the interval of [1,10]. For instance, for $ED = 100m$ and $\Delta ED = 10\%$, the free-flow conditions is identified if $TD \in [90 - 100]m$. Consider a scenario where $TD = 72m$, $\phi = 1 - \frac{TD}{ED - \Delta ED} \rightarrow 1 - \frac{72}{90} \rightarrow 0.2$. In this case, the vehicle is 20% behind of the ideal distance considering free-flow conditions, so the contention factor is $CF = \frac{90}{72} = 1.25$. If $TD = 45m$, $\phi = 1 - \frac{45}{90} \rightarrow 0.5$. The vehicle is 50% behind of the ideal distance and the $CF = \frac{90}{45} = 2$. As soon as the value of ϕ grows, the Contention factor (CF) increases fast, indicating a congested environment. For instance, in the case where $TD = 18m$, $\phi = 1 - \frac{18}{90} \rightarrow 0.8$. The vehicle is 80% behind of the ideal distance and the $CF = \frac{90}{18} = 5$. If $TD = 9m$, $\phi = 0.9$ and $CF = \frac{90}{9} = 10$. For values of $TD < 9m$ and $\phi > 0.9$, CF grows indefinitely and a small change on CF may introduce an error in the congestion estimation. Considering an extensive analysis, we introduce the limit of 10 in the Congestion Factor.

The coefficient CF presents the momentary quantification analysis of the displacement. In other words, it defines the current perception of the traffic condition. However, only instantaneous analyzes cannot provide a complete study of the movement, and clustering these independent perceptions allows to classify them in Congestion Levels (CL). The Congestion Levels are useful in two cases. (i) When the CL changes, the vehicle disseminates the new estimated CL for its vicinity. (ii) When a vehicle receives an advertised CL, it uses the information to weigh its graph $G = (V, E)$ to find alternative routes (Section 4.2.4). Equation 4.2 shows how the congestion level is calculated.

$$CL_{road} = \overbrace{1}^{\text{free\_flow}} + \left\lfloor \frac{1}{NCL} \cdot \sum_{i=0}^{t_{current}} CF_{t_i} \right\rfloor \tag{4.2}$$

NCL represents the Number of Congestion Levels, defined by the system designer. CF_{t_i} represents the momentary contention factor at each time step $t_i = \{0, 1, \ldots, t_{current}\}$ while the vehicle is moving in the considered road. The time step is each analysis cycle based on second-to-second measurements. When $CL_{road} = 1$ of a specific *road*, the vehicles are moving without or with a small variation of traffic contention. As CL is getting closer to NCL, higher traffic retention are observed. During the displacement, each momentary analyses (represented by CF_{t_i}) is grouped with the analyzes already performed $\sum_{i=0}^{t_{current}} CF_i$, where $t_{current}$ represents the current step. When $\sum_{i=0}^{t_{current}} CF_i = 0$, the displacement is observed in an ideal condition and $CL_{road} = 1$. On the other hand, in situations, such as $\frac{\sum CF_{t_i}}{NCL} > CL_{road_{t_{i-1}}}$, the vehicle is observing an increase in the congestion. To minimize errors in momentary measurements, the equation considers only the integer value of $\frac{\sum CF_{t_i}}{NCL}$.

Figure 13 shows the displacement analysis of a vehicle between segments $\{A \rightarrow B\}$. At each step ($t_i = 0, 1, ..., t_{current}$), the parameters ϕ – distance fluctuation, CF_{t_i} – contention factor, $\sum CF_{t_i}$ – aggregation of contention factors and CL_{t_i} – congestion level are estimated. The vertical doted red line represent changes in contention level CL. For this example, we set $NCL = 10$. The vehicle, until the step $t_i = 4$, estimates

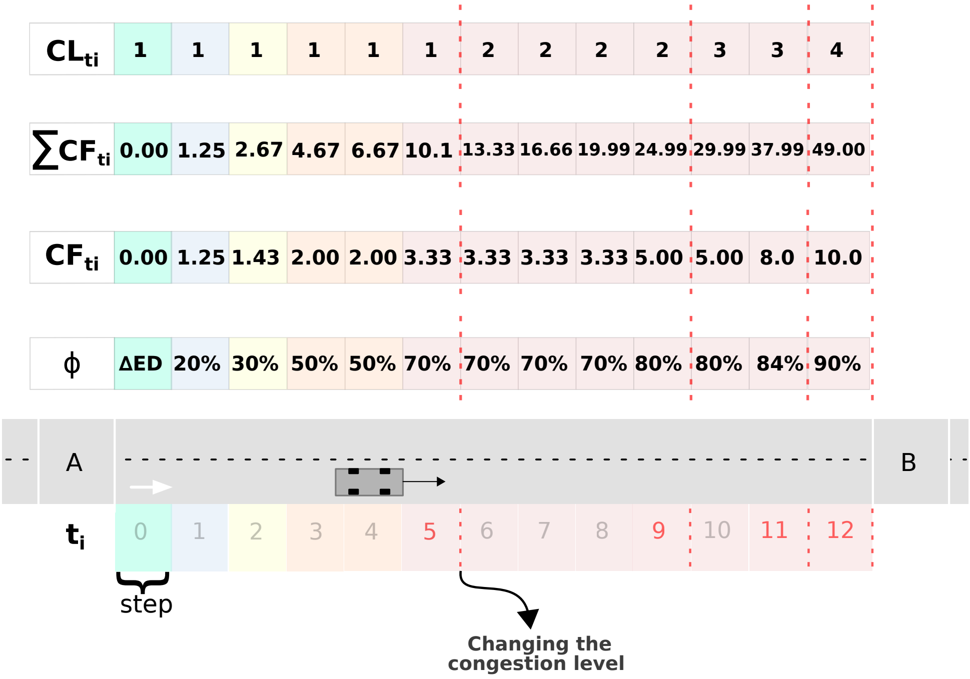


Figure 13 – Congestion Classification example

the congestion level of the considered road in $CL_{road_{t_4}} = 1 + \left\lfloor \frac{1}{10} \cdot 6,67 \right\rfloor \longrightarrow CL_{road_{t_4}} = 1 + \lfloor 0,667 \rfloor \longrightarrow CL_{road_{t_4}} = 1$. However, when $t_i = 5$, $CL_{road_{t_5}} = 1 + \left\lfloor \frac{1}{10} \cdot 10,01 \right\rfloor \longrightarrow CL_{road_{t_5}} = 1 + \lfloor 1,001 \rfloor \longrightarrow CL_{road_{t_5}} = 2$ and the vehicle detects a congestion level change. Other congestion level changes are detected at t_9 and t_{11}.

Vehicles, during their trip, monitor the conditions of their displacement. When changes in the congestion level estimation are detected, the vehicles are responsible for disseminating such information proactively to their vicinity. The **Proactive Information Dissemination** protocol describes this process. On the other hand, when vehicles do not have information about the next segment of their route, they can request traffic information using the **Reactive Knowledge Discovery** protocol. These communication protocols are described in Sections 4.2.2 and 4.2.3, respectively.

4.2.2 Proactive Information Dissemination

The Proactive Information Dissemination protocol is responsible for providing and sharing sufficient information for alternative route decisions with low use of the wireless network medium access. The dissemination protocol was designed to execute in a distributed and highly mobile environment using the Vehicle-to-Vehicle communication. When necessary, each vehicle shares its congestion level to the vicinity, and two modules compose this process: (i) Adaptive Knowledge Sharing and (ii) Knowledge Maintenance. In the first module, the dissemination of information is executed in an adaptive way taking into account the evolution and changes of congestion levels. The goal of knowledge maintenance is to preserve the information about the congestion level of the road considering the mobile environment. The following sections detail these modules.

Adaptive Knowledge Sharing

Each vehicle, while traversing its route, continually monitors changes in the congestion level of the road (CL_{road}). When it detects modifications, the vehicle verifies the need to send a notification to its neighbours. The vehicle conducts the verification by checking its local database for traffic information, which contains the received and estimated tuples $< road_{id}, CL_{id} >$. When the vehicle is moving in $road_{id}$ and the congestion level changes, it checks if the database contains any information about $road_{id}$. In the case that the verification fails, the vehicle updates its database and shares the estimated information with its neighbours. The verification failure occurs when the vehicle has neither received nor estimated any information regarding the $road_{id}$ yet. If its database contains information regarding $< road_{id}, CL_{id} >$, the vehicle compares both estimations. The vehicle updates the database and shares the estimation if the received/estimated one is greater than the stored value. This scenario indicates that the traffic flow is increasing in the considered road, and a vehicle must notify its neighbours. However, if the congestion level is smaller compared to the one in the database, knowledge sharing is suppressed. The vehicle then updates the database with the older estimated congestion level between the two ones. We consider that the sender vehicle has travelled a longer distance in the road segment than the receiver vehicle has done; thus, it might have a better knowledge of the traffic flow.

Vehicles that execute the information sharing send and receive notifications by considering one-hop neighbours. However, an area increase of Knowledge Sharing enables the handling of intense traffic flow scenarios; thus, we introduce a *Adaptive Knowledge Sharing*. Generally, a vehicle shares its control level information to its one-hop neighbours, using a Time-to-Live (TTL) $\rightarrow TTL = 1$, when it estimates a $CL = 3$ *or* 4. In the proposed congestion classification, a congestion level of 3 or 4 means that the traffic is heavy but causes slowness only in adjacent roads. On the other hand, for $CL > 4$, the information should reach greater distances for assisting vehicles to find alternative routes since the road demonstrates signs of congestion. For this purpose, we define the following criteria for disseminating knowledge: $CL = [5, 6] \longrightarrow TTL = 2$, $CL = [7, 8] \longrightarrow TTL = 3$, and $CL = [9, 10] \longrightarrow TTL = 4$.

The urban scenario illustrated in Figure 14 shows different areas of *Adaptive Knowledge Sharing* considering the white-colour vehicle placed at the centre of the

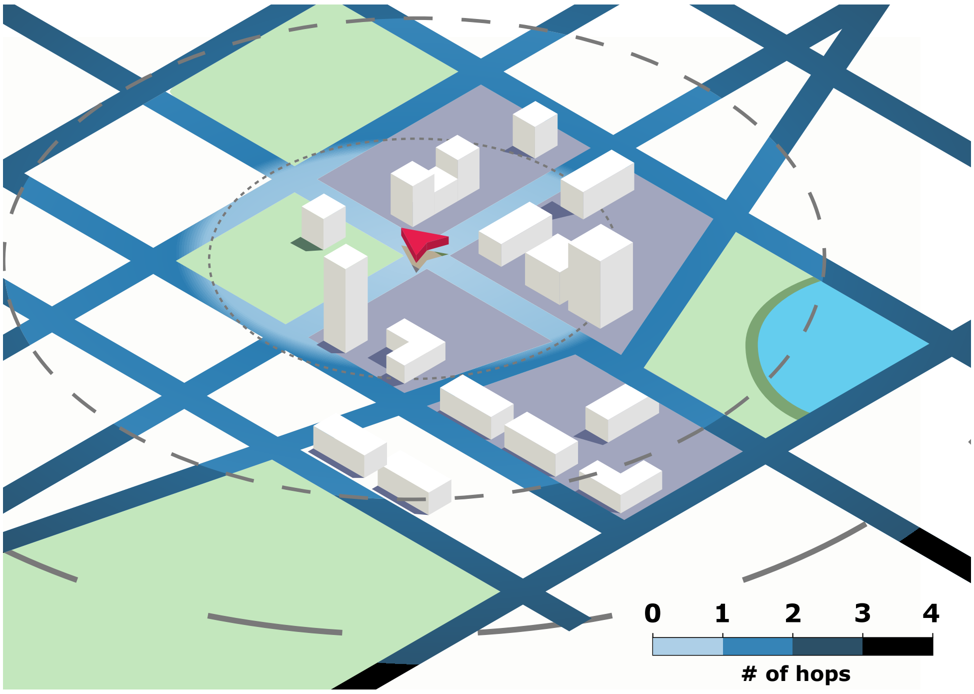


Figure 14 – Reach of multiple neighbourhoods

figure. $TTL = 1$ illustrates the first neighbourhood, $TTL = 2$ illustrates the second neighbourhood, and other neighbourhoods follow subsequent $TTLs$. For values of $TTL \geq 2$, we introduce a forward mechanism in order to reduce the broadcast storm problem. As a result, we define a target region as angular coordinates centred at the sender vehicle, which shares its congestion level. This process is illustrated in Figures 15. Only the vehicles inside the angular intervals can forward the message, and the devised mechanism defines a forwarding area considering the city map and the number of adjacent roads.

The defined angular regions change based on the layout of the roads since vehicles move only inside roads. For each adjacent road, we consider an angular region of 45°, where the data dissemination takes place. To better control the broadcast problem, only one vehicle inside each angular interval forwards the message; the vehicle that has a greater distance from the sender forwards the message first, cancelling the other broadcasts. It is worth noticing that a message from a vehicle inside one angular interval does not cancel the forwarding procedure of another angular interval. In this way, a devised dissemination mechanism minimizes the overloading of the wireless medium access since only one vehicle of each angular interval broadcasts the message. This restrictive policy thus reduces the number of duplicate messages and the broadcast storm problem. This process occurs in the case of multiple neighbourhoods, where $TTL \geq 2$, in order to provide adequate and sufficient traffic information for a large number of vehicles around the congested region.

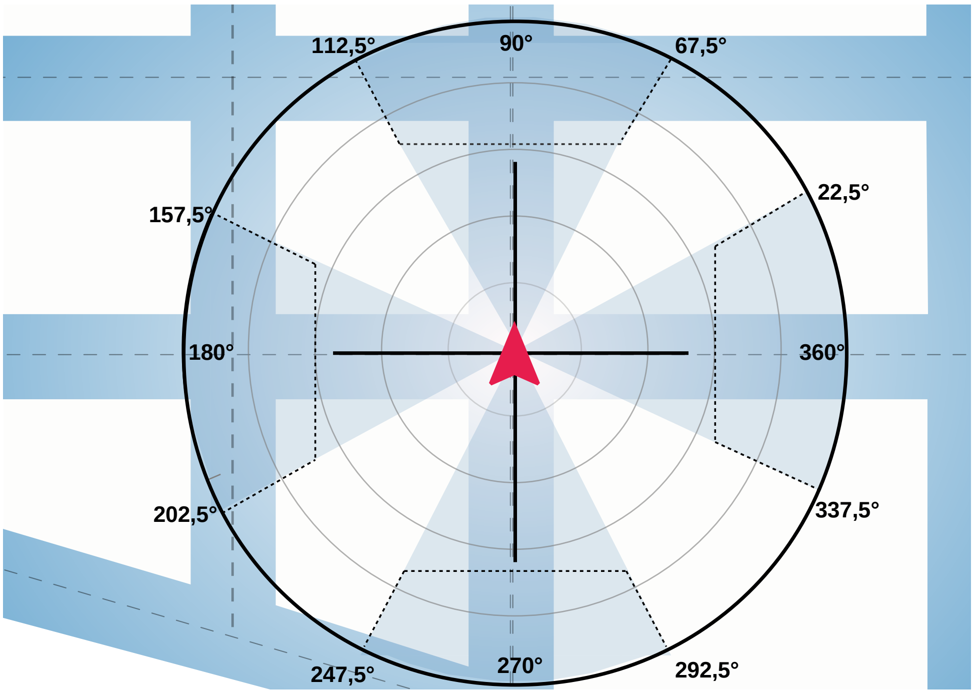


Figure 15 – Zoom in the 1st neighbourhood

Knowledge Maintenance

The Knowledge Maintenance module aims at enhancing the sharing of traffic conditions in cases where information from the Knowledge Sharing module causes insufficient traffic knowledge. When the vehicle enters a new road, it initializes a knowledge maintenance timer. When this timer times out, the vehicle disseminates the congestion level of the road to its neighbours. Consequently, the proposed strategy complements the dissemination of the information in the cases mentioned in the previous section, which shares a new estimation of the congestion level or newly received information. Additionally, the vehicle also disseminates the traffic information contained in its database every **T** time units. In other words, vehicles proactively maintain road knowledge by increasing the availability of information on the vehicle network.

A vehicle eventually receives data about the road where it is moving through knowledge maintenance, in which information sharing comes from another vehicle or when a change in congestion level is detected. As a result, whenever a vehicle receives this traffic data, its timer is reset since the traffic information is available, thus eliminating the need for knowledge maintenance. Finally, to minimize the number of transmissions and network usage, maintenance messages are directed only to the first neighbourhood of a vehicle without any further message forwarding. The dissemination takes place only when the congestion level is higher than a pre-defined threshold (β) to decrease the number of information messages during knowledge maintenance. The threshold is defined by the system designer to meet application requirements in terms of traffic congestion and control.

4.2.3 Reactive knowledge discovery

The Reactive knowledge discovery protocol is responsible for allowing vehicles to request information when failures in the knowledge sharing or maintenance process occur. Several factors can originate such failures, for instance, sparse or disconnected networks, signal attenuation, and packet collisions due to network overload, possibly caused by different applications that may be executed using the vehicle communication/wireless interface channel. The Reactive knowledge discovery protocol is divided into two modules: (i) Information Request-Response and (ii) Alert Mode.

In (i) Information Request-Response, whenever necessary, vehicles can request information from their neighbourhood using Information Request-Response (IRR) module. In this case, a vehicle sends an IRR message to vehicles inside the specific *target* road, which is a road without traffic information. This message triggers the election of a leader that replies with its congestion level estimation of the road. The leader selection chooses the vehicle with the most travelled distance within the road segment as a policy for targeting the vehicle with the best traffic perception. If the road already presents a leader, the leader then requests information from the vehicles inside the road. The leader issues this request message since vehicles and their respective traffic perceptions may change over a short period. It is essential to point out that the lifetime of an elected leader is its stay on the road. The (ii) Alert Mode module starts when many vehicles request information about a specific street. In this case, the knowledge maintenance is not sufficient to preserve the road traffic information. Vehicles inside the requested road thus behave in Alert Mode in order to increase traffic information availability.

Information Request-Response

The information Request-Response module implements an election protocol that consists of issuing request messages, performing leader election, and announcing the election outcome through response messages. The Leader Election steps are illustrated in Figure 16.

The defined steps and time intervals were based on the 801.11p mac protocols and designed to have an efficient and timely response, described as follows:

Leader response window: expected interval for leader response containing the road congestion level.

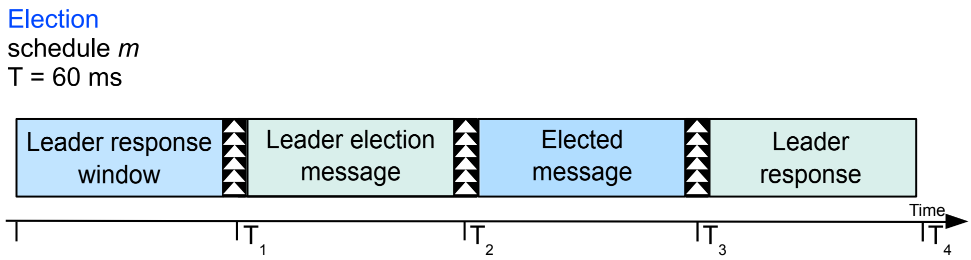


Figure 16 – Leader election mechanism

Leader election message interval: in the case of road without a leader, the vehicles broadcast their road displacement invoking an election.

Elected message interval: the elected vehicle is chosen and it sends a broadcast for the entire road.

Leader response interval: response message with the congestion level of the leader.

The first leader election interval, between T_0 and T_1 (*Leader respond window*), is intended for immediate response when there is a leader for the requested road segment. Upon receiving the request, other vehicles schedule their responses in case a leader election is required. These vehicles cancel this new election if a leader response message arrives within the interval between T_0 and T_1.

If the road does not have a leader or the leader's communication fails, a new election process starts. Thus, within the interval *leader election message*, vehicles that schedule the leader election message in the previous step broadcast or forward the message with their travel time on the road. Each vehicle schedules these messages inversely proportional to its travel time on the road; in other words, vehicles with more travel time in a road send their congestion level first, cancelling the other ones. we adopt this policy due to the observation that vehicles showing longer travel time contain more aggregated knowledge about road traffic information.

After the *Leader election* interval, the vehicles verify all received information and the vehicle with the longest travel time broadcasts a *Elected message*, notifying the other vehicles. This step ensures that, in the event of a new request, vehicles know the presence of a leader. The leader then creates a response message containing its congestion level and sends the message to the vehicle that initiated the request – leader response interval. Vehicles can determine if an elected leader is not in the respective road anymore by observing the leader response window and not receiving any message. It is crucial to point out that the election process executes in Tms Thus, if a vehicle executes the Information Request-Response module, it receives the response after Tms.

Alert Mode

In the Proactive Information Dissemination protocol, the vehicle suppresses the knowledge maintenance if the estimated congestion level CL is less than a pre-defined threshold, β. Due to this suppression or communication network failures, the available traffic information could be insufficient for decisions about alternative routes. Thus, the *Alert Mode* starts for a vehicle that travels on a road where it frequently executes the *Information Request-Response* module. Thus, vehicles that are in Alert Mode for a given road must execute the knowledge maintenance for any congestion level changes. Besides, the knowledge maintenance interval **T** is divided by 2. The goal of the Alert Mode is to increase the availability of information on a popular road – a road with many traffic information requests.

The alert mode is therefore reactively activated according to the frequency of the content requests, and its deactivation occurs as vehicles move to the next road segment. It is noteworthy that the Alert Mode is temporal; if a set of vehicles on the road is in Alert Mode when they finish the route on the road, this mode deactivates automatically. On the other hand, if the road receives many traffic information requests, the mode activates again as different vehicles now participate in the Information Request-Response.

4.2.4 Re-routing Process

During its displacement, a vehicle aggregates knowledge about the roads in its vicinity. Thus, whenever necessary and when possible, it calculates an alternative route with the least congestion. As vehicles approach intersections, they check for traffic congestion changes in the roads of their routes. In order to calculate a new route, each vehicle must update its database considering the weight w_{ij} for each road e_{ij}, as described in Equation 4.3.

$$w_{ij} = \frac{D_{ij}}{V_{max_{ij}}} \times CL_{ij} \tag{4.3}$$

where ij represents the evaluated road, D_{ij} describes the road size, $V_{max_{ij}}$ denotes the maximum allowed speed for the road, and CL_{ij} designates the congestion level for the road ij. For roads where there is no CL_{road} information, even in the case of reactive knowledge discover, we use $CL = 1$; we assume that the road displacement observes a free-flow. In other words, edge weights are proportional to the travel time considering free-flow multiplied by the congestion level; thus, the weight increases as the congestion level also increases. With the weighted graph $G = (V, E)$, the vehicle calculates the minimum cost path. If the new path is different from the current one, there is an alternative route to follow; otherwise, the vehicle is already in the minimum cost path.

4.3 Summary of the Chapter 4

As we describe in the previous sections, *ON*-DEMAND Traffic Management System contains a Road Traffic Analysis, Communication protocols – Proactive Information Dissemination and Reactive Knowledge Discovery, and a Re-Routing process. Figure 17 describes the complete process of the proposed traffic management solution. The *Road Traffic Analysis* task verifies the traffic contention/congestion during the vehicles' routes. The vehicle shares this information with its neighbours considering a *Proactive* or *Reactive* dissemination protocols. The *Proactive* Information Dissemination is composed by two modules named *Adaptive Knowledge Sharing* and *Maintenance* and they are executed in order to create a distributed database of street-traffic-information among the vehicles. If the vehicle verifies a missing entry in the database, it executes the *Reactive* knowledge discovery protocol. The *Reactive* protocol has two modules named *Information Request-Response* and *Alert mode*. Using the information inside its database, the vehicle execute the *Re-routing process* in order to find alternative routes with lower congestion.

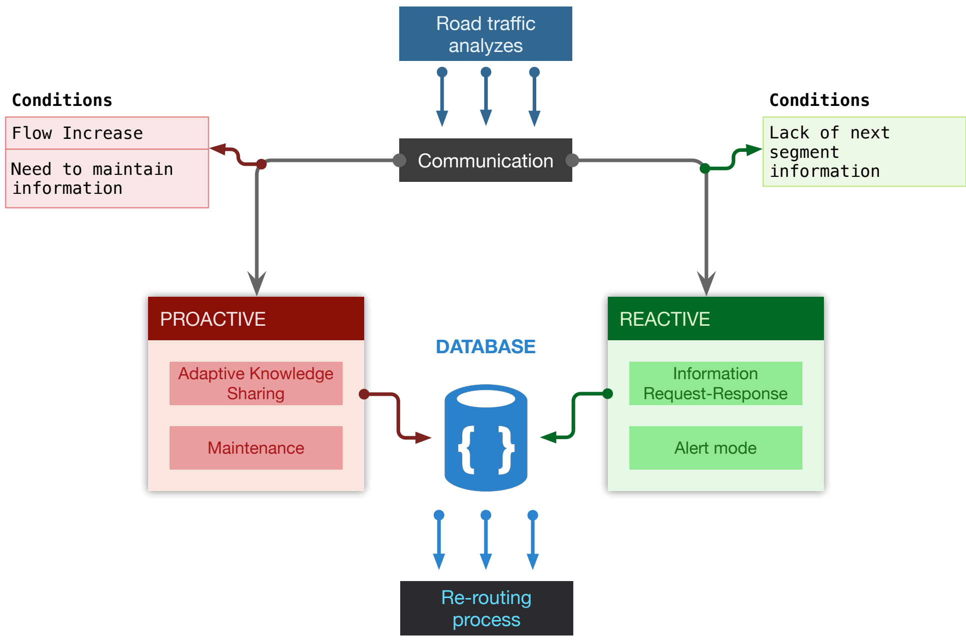


Figure 17 – Overview

Figures 18 and 19 show an overview of our communication protocols and their behaviour. During their routes, vehicle analyzes their displacement; based on the collected information, they execute the appropriate communication protocol. The

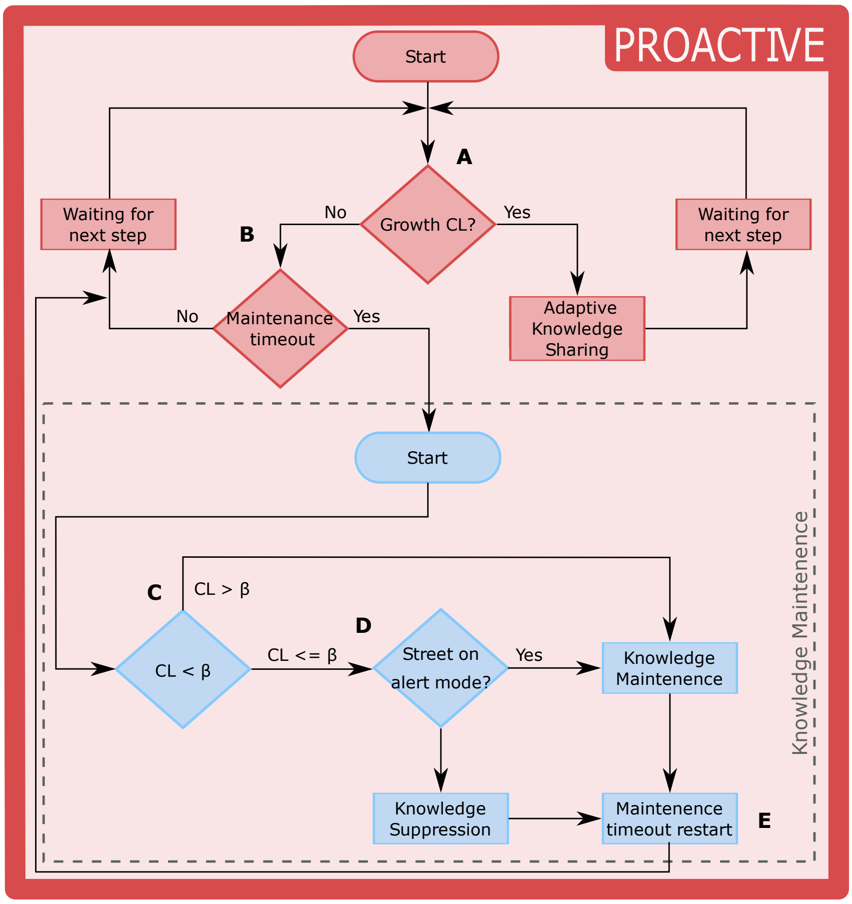


Figure 18 – Proactive Information Dissemination

Proactive Information Dissemination initiates when the vehicle is monitoring the congestion level of a road, as illustrated in Figure 18. From this proactive approach, we devised two fundamental behaviours: (i) when there is a change in congestion levels and (ii) when there is a need to maintain traffic information. In the first behaviour, each vehicle that detects an increase in the congestion level proactively disseminates this information according to the Adaptive Knowledge Sharing module, as depicted in Label A of Figure 18. The vehicle waits for the next step to perform a new congestion level estimation. Each system designer defines the length of these steps; in our particular study case, we defined it as *one second*. However, considering a different scenario or traffic behaviour, the designer should tune it properly. If the congestion level is the same or smaller, the vehicle verifies the need for information maintenance. In other words, the vehicle verifies the knowledge maintenance timer, as illustrated in Label B of Figure 18. If the timer has expired, the vehicle triggers the knowledge maintenance module, otherwise, it waits for the next step.

Vehicles execute the Knowledge Maintenance module to preserve traffic information. However, to better use the wireless communication medium, a vehicle broadcasts the road traffic information only if the road congestion level is higher than

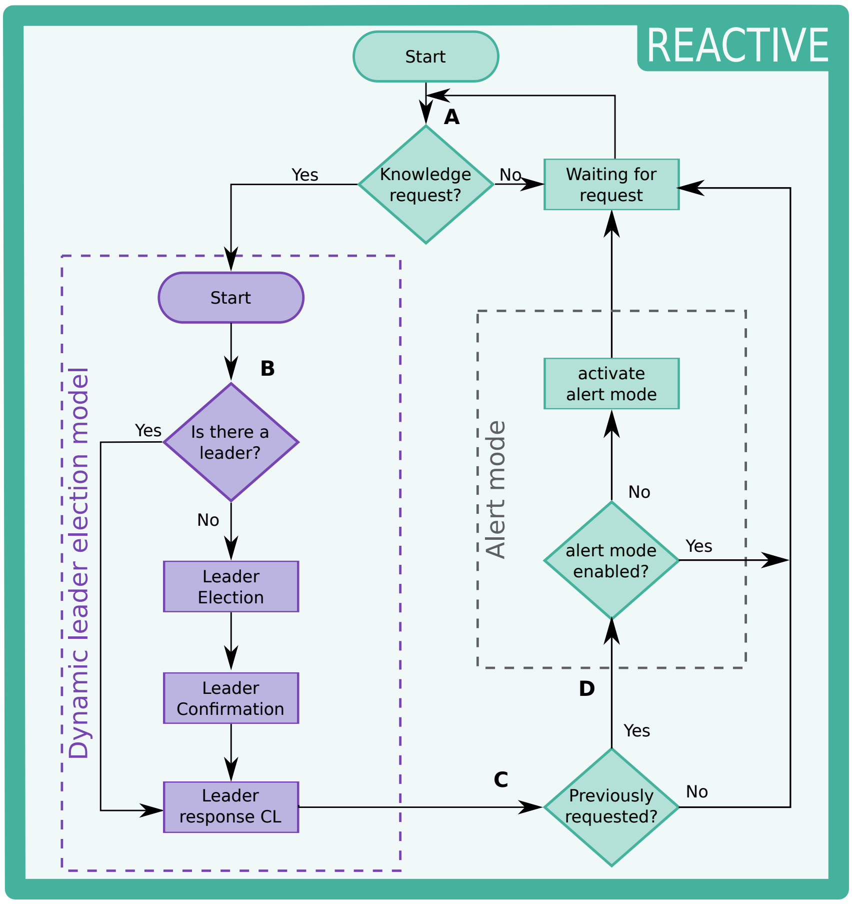


Figure 19 – Reactive Knowledge Discovery

a predefined threshold, $CL > \beta$, as depicted in Label C of Figure 18. In this case, the vehicle performs knowledge maintenance. It then re-starts the knowledge maintenance timer, which leads to the wait for the next time step and congestion level estimation, as described in Label E of Figure 18. If the congestion level is smaller than the threshold, $CL \leq \beta$, shown in Label D of Figure 18, the vehicle verifies if the road is on alert mode. As we described in Section 4.2.3, the Alert Mode relates to high-popularity roads, often receiving reactive information requests. The Alert Mode allows a vehicle to disseminate road traffic information for any value of CL. If the road is not in alert mode, vehicles suppress their knowledge maintenance, and they re-start their knowledge maintenance timer. Finally, as shown in Figure 18, the entire process repeats on all roads and at every time step cycle.

When travelling and when necessary, vehicles perform new route estimation based on the process proposed in Section 4.2.4 to avoid traffic jams or to find routes with lower traffic load. For this purpose, vehicles keep a database with up-to-date information of adjacent roads to the one the vehicle traverses. Thus, to minimize the occurrence and effects of missing information in the case when knowledge maintenance is not sufficient, vehicles can request knowledge of adjacent roads from a reactive and on-demand knowledge discovery model. The reactive knowledge request process is presented in Figure 19. This process starts when the vehicle performs a new route estimation, and it verifies if it is necessary to request traffic knowledge information, as depicted in Label A of Figure 19. If it is not necessary, the vehicle waits for the next route estimation. Otherwise, it requests all missing information to their respective roads. This request triggers the leader election in order to discover the road traffic information.

The leader election starts by verifying if there already exists a road leader, as described in Label B of Figure 19. If there is a leader, the leader timely responds with its road congestion level estimation; otherwise, the leader election process is started. The vehicle with the longest travelled distance in the road segment becomes the leader, and it sends a leader confirmation message to all vehicles on the road. The elected leader sends a reply message containing the road congestion level CL. The detailed leader election algorithm is described in Section 4.2.3. After the response, the leader verifies the need to activate an Alert Mode in the respective road, as illustrated in Label C of Figure 19. If the requested message is the first one of the elected leader, there is no need to activate the Alert Mode since it increases transmitted messages and wireless communication access. However, if the leader receives more than one knowledge request, we can interpret that knowledge maintenance is not working correctly. As a result, there is a need to activate the Alert Mode if it is not already activated, as illustrated in Label D of Figure 19; this activation must be checked for all request messages.

5 Performance analysis

This chapter describes the simulation definitions and tools, parameters and, the scenarios used to assess the proposed traffic management system. The ON-DEMAND is compared to PANDORA, DIVERT, *s*-NRR and OVMT (Original Vehicle Mobility Traffic), where PANDORA is also a distributed V2V solution; DIVERT and *s*-NRR employ the use of a central server; OVMT is an approach where vehicles follow the shortest path and do not execute any kind of vehicle re-routing strategy to avoid congested roads.

5.1 Simulation definitions

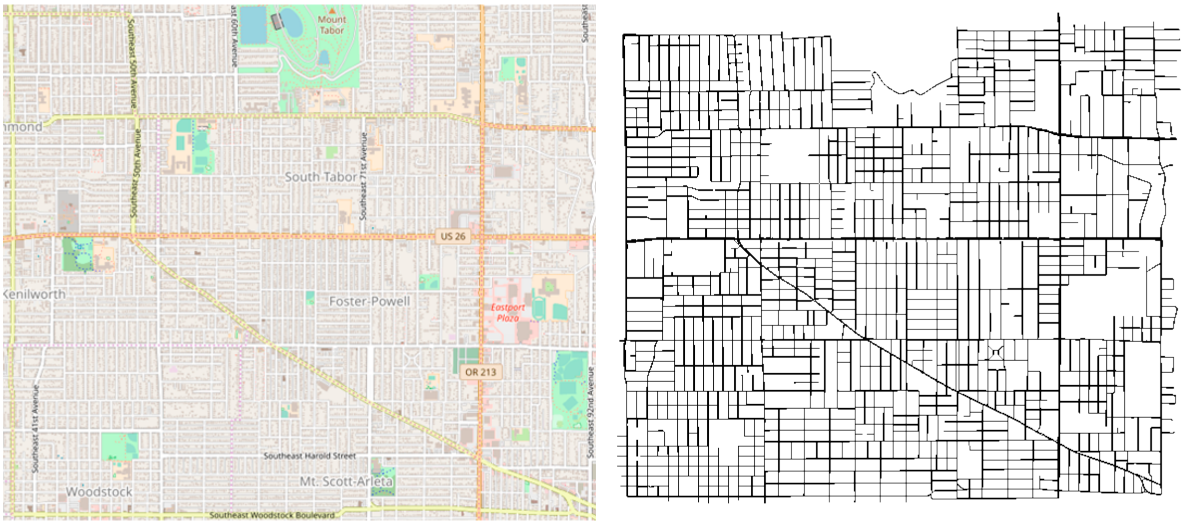
The performance of the proposed solution is evaluated by simulating the communication and mobility of a vehicular environment considering real-world scenario, features and parameters. SUMO 0.25 (Simulation of Urban Mobility) (LOPEZ, 2018) is used to create and manage the mobility of vehicles, OMNET++ 5.1.1 (VARGA; HORNIG, 2008) and Veins 4.6 (SOMMER, 2011) to simulate the vehicular communication using the 802.11p standard. The EMIssions from Traffic (EMIT) (Cappiello, 2002) model implemented by SUMO was used to calculate CO2 emissions and fuel consumption. EMIT uses a statistical model based on the formula HBEFA2[1] to calculate CO_2 emissions and fuel consumption, considering the vehicle speed and acceleration. The simulations were performed considering a realistic road map of the metropolitan region of Portland - USA, obtained through the OpenStreetMap tool (OpenStreetMap contributors, 2017), under a 17km^2 region as illustrated in Figure 20. The OpenStreetMap provides the road map with the real number of lanes, directions, traffic lights, speed limits, vehicle preference among others.

Parameters	Evaluations	Best values
NCL	[5, 10, 15, 20]	10
T (s)	[10, 20, 30, 40]	10
ΔED (%)	[10, 20, 30, 40] of ED	20

Table 3 – ON-DEMAND parameters

Three parameters were considered in ON-DEMAND evaluation, being these, Number of Congestion Levels (NCL), knowledge maintenance interval T and Variation of Expected Distance (ΔED) and Table 3 shows the best values. NCL = 10 shows

[1] https://www.hbefa.net/e/index.html



(a) OpenStreetMap (b) SUMO

Figure 20 – Map of Portland

the best trade-off value to represent traffic congestion and number of transmitted messages, since the adaptive knowledge sharing is executed when the congestion level changes (Section 4.2.2). The time step to estimate the Contention Factor (CF) and the Beacon interval of the PANDORA were set to 2 seconds, the same value used in (SOUZA, 2017). Besides, Section 5.3 and Section 5.4 will present an Exploration Analysis given CF, NCL, and T and a comparison between branches of ON-DEMAND solution NRD and *Just*-REACTIVE, respectively. The results were obtained considering 33 different simulations with a confidence interval of 95%. The source and destination of all vehicles were randomly chosen from the list of roads in the considered Portland map. Table 4 shows the default simulation parameters used to assess this evaluation.

The traffic management services were evaluated considering the communication network impact and traffic efficiency. For the communication network evaluation the following metrics were considered:

Transmitted Messages The number of transmitted messages for vehicular traffic management considering each solution;

Packet Collision Average packet collision due to network overload. For higher values, the data delivery ratio is reduced which can have a negative effect on system performance;

Delivery ratio The ratio between packets received and packets sent on the network. For best delivery ratio values, more knowledge was sent successfully.

Data usage Data usage considers the size of each message in each protocol.

Parameters	Values
OSM bound box	-122.639666, 45.468648, -122.564052, 45.522789
Traffic densities	$50 \sim 350$ vehicles/km^2
Normal traffic density	100 vehicles/km^2
Rush-hour traffic density	300 vehicles/km^2
Channel frequency	5.890e9 Hz
Propagation model	Two ray
Vehicle communication range	300 m
Antenna model	Omnidirecional
Bit rate	18 Mbit/s
PHY model	IEEE 802.11p
MAC model	EDCA

Table 4 – Simulation parameters.

The traffic efficiency was evaluated considering the above metrics. Also, the CDF of the relative travel time compared to the OVMT and the trip duration distribution for all solutions was evaluated.

Travel Time The average travel time for all vehicles to complete its travels. Lower values mean that TMS can reduce the impacts of traffic jams;

Distance Distance travelled for all vehicles on the its displacements. TMSs increase the distance for vehicles to travel on roads with lower overloads;

Speed Average speed during vehicle trips. Higher averages mean routes with a lower cost;

Time Loss The time lost in transit, i.e., the difference between the time spent in the current scenario against free-flow conditions. Higher values mean more traffic disruptions and consequently more gas costs and more environmental pollution;

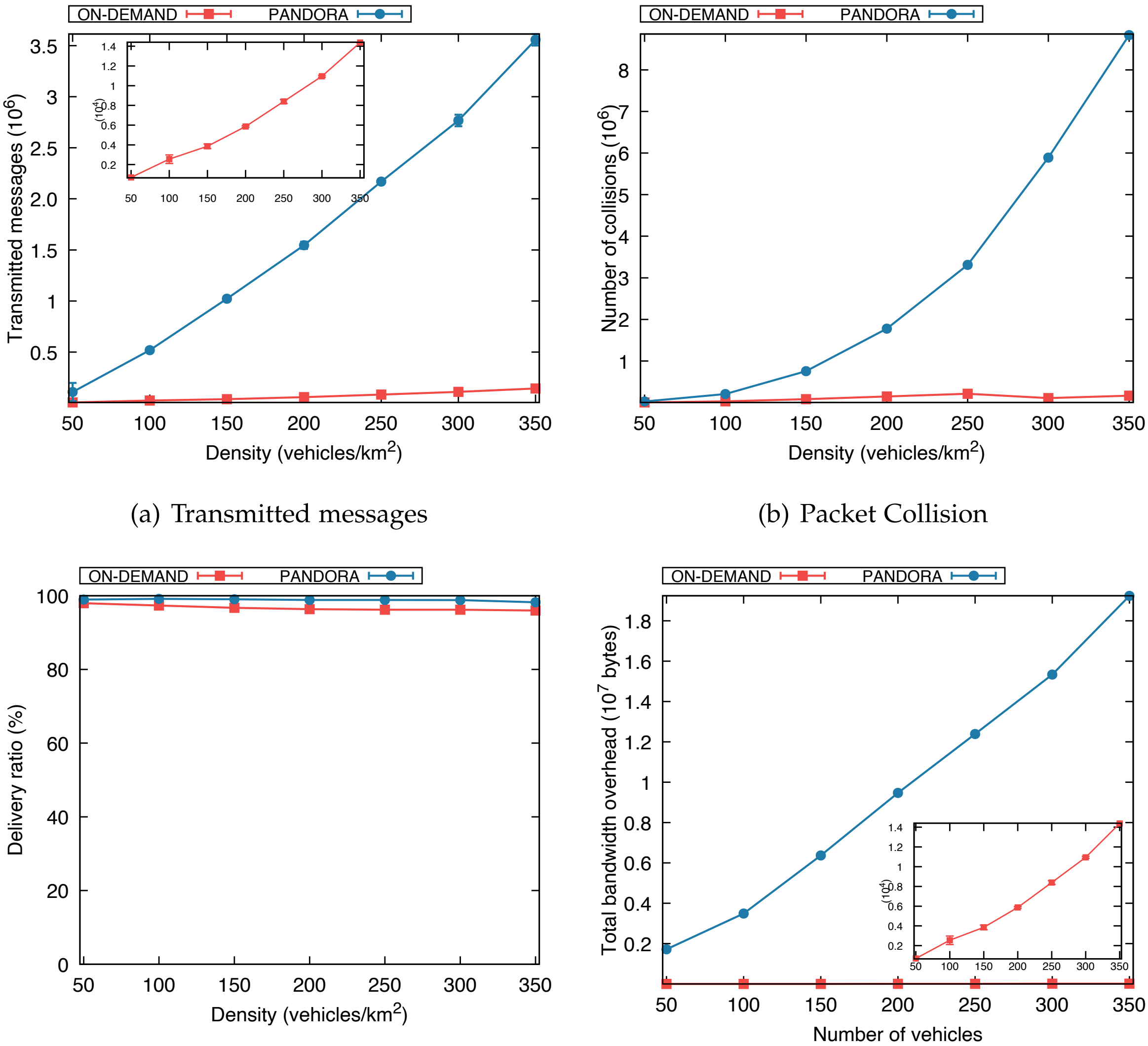
Fuel consumption Average fuel consumption of all vehicles;

CO_2 emission The average CO_2 emission considering each vehicle present in the simulation.

5.2 ON-DEMAND vs. PANDORA vs. DIVERT. vs. *s*-NRR

5.2.1 Network evaluation

The main objective of this evaluation is to analyze the cost of network communication to share traffic knowledge. In this analysis, it is considered only the solutions



(a) Transmitted messages

(b) Packet Collision

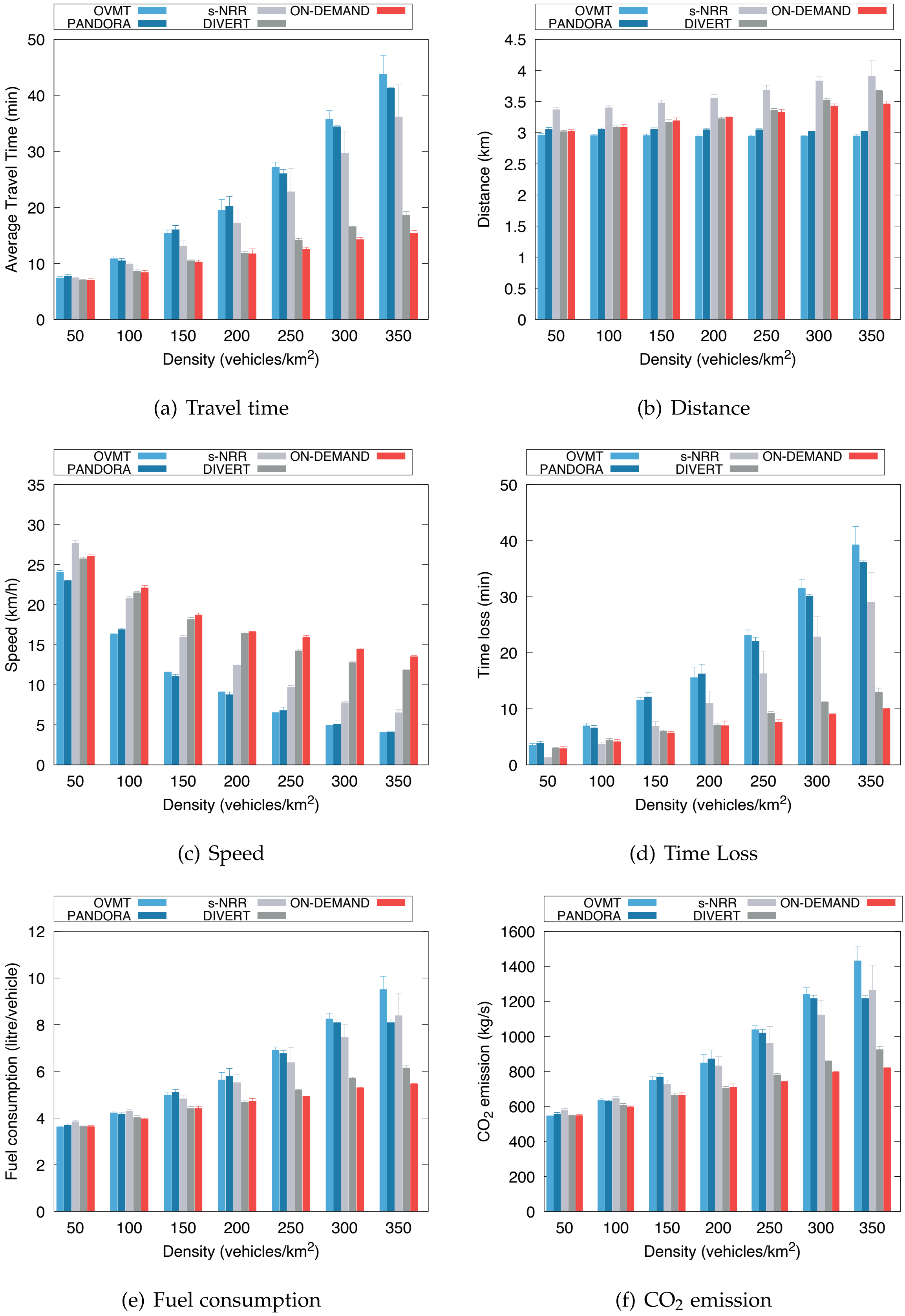
(c) Delivery ratio

(d) Data usage

Figure 21 – Communication results

that use the IEEE 802.11p communication standard, which are the ON-DEMAND and PANDORA. The centralized solutions use RSU or Cellular communication to perform the traffic re-routing. Figure 21 shows the communication results considering different density of vehicles in the road scenario. The PANDORA solution shares the traffic information using a beacon interval of 2 seconds, which leads to a high number of transmitted messages (Figure 21(a)). As the ON-DEMAND system evaluates the contention factor every 1 second, but shares the traffic information only when there is a change in the congestion level (CL), knowledge maintenance timeout or reactive knowledge discovery execution, the number of transmitted messages is reduced. On average, ON-DEMAND transmits 10^2 times lower messages compared to the PANDORA for all number of vehicles in the scenario.

Figure 21(b) shows the number of packet collision in order to execute both protocols. As the PANDORA transmits more messages, it overloads the wireless



(a) Travel time

(b) Distance

(c) Speed

(d) Time Loss

(e) Fuel consumption

(f) CO_2 emission

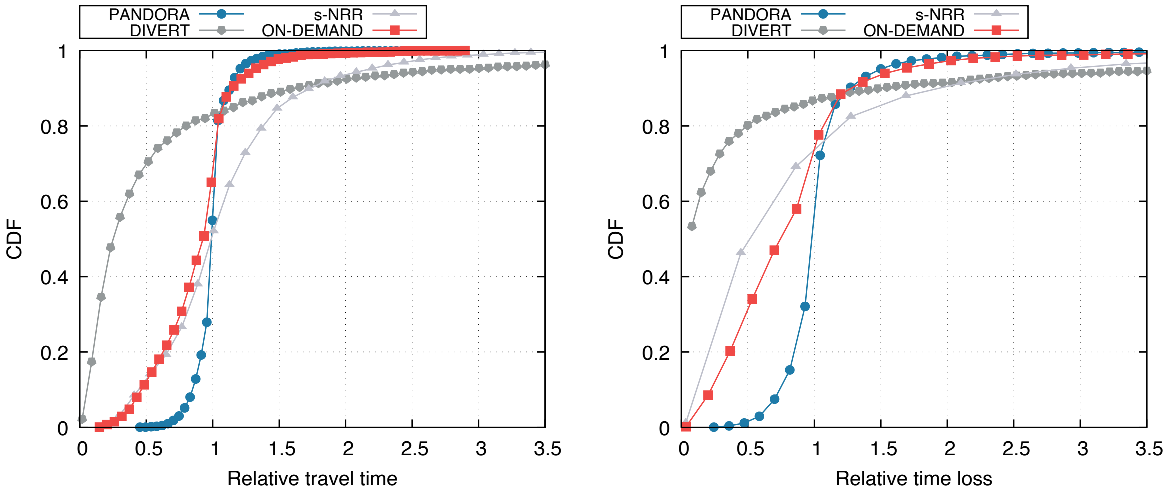
Figure 22 – Traffic efficiency results

medium access causing a high number of packet collision. As it is possible to verify, even transmitting a lower number of messages, the number of packet collision of the ON-DEMAND is greater than zero and, in this case, the adaptive knowledge sharing or knowledge maintenance may not work properly, showing the necessity of the reactive knowledge discovery. The proposed solution is able to increase the available traffic information, improving the traffic efficiency metrics (Figure 22). Since PANDORA does not employ multi-hop information dissemination, its delivery ratio is 2% greater compared to ON-DEMAND (Figure 21(c)). However, even with a larger dissemination area and using multi-hop communication, ON-DEMAND is able to delivery satisfactory results.

Finally, Figure 21(d) presents data usage which denotes how much data vehicle uploads or downloads using WAVE protocol. For this analysis, each kind of message must be map considering how much data can be load. For example, PANDORA uses three different message types, being: Beacon Message, Graph Table and, Data Message. Beacon Message loads the lowest weight around 40 bytes. However, Graph Table stores an array of edges that depends on the critical area size. So, if the critical area is the whole map, which message can store around 4×7680 (Road Segments) $= 30720$ bytes. DataMessage is the heaviest type that can load, in the worst case, more than 10 MB each. On the other hand, the ON-DEMAND message has a similar weight compared to PANDORA BeaconMessage, where minimizes the overload of the network. So, for all densities, ON-DEMAND uses less than 10^2 bytes compared to PANDORA.

5.2.2 Traffic efficiency evaluation

The travel time is illustrated in Figure 22(a) considering different density of vehicles in the scenario. Considering a low density of vehicles (50 vehicles/km^2), i.e., there is no congestion, all solutions have similar results. When the number of vehicles was increased and consequently the traffic jams, the DIVERT and ON-DEMAND traffic management systems present better results compared to the other solutions. It is important to verify that PANDORA does not present satisfactory results in the considered density of vehicles, having the travel time similar to the OVMT, which does not employ any kind of traffic re-routing. This is due to the fact that PANDORA presents better results only when a small area (area of interest) of road map presents traffic congestion (SOUZA, 2017). When the density of vehicles is 300 vehicles/km^2 the proposed ON-DEMAND decreases the travel time in 41%, 39% e 31% and 10% compared to the OVMT, PANDORA, *s*-NRR and DIVERT respectively. Thus, the use of congestion levels to classify the traffic information in order to verify alternative routes to decrease the travel time present better results compared to the HCM used by the PANDORA or number of vehicles used by the DIVERT and *s*-NRR.



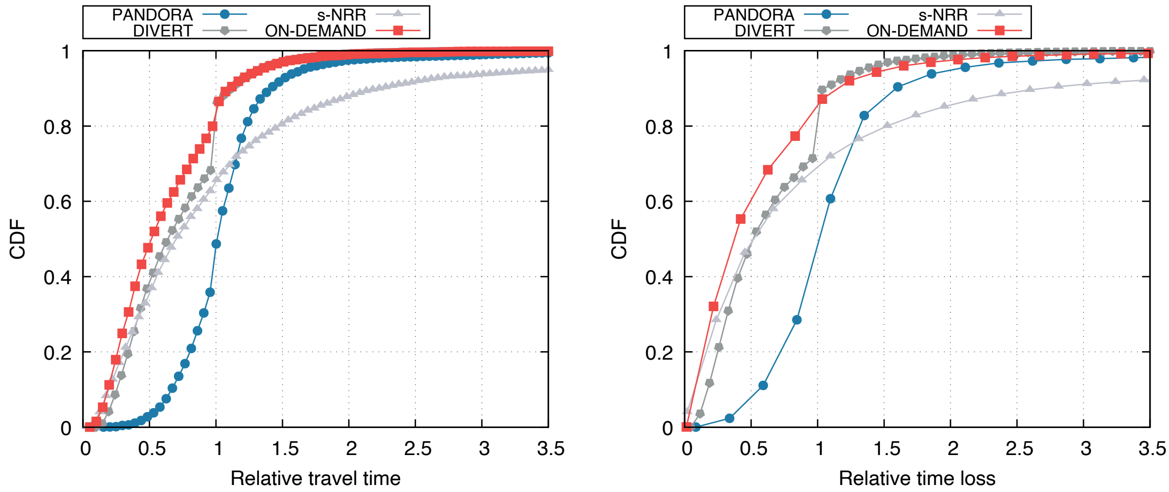
(a) Relative travel time

(b) Relative time loss

Figure 23 – Normal traffic density

Figure 22(b) shows the average distance travelled by vehicles. It is noteworthy that OVMT has the shortest average distance since it does use consider re-routing. On the other hand, the traffic management solutions change the vehicle route to reduce the travel time and, as a consequence, they increase the travelled distance. In addition, the increase in vehicular flow also increases the travelled distance since more re-routing is performed. The *s*-NRR and DIVERT solutions have the global view of the traffic information and, for smaller changes in traffic condition, they estimate new vehicles routes, increasing even more the travelled distance. The distributed solutions are able to find alternative routes with a small increase in the distance. For instance, considering 4250 vehicles, PANDORA, ON-DEMAND, DIVERT and *s*-NRR increase the distance in 3%, 15%, 19% and 23% over the OVMT respectively. However, even increasing the travelled distance, ON-DEMAND is able to find better routes with lower travel times.

The average speed of all vehicles is illustrated in Figure 22(c). The OVMT and PANDORA have similar average speed for all evaluated density of vehicles. For network density greater than 100 vehicles/km^2, the proposed ON-DEMAND and DIVERT are able to find alternative routes with lower traffic congestion, thus increasing the average speed of all trips with a small increase in the travelled distance. The *s*-NRR is also able to find faster routes, but with a greater increase in the travelled distance. For network densities greater than 150 vehicles/km^2, the ON-DEMAND presents an increase of 72%, 70%, 50% and 8% in the average speed compared to the OVMT, PANDORA, *s*-NRR and DIVERT, respectively. Figure 22(d) shows the lost time in traffic jams. As the goal of traffic management approaches is to find alternative routes with lower traffic congestion, it is possible to verify that the solutions can actually achieve the goal, since time lost in traffic jams is reduced for all solutions. This reduction directly impacts fuel consumption and CO_2 emissions which are also considered as targets

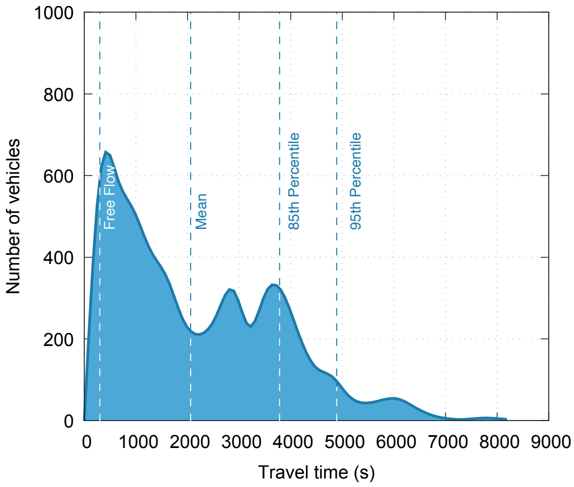


(a) Relative travel time (b) Relative time loss

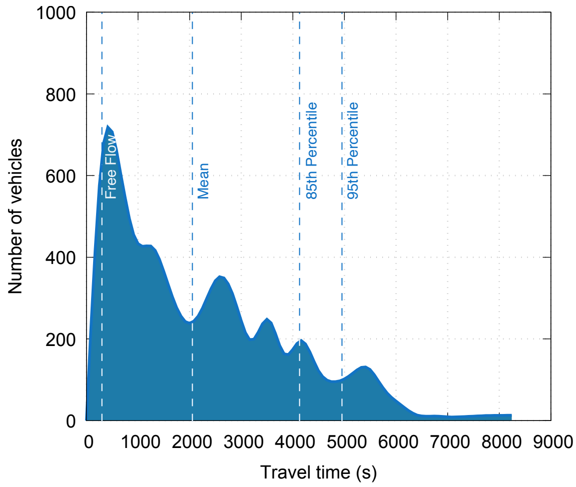
Figure 24 – Rush hour traffic density

issues for a TMS. Figures 22(f) and 22(e) perform CO2 emission and fuel consumption, respectively. Fuel consumption and CO2 emission are directly linked to the vehicle's time on the map, stopped or moving. The DIVERT and ON-DEMAND approaches have lower values, also due to the shorter travel time. An interesting case is to evaluate the PANDORA strategy, which despite having a shorter duration than the OVMT approach, in some cases has a higher consumption.

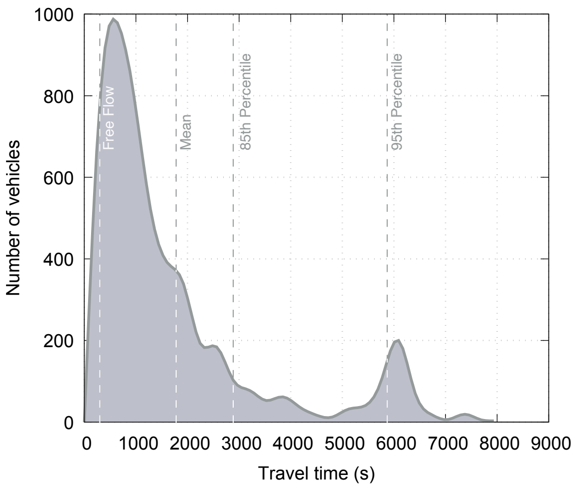
Figures 23 and 24 evaluate the ratio between the traffic management solutions and the OVMT considering a Cumulative Distribution Function of the travel time and time loss under different densities of vehicles in the network. The x-axis represents the ratio between the solutions and the y-axis represent the cumulative percentage of vehicles that satisfy the ratio. Figure 23(a) shows the relative travel time considering a normal traffic density (100 vehicles/km^2). The DIVERT, which has the global view of the traffic congestion, organize the vehicular traffic flow in order to decrease the travel time. It is possible to verify that 70% of the vehicles executing the DIVERT have a travel time lower than 0.5$\times$ OVMT (relative travel time $\leq$ 0.5). The PANDORA, DIVERT and ON-DEMAND have 80% of the vehicles with a travel time lower than the OVMT (relative travel time $\leq$ 1), where the *s*-NRR has only 55% of the vehicles. It is important to point out that (i) the TMS solutions are not able to decrease the travel time for all vehicles, since some alternative routes might present a traffic jam which were not estimated, i.e., a number of vehicles change their routes to similar paths causing new congestion; and (ii) a vehicle may change its route but the congestion of the previous one was in time to decrease, i.e., a "bad decision". Figure 23(b) shows the relative time loss of all solutions. The DIVERT, *s*-NRR, ON-DEMAND and PANDORA decrease the travel time in 90%, 79%, 77% and 76% respectively.



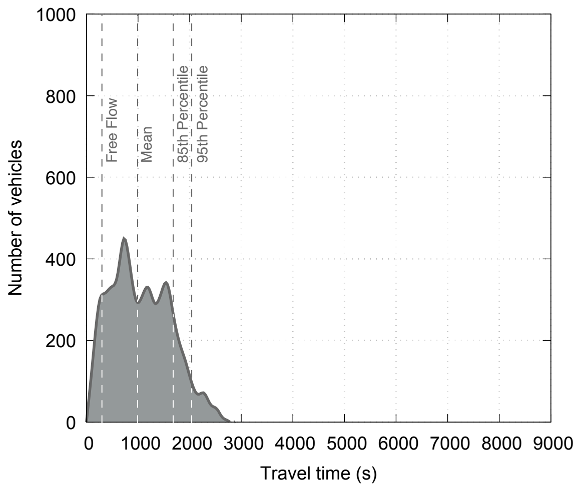
(a) OVMT



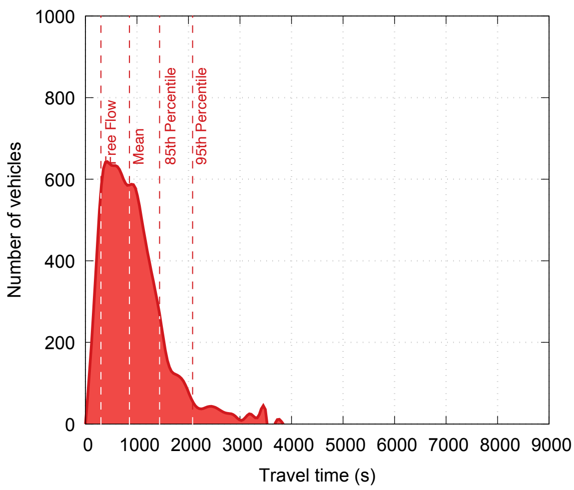
(b) PANDORA



(c) *s*-NRR

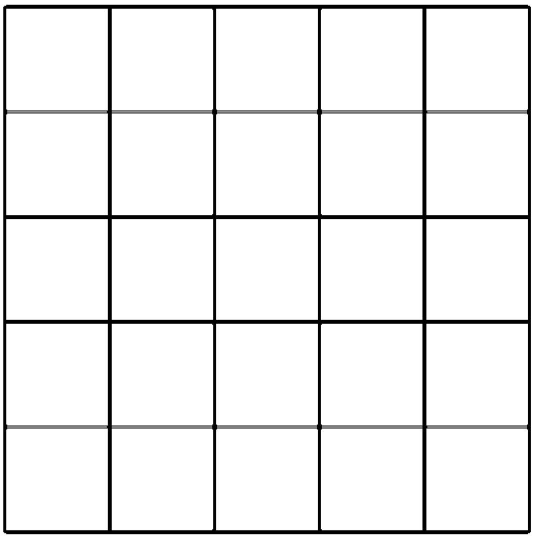


(d) DIVERT

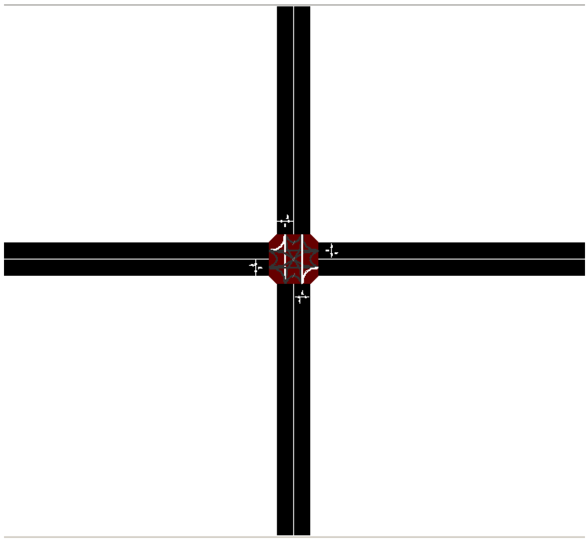


(e) ON-DEMAND

Figure 25 – Trip duration distribution



(a) Grid map



(b) Zoom in road segments structure

Figure 26 – 1 km x 1 km Manhattan Grid map

Considering a rush hour traffic density (300 vehicles/km^2), illustrated in figure 24, the TMS solutions present similar results compared to normal traffic density, however, the global view of the DIVERT does not improve its ability to decrease the travel time and time loss compared to the proposed ON-DEMAND, which is totally distributed and has a local view of the traffic condition. The proposed vehicle displacement analysis couple with the active and reactive data sharing protocols can in fact perform a traffic estimation and increase the traffic information among the vehicles. For instance, ON-DEMAND, DIVERT, *s*-NRR and PANDORA decrease the travel time compared to the OVMT in 83%, 75%, 68% and 50% respectively.

Figure 25 presents the analysis of vehicles' travel time distributions considering the performance and reliability measurements proposed in (TRB, 2010) with the rush hour scenario. The vertical lines indicate (i) free-flow, where it is estimated the average travel time if all vehicles were travelling considering a free-flow scenario; (ii) mean, which is the average travel time of all vehicles; (iii) 85th Percentile of the Travel Time and (iv) 95th Percentile of the Travel Time. In this analysis, it is possible to verify that the PANDORA and *s*-NRR have more vehicles with lower travel time, i.e., more than 700 vehicles with a travel time similar to a free-flow environment. However, these solution are not able to maintain this behaviour and the last vehicles finish their trip around 8000 seconds. Considering the 85th Percentile, 85% of vehicles finish their trip in less than 1500 seconds considering the proposed ON-DEMAND, where in the DIVERT, *s*-NRR, OVMT and PANDORA the vehicles finish their trips in 1700, 2930, 3880 and 4030 seconds respectively.

5.3 Exploratory Analysis of ON-DEMAND

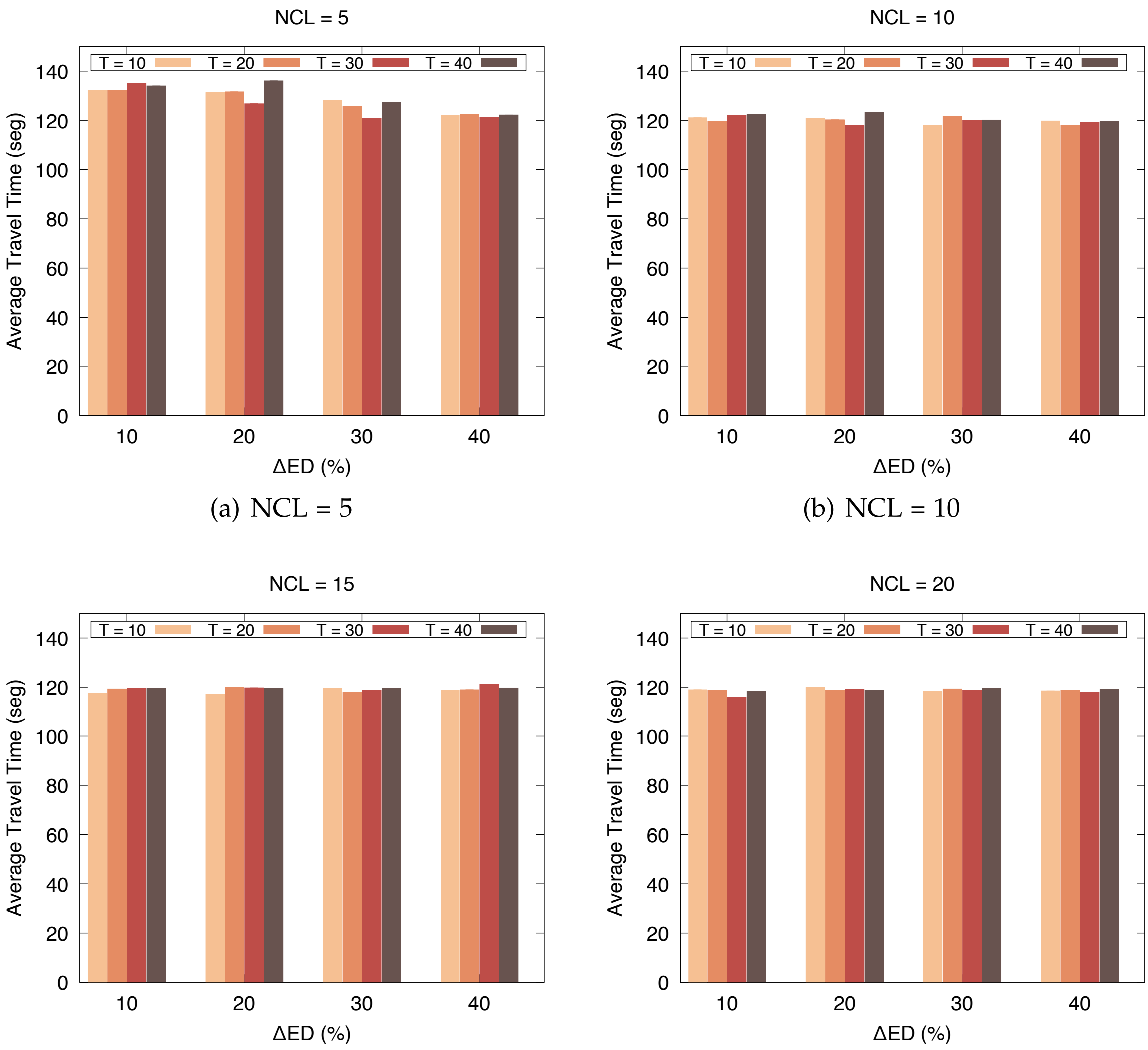
In view of the behaviour of the proposed TMS, this section aims to analyze and explore the variation of three ON-DEMAND parameters. Thus, the Number of Congestion Levels (NCL), the Maintenance Timeout (T) and the Variation of the Expected Distance (ΔED) are evaluated. This analysis is divided into two vehicle densities, being these (i) 300 vehicles/km^2 and (ii) 1000 vehicles/km^2, considering a 1 km x 1 km Manhattan Grid map. This map presents in Figure 26, consists of 120 road segments (two-way) with 200 meters each one that forms 25 squares of the same size. For each density, the parameters can assume four different values and result in 64 simulations. Table 3 shows the parameters and values used in this analysis. Furthermore, the parameters consider ON-DEMAND protocol (no variations) as it was the solution that got a better performance.

It stands out that the Adaptive Knowledge Sharing protocol must be modified when congestion levels are increased or decreased, that is, the maximum level will also increase or decrease. Thus, the reach of multi-hop communication is the same, however, it will be triggered in situations different. For example, in the standard case, the $NCL = 10$ the vicinity are divided in $CL = [5, 6] \longrightarrow TTL = 2$, $CL = [7, 8] \longrightarrow TTL = 3$, and $CL = [9, 10] \longrightarrow TTL = 4$. On the other hand, if the new $NCL = 15$, the levels will increase and now $CL = [10, 11] \longrightarrow TTL = 2$, $CL = [12, 13] \longrightarrow TTL = 3$, and $CL = [14, 15] \longrightarrow TTL = 4$. The TTL calculation is presented in formula 5.1.

$$TTL = \begin{cases} 1 & for\ CL \in [0\ ,\ NCL - \frac{LLTTL}{NTTL}) \\ 2 & for\ CL \in [NCL - \frac{LLTTL}{NTTL}, NCL - 2 * \frac{LLTTL}{NTTL}) \\ 3 & for\ CL \in [NCL - 2 * \frac{LLTTL}{NTTL}, NCL - 3 * \frac{LLTTL}{NTTL}) \\ 4 & for\ CL \in [NCL - 3 * \frac{LLTTL}{NTTL},\ NCL] \end{cases} \tag{5.1}$$

where the Number of Time-to-Live (NTTL) and LLTTL represents the lower limit for trigger the multi-hop dissemination. Thus, through extensive experimental analyzes, the best value of LLTTL represents 50% of NCL the same value used for the Alert Mode. The parameter choice considers the relationship between travel time and the number of messages transmitted. Nevertheless, Appendix A exposes the performance of all criteria, being these: travelled distance, time loss, fuel consumption, CO2 and, Speed.

Figure 27 and 28 are classified in four CLs where is shown the analysis of the parameters considering 300 and 1000 vehicles/km^2, respectively. The x-axis represents the variation of ΔED and the y-axis represent the Average Travel Time in seconds. It is worth mentioning some points in this analysis, higher values for ΔED mean less



(a) NCL = 5

(b) NCL = 10

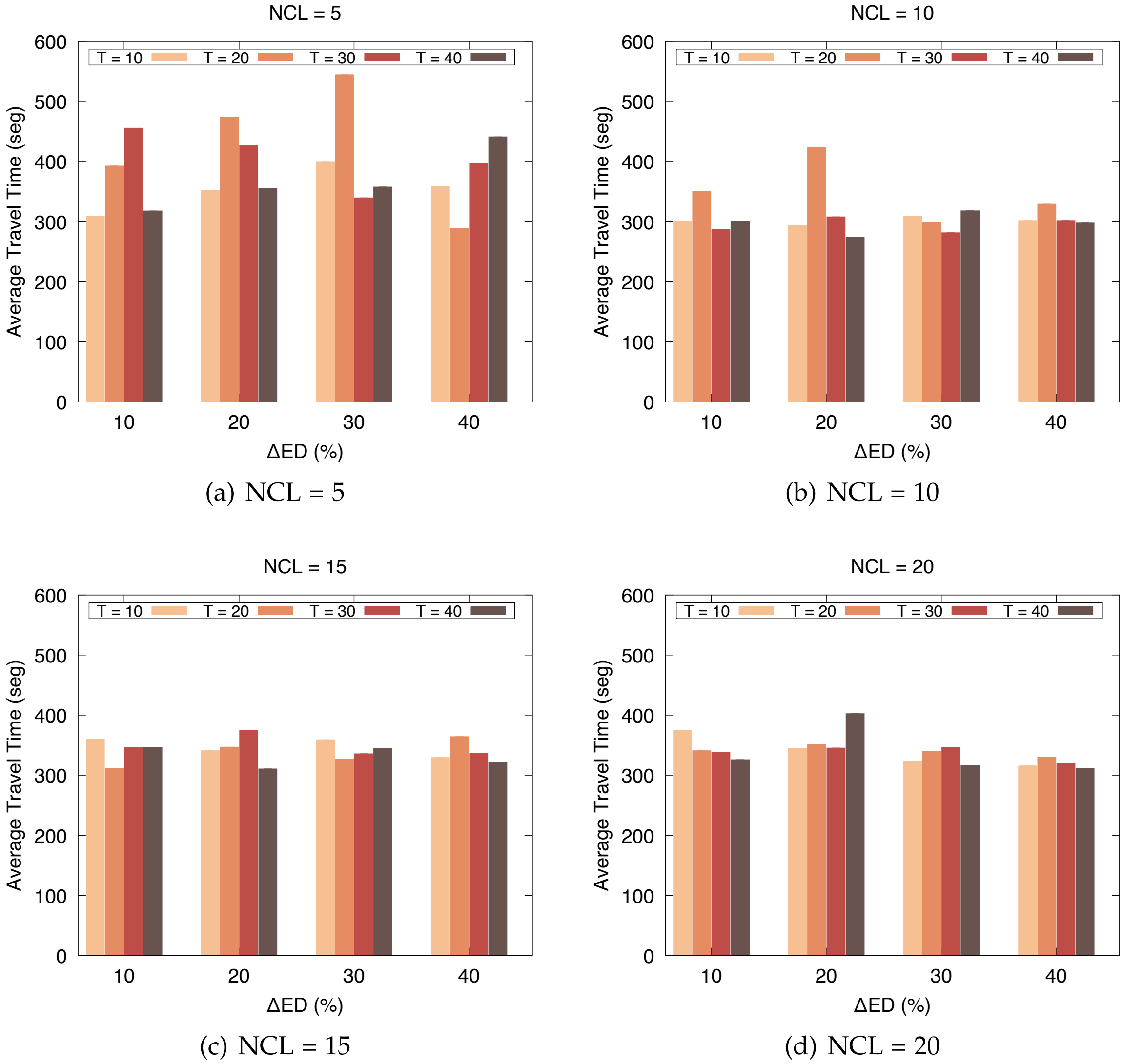
(c) NCL = 15

(d) NCL = 20

Figure 27 – Travel Time analysis considering 300 vehicles/km^2

sensitivity to small flow changes, more congestion levels are related to more precision especially for severe traffic jams and, higher values for T means fewer messages for maintenance. In Figure 27, the difference between the best and the worst result is about 15%, that is, a reflection of a scenario in which the congestion is not serious. In this sense, if only traffic parameters are considered, the impact of this decision for $NCL = 10, 15$ or 20 will not be substantial. However, when the NCL is increased, more accurately, the high traffic flow will be divided into more levels, i.e, more information for sharing.

In Figure 28, considering 1000 vehicles, the impact of choice between the evaluated parameters is more substantial than the 300 vehicle scenario. Thus, for NCL = 5, the influence of the maintenance interval is more significant. The maintenance timeout T = 10 and T = 40 are more stable compared to T = 20 and T = 30. Also, the travel time for NCL = 5 is higher than other values i.e few congestion levels are not able to describe the real size of traffic jams. However, for values NCL = 10, 15 and 20, the travel time difference is trivial, where NCL = 10 produces the best results. Considering NCL = 10, the difference between the higher and lower values is lower than 5% in this scenario.



(a) NCL = 5

(b) NCL = 10

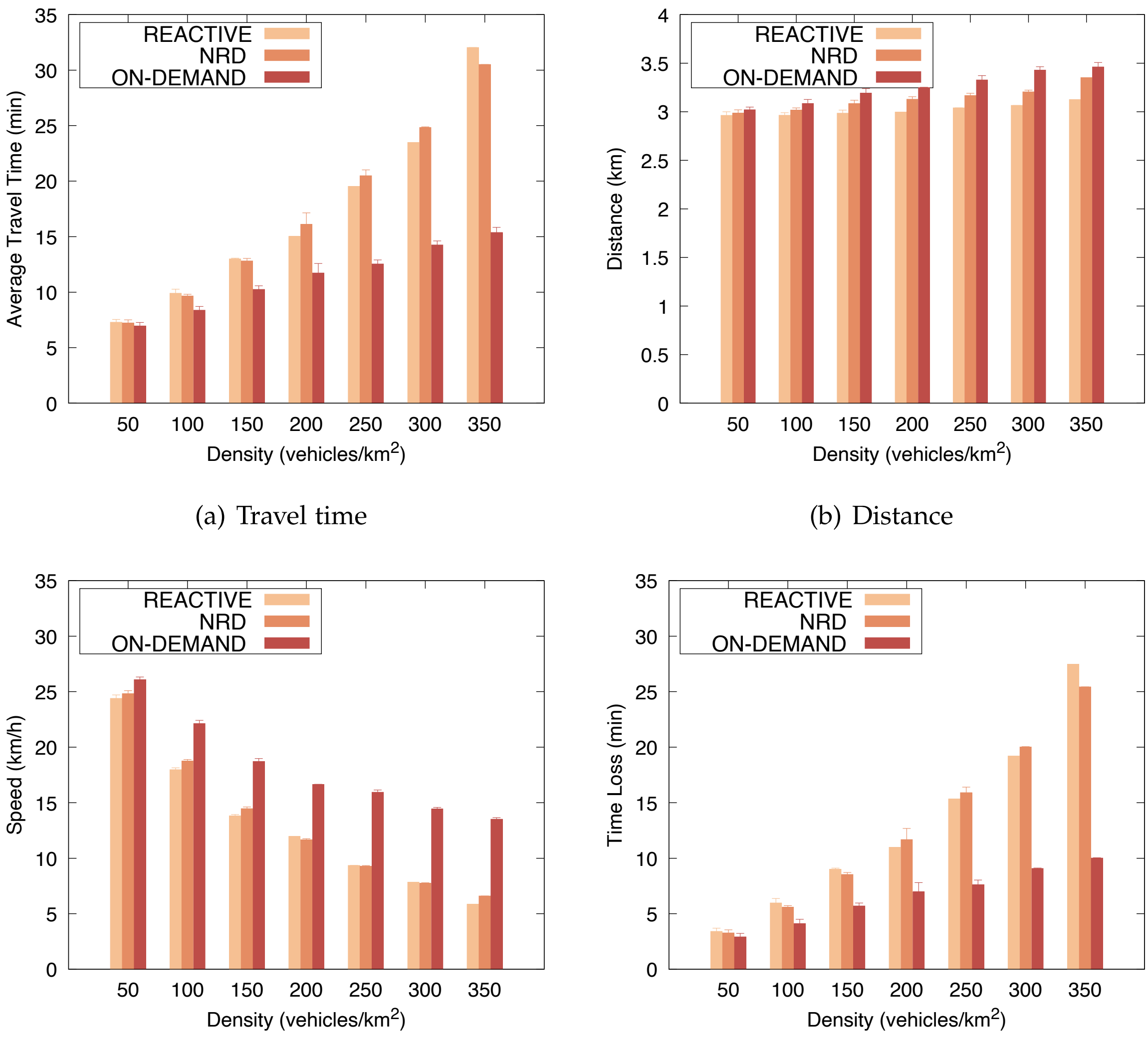
(c) NCL = 15

(d) NCL = 20

Figure 28 – Travel Time analysis considering 1000 vehicles/km^2

5.4 ON-DEMAND vs. NRD vs. *Just*-REACTIVE

ON-DEMAND protocol presents two particulars cases: (i) The ON-DEMAND Next Road Decision (NRD) and (ii) ON-DEMAND *Just*-Reactive. The first case is a protocol for the choice of the Next Road Segment based on the construction of a distributed knowledge from 1-hop traffic flow information. In other words, the multi-hop communication established by the Adaptive Knowledge Sharing mechanism is disabled. Only the first neighbourhoods vehicles, i.e, TTL = 1, might receive the knowledge. In the second case, the protocol works completely reactive, where, Proactive Information Dissemination is disabled. *Just*-Reactive works in a request-response model where vehicles follow the T interval to request information when T > 10 and it is a result of knowledge faults detection. Figure 29 exposes an analysis considers the follows parameters, travel time, distance, speed and, time loss in a Portland 17km^2 map. ON-DEMAND shows better results considering all of the evaluated parameters, which indicates the complementarity of the reactive and proactive modules.



(a) Travel time

(b) Distance

(c) Speed

(d) Time loss

Figure 29 – Travel Time analysis considering 300 vehicles/km^2

Figure 29(a) shows a travel time comparison between ON-DEMAND branch solutions. Thus, when the network has few congestion points (50 vehicles/km^2), all the branch solutions have similar results. As the number of vehicles increases, the travel time also increases for all and, as the number of congestion points increases, the difference among the solutions becomes more evident. When the scenario has 300 vehicles/km^2, ON-DEMAND presents an average travelled time of 40% and 42%

lower when compared to *Just*-Reactive and NRD solutions, respectively. Figure 29(b) illustrates the average travelled distance. The ON-DEMAND solution, which has greater available knowledge, can verify major changes in the vehicle's route. On the other hand, as NRD presents a locally congested path detection model, the vehicles calculate alternative routes with 1st neighbourhood information. Considering 250 vehicles/km^2, the travel distance of ON-DEMAND is, on average, 10% higher compared to the other solutions. The NRD and *Just*-REACTIVE find alternative routes with a moderate increase in the travelled distance, having an increase of 5% in NRD and 10% in *Just*-REACTIVE. It is important to emphasize that the ON-DEMAND can reduce travel time with a low impact on the travel distance, which is not verified in *Just*-REACTIVE and NRD.

Figure 29(c) presents the average vehicle speed. The NRD and *Just*-REACTIVE have similar average speeds for different numbers of vehicles in the scenario. Considering the scenario with few congestion points (50 vehicles/km^2), the ON-DEMAND finds alternative routes with a small impact in the distance, increasing the average speed but presenting inferior results compared with the NRD and *Just*-REACTIVE. The time lost when vehicles are moving is evaluated in Figure 29(d). Since the objective of the approaches for traffic management is to find alternative routes, it is possible to verify that the solutions can manage the route of vehicles to reach the objective and they reduce the vehicle's time lost in all solutions. Considering 250 vehicles/km^2, ON-DEMAND reduces the time lost by 38% and 40% compared to *Just*-REACTIVE and NRD solutions.

5.5 Summary of the Chapter

Chapter 5 evaluates and details the ON-DEMAND performance from different perspectives. Firstly, the simulation definitions with parameters, map, literature algorithms and, WAVE configurations. Section 5.2 presents the most relevant evaluation of the literature comparison from network and traffic aspects. Section 5.3 shows an Exploratory Analysis of ON-DEMAND, which describes how is the impact of each parameter on the solution. Section 5.4 compares the ON-DEMAND branches and shows how the connection between proactive and reactive modules is essential.

6 Conclusion and Future Work

This Chapter is organized as follows. Section 6.1 presents the summary of this thesis and Section 6.2 presents the future work.

6.1 Summary of this thesis

With the advances in wireless technologies, especially with the development of VANETs, it has become possible to develop intelligent transport systems, which allow traffic management in real-time. This master's thesis proposes the ON-DEMAND: An Adaptive and Distributed Traffic Management System for VANETs. ON-DEMAND uses only V2V distributed vehicular communication in order to create a local traffic information view. The main objective of the proposed TMS is to decrease the average travel time of vehicles with a low impact of the travelled distance considering congested urban scenarios. ON-DEMAND is divided into three main steps: (i) Road Traffic Analysis, (ii) Proactive and Reactive Traffic Information Dissemination and (iii) Rerouting procedure to estimate alternative routes. Vehicles estimate and proactively disseminate the congestion level of the travelling road to other vehicles. The proactive dissemination protocol sends the traffic information using an adaptive forward procedure, where the information of congested roads should be disseminated to more vehicles besides one-hop neighbours. In the case the vehicle does not have sufficient traffic information of nearby roads, it executes the Reactive Traffic Knowledge Discovery. Using all received information, the vehicle, distributively and using local information, estimate alternative routes with lower congestion.

Simulation results show that ON-DEMAND Vehicular Traffic Management System can reduce traffic jams, decreasing the average travel time, time lost, travelled distance, fuel consumption, CO_2 emissions and can increase the average speed. The proposed solution also decreases the network wireless overload to perform vehicular traffic management compared to a literature solution. Besides, based on extensive analysis, this work presents an evaluation of each parameter considered in the Road Traffic Analysis and Communication standards. It highlights the impact of NCL, T, and ΔED, where those parameters are responsible to make the ON-DEMAND more or less accurate. However, more accurate means more messages. Thus, the values of NCL = 10, T = 10, ΔED = 20% define the balance considering the relationship between precision *vs*. network overload. Finally, the design of the communication modules works in a decoupled way, which allows the evaluation from NRD and *Just*-REACTIVE perspectives. The NRD is a Next Road Decision protocol that receives information only in the 1st neighbourhood. *Just*-REACTIVE is request-response based. The performance analysis exposes that which part of ON-DEMAND can work separates, though, the combined performance is more efficient.

6.2 Future Work

The future works will investigate several open-ended questions identified during this thesis development. These questions considered several adjusts, improvements and try to make the ON-DEMAND protocol closer to the realistic environments. The division of the proposed improvements is classified in majors and minors:

Majors

Realistic scenarios The applicability of the system in real environments may implement from realistic traces such as the city of Cologne (Uppoor; Fiore, 2011) in Germany or the City of Luxembourg (Codeca, 2015). From this perspective, those datasets improve solution reliability by scenarios closer to day by day in urban centres.

Load balance One alternative to consider the load balance is from integrating a distributed Footprint (PAN, 2017) technique with the rerouting procedure to improve the vehicles and routes. The footprint is a technique based on collaborative networks, moreover, Vehicle Social Networks (VSNs) also assists the same improvement.

Markov Decision Process (MDP) (BELLMAN, 1957) Model decision making in situations where the results are random, such as a vehicle environment. Thus, the solution for an MDP will describe the best action, probability, for each state in the MDP known as the ideal policy. Therefore, the new route algorithm can implement an MDP model to improve reliability.

Collaborative decision Investigate a collaborative data dissemination protocol to reduce the number of messages to create the distributed knowledge of traffic information.

Cluster algorithm The proposed leader election algorithm based on the travel experience makes one vehicle responsible for knowledge aggregate. Nevertheless, there is no fault tolerance. Thus, the evolution of ON-DEMAND should implement a new leader election model more efficient and reliable.

Traffic lights The Road Traffic Analysis works without traffic lights management. Thus when vehicles are travelling on roads with those infrastructures, the travel time and time loss will increase. Thus, vehicles will send information about stop time in that region and, vehicles will avoid streets with traffic lights. However, with the implementation of this management, vehicles can request information about how long they need to wait and consider or not that road.

Minors

- Evaluate the impact of vehicles without OBU. For example from 10% to 50% non-OBU vehicles.
- Consider 5G + VANETS.
- Improvement of network evaluation from Bandwidth and Coverage perspective.
- Highway scenarios.
- Solution behaviour after accident or closed road.
- Comparison with more distributed solutions.

Bibliography

BOARD, T. R.; SCIENCES, E. National Academies of; MEDICINE. *Development and Deployment of Standards for Intelligent Transportation Systems: Review of the Federal Program – Special Report 280*. Washington, DC: The National Academies Press, 2004. Disponível em: <https://www.nap.edu/catalog/10897/development-and-deployment-of-standards-for-intelligent-transportation-systems-review>. Cited 3 times on pages 11, 28, and 30.

SAHOO, P. K.; CHIANG, M.-J.; WU, S.-L. Svanet: A smart vehicular ad hoc network for efficient data transmission with wireless sensors. *Sensors*, v. 14, n. 12, p. 22230–22260, 2014. ISSN 1424-8220. Disponível em: <https://www.mdpi.com/1424-8220/14/12/22230>. Cited 2 times on pages 11 and 35.

ALVES, R.; CAMPBELL, I.; COUTO, R.; CAMPISTA, M.; MORAES, I.; RUBINSTEIN, M.; COSTA, L.; DUARTE, O. C. M. B.; ABDALLA, M. Redes veiculares: Princípios, aplicações e desafios. In: _____. [S.l.: s.n.], 2009. p. 199–254. Cited 2 times on pages 11 and 36.

PAN, J.; POPA, I. S.; BORCEA, C. Divert: A distributed vehicular traffic re-routing system for congestion avoidance. *IEEE Transactions on Mobile Computing*, v. 16, n. 1, p. 58–72, 2017. ISSN 1536-1233. Cited 7 times on pages 11, 22, 33, 42, 43, 49, and 83.

BRENNAND, C. A. R. L.; FILHO, G. P. R.; MAIA, G.; CUNHA, F.; GUIDONI, D. L.; VILLAS, L. A. Towards a fog-enabled intelligent transportation system to reduce traffic jam. *Sensors*, v. 19, n. 18, 2019. ISSN 1424-8220. Disponível em: <https://www.mdpi.com/1424-8220/19/18/3916>. Cited 4 times on pages 11, 45, 46, and 49.

BRENNAND, C.; BOUKERCHE, A.; MENEGUETTE, R.; VILLAS, L. A novel urban traffic management mechanism based on fog. *IEEE Symposium on Computers and Communications (ISCC)*, 07 2017. Cited 7 times on pages 11, 22, 33, 42, 44, 46, and 49.

LOO, J.; MAURI, J. L.; ORTIZ, J. H. *Mobile Ad Hoc Networks: Current Status and Future Trends*. 1st. ed. Boca Raton, FL, USA: CRC Press, Inc., 2011. ISBN 1439856508, 9781439856505. Cited 2 times on pages 13 and 39.

ACEA. *The 2030 Urban Mobility Challenge*. [S.l.], 2016. Disponível em: <https://www.acea.be/uploads/publications/The_2030_Urban_Mobility_Challenge_-_ACEAs_Contribution_May_2016.pdf>. Cited on page 21.

DJAHEL, S.; DOOLAN, R.; MUNTEAN, G. M.; MURPHY, J. A communications-oriented perspective on traffic management systems for smart cities: Challenges and innovative approaches. *IEEE Communications Surveys Tutorials*, v. 17, n. 1, p. 125–151, 2015. ISSN 1553-877X. Cited on page 21.

Xia, F.; Rahim, A.; Kong, X.; Wang, M.; Cai, Y.; Wang, J. Modeling and analysis of large-scale urban mobility for green transportation. *IEEE Transactions on Industrial Informatics*, v. 14, n. 4, p. 1469–1481, April 2018. ISSN 1941-0050. Cited on page 21.

MABOGUNJE, A. L. Systems approach to a theory of rural-urban migration. *Geographical Analysis*, Wiley Online Library, v. 2, n. 1, p. 1–18, 1 1970. ISSN 1538-4632. Disponível em: <https://doi.org/10.1111/j.1538-4632.1970.tb00140.x>. Cited on page 21.

COOKSON, G.; PISHUE, B. Inrix europe's traffic hotspots: Measuring the impact of congestion in europe. *INRIX research*, 2016. Cited on page 21.

COOKSON, G.; PISHUE, B. Inrix global traffic scorecard. *INRIX research*, 2018. Cited on page 21.

EKBLAD, S. Stressful environments and their effects on quality ot life in third world cities. *Environment and Urbanization*, v. 5, n. 2, p. 125–134, 1993. Disponível em: <https://doi.org/10.1177/095624789300500210>. Cited on page 21.

SYSTEMATICS, I. C. *Traffic Congestion and Reliability: Trends and Advanced Strategies for Congestion Mitigation*. [S.l.], 2005. Cited on page 21.

SOUZA, A. M. de; BRENNAND, C. A.; YOKOYAMA, R. S.; DONATO, E. A.; MADEIRA, E. R.; VILLAS, L. A. Traffic management systems: A classification, review, challenges, and future perspectives. *International Journal of Distributed Sensor Networks*, v. 13, n. 4, p. 1550147716683612, 2017. Cited 2 times on pages 21 and 23.

SHAHGHOLIAN, M.; GHARAVIAN, D. Advanced traffic management systems: An overview and a development strategy. *arXiv preprint arXiv:1810.02530*, 2018. Cited on page 21.

Wang, J.; Huang, Y.; Feng, Z.; Jiang, C.; Zhang, H.; Leung, V. C. M. Reliable traffic density estimation in vehicular network. *IEEE Transactions on Vehicular Technology*, v. 67, n. 7, p. 6424–6437, July 2018. ISSN 1939-9359. Cited on page 21.

SOUZA ALLAN M.; MAIA, G. B. T. V. L. A. de. An interest-based approach for reducing network contentions in vehicular transportation systems. *Sensors*, v. 19, n. 10, p. 2325, 2018. Cited on page 21.

AHMED, E.; GHARAVI, H. Cooperative vehicular networking: A survey. *IEEE Transactions on Intelligent Transportation Systems*, v. 19, n. 3, p. 996–1014, 2018. Cited 3 times on pages 22, 23, and 34.

WANG, S.; DJAHEL, S.; MCMANIS, J. An adaptive and vanets-based next road re-routing system for unexpected urban traffic congestion avoidance. In: . [S.l.: s.n.], 2015. Cited 6 times on pages 22, 33, 42, 43, 44, and 49.

WANG, S.; DJAHEL, S.; ZHANG, Z.; MCMANIS, J. Next road rerouting: A multiagent system for mitigating unexpected urban traffic congestion. *IEEE Transactions on Intelligent Transportation Systems*, v. 17, p. 1–12, 03 2016. Cited 2 times on pages 22 and 43.

WANG, S.; DJAHEL, S.; MCMANIS, J. A multi-agent based vehicles re-routing system for unexpected traffic congestion avoidance. In: *17th International IEEE Conference on Intelligent Transportation Systems (ITSC)*. [S.l.: s.n.], 2014. p. 2541–2548. ISSN 2153-0009. Cited 3 times on pages 22, 43, and 49.

LOURENçO, M.; GOMIDES, T. S.; SOUZA, F. S. H. de; MENEGUETTE, R. I.; GUIDONI, D. L. A traffic management service based on v2i communication for vehicular ad-hoc networks. In: *Proceedings of the 10th Latin America Networking Conference on ZZZ - LANC '18*. ACM Press, 2018. Disponível em: <http://dx.doi.org/10.1145/3277103.3277132>. Cited 4 times on pages 22, 33, 42, and 49.

SOUZA, A. M. de; FONSECA, N. L. S. da; VILLAS, L. A. A fully-distributed advanced traffic management system based on opportunistic content sharing. *2017 IEEE International Conference on Communications (ICC)*, p. 1–6, 2017. Cited 6 times on pages 22, 42, 47, 49, 68, and 72.

MENEGUETTE, R. I.; FILHO, G. P. R.; GUIDONI, D. L.; PESSIN, G.; VILLAS, L. A.; UEYAMA, J. Increasing intelligence in inter-vehicle communications to reduce traffic congestions: Experiments in urban and highway environments. *PLOS ONE*, Public Library of Science, v. 11, n. 8, p. 1–25, 08 2016. Disponível em: <https://doi.org/10.1371/journal.pone.0159110>. Cited 3 times on pages 22, 47, and 49.

SCORECARD, U. M. *The Texas A&M Transportation Institute – Urban Mobility Scorecard*. 2015. <https://mobility.tamu.edu/ums/report/>. Cited on page 22.

ORGANIZATION, W. H.; UNAIDS. *Air quality guidelines: global update 2005*. [S.l.]: World Health Organization, 2006. Cited on page 22.

LIU, Q.; LUCAS, K.; MARSDEN, G.; LIU, Y. Egalitarianism and public perception of social inequities: A case study of beijing congestion charge. *Transport Policy*, v. 74, p. 47 – 62, 2019. ISSN 0967-070X. Disponível em: <http://www.sciencedirect.com/science/article/pii/S0967070X18300386>. Cited on page 22.

THAI, J.; LAURENT-BROUTY, N.; BAYEN, A. M. Negative externalities of gps-enabled routing applications: A game theoretical approach. In: *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. [S.l.: s.n.], 2016. p. 595–601. Cited 2 times on pages 23 and 42.

LANA, I.; SER, J. D.; VELEZ, M.; VLAHOGIANNI, E. I. Road traffic forecasting: Recent advances and new challenges. *IEEE Intelligent Transportation Systems Magazine*, v. 10, n. 2, p. 93–109, 2018. Cited on page 23.

WU, C.; JI, Y.; LIU, F.; OHZAHATA, S.; KATO, T. Toward practical and intelligent routing in vehicular ad hoc networks. *IEEE Transactions on Vehicular Technology*, v. 64, n. 12, p. 5503–5519, 2015. Cited on page 23.

DIETZEL, S.; PETIT, J.; KARGL, F.; SCHEUERMANN, B. In-network aggregation for vehicularad hocnetworks. *IEEE Communications Surveys Tutorials*, v. 16, n. 4, p. 1909–1932, 2014. Cited on page 23.

PISA, I.; BOQUET, G.; VICARIO, J. L.; MORELL, A.; SERRANO, J. Vaima: A v2v based intersection traffic management algorithm. In: *2018 14th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*. [S.l.: s.n.], 2018. p. 125–128. Cited on page 23.

Gomides, T. S.; Fernandes, M. L.; Sumika Hojo de Souza, F.; Villas, L.; Guidoni, D. L. Fire-nrd: A fully-distributed and vanets-based traffic management system for next road decision. In: *2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. [S.l.: s.n.], 2019. p. 554–561. Cited on page 24.

Gomides, T. S.; De Grande, R. E.; Sumika Hojo de Souza, F.; Guidoni, D. L. Sgtd: Sistema de gerenciamento de tráfego distribuído para redes veiculares. In: *Anais do XXXVII Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*. Porto Alegre, RS, Brasil: SBC, 2019. p. 1042–1055. ISSN 2177-9384. Disponível em: <https://sol.sbc.org.br/index.php/sbrc/article/view/7421>. Cited on page 24.

Gomides, T. S.; De Grande, R. E.; Sumika Hojo de Souza, F.; Guidoni, D. L. Um sistema adaptativo e colaborativo para minimizar congestionamentos utilizando comunicação entre veículos. In: *Anais do XXXVIII Simpósio Brasileiro de Redes de Computadores e Sistemas Distribuídos*. Porto Alegre, RS, Brasil: SBC, 2020. Cited on page 24.

Gomides, T. S.; De Grande, R. E.; Sumika Hojo de Souza, F.; Guidoni, D. L. Rider: Proactive and reactive approach for urban traffic management in vehicular networks. In: *2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS)*. [S.l.: s.n.], 2020. Cited on page 24.

GOMIDES, T. S.; GRANDE, R. E. D.; SOUZA, A. M. de; SOUZA, F. S.; VILLAS, L. A.; GUIDONI, D. L. An adaptive and distributed traffic management system using vehicular ad-hoc networks. *Computer Communications*, v. 159, p. 317 – 330, 2020. ISSN 0140-3664. Disponível em: <http://www.sciencedirect.com/science/article/pii/S0140366419319942>. Cited on page 24.

SUSSMAN, J. M. Its: A short history and a perspective on the future. In: _____. *Perspectives on Intelligent Transportation Systems (ITS)*. Boston, MA: Springer US, 2005. p. 3–17. ISBN 978-0-387-23260-7. Disponível em: <https://doi.org/10.1007/0-387-23260-5_1>. Cited 2 times on pages 28 and 31.

LORCH, J. R.; ADYA, A.; BOLOSKY, W. J.; CHAIKEN, R.; DOUCEUR, J. R.; HOWELL, J. The smart way to migrate replicated stateful services. *SIGOPS Oper. Syst. Rev.*, Association for Computing Machinery, New York, NY, USA, v. 40, n. 4, p. 103–115, abr. 2006. ISSN 0163-5980. Disponível em: <https://doi.org/10.1145/1218063.1217946>. Cited on page 29.

Jiang, D.; Taliwal, V.; Meier, A.; Holfelder, W.; Herrtwich, R. Design of 5.9 ghz dsrc-based vehicular safety communication. *IEEE Wireless Communications*, v. 13, n. 5, p. 36–43, October 2006. ISSN 1558-0687. Cited on page 29.

ISO/TC 204 Intelligent transport systems. ISO 21217:2010 - intelligent transport systems — communications access for land mobiles (calm) — architecture. *ISO*, 2010. Disponível em: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/05/50507.html>. Cited on page 29.

SUSSMAN, J. *Introduction to Transportation Systems*. Artech House, 2000. (Artech House ITS library). ISBN 9781580531412. Disponível em: <https://books.google.com.br/books?id=PDZPAAAAMAAJ>. Cited on page 30.

Nasim, R.; Kassler, A. Distributed architectures for intelligent transport systems: A survey. In: *2012 Second Symposium on Network Cloud Computing and Applications*. [S.l.: s.n.], 2012. p. 130–136. ISSN null. Cited on page 31.

TRANSPORT, P. C. on I.; CHEN, K.; MILES, J.; CONGRESSES, P. I. A. of R. *ITS Handbook 2000: Recommendations from the World Road Association (PIARC)*. Artech House, 1999. (Artech House ITS library). ISBN 9781580531030. Disponível em: <https://books.google.com.br/books?id=kCDvpfrMFNsC>. Cited on page 31.

DIRECTOR, S. E. S. D. Review of the state of development of advanced vehicle control systems (avcs). *Vehicle System Dynamics*, Taylor & Francis, v. 24, n. 6-7, p. 551–595, 1995. Disponível em: <https://doi.org/10.1080/00423119508969108>. Cited on page 32.

Pan, J.; Khan, M. A.; Popa, I. S.; Zeitouni, K.; Borcea, C. Proactive vehicle re-routing strategies for congestion avoidance. In: *2012 IEEE 8th International Conference on Distributed Computing in Sensor Systems*. [S.l.: s.n.], 2012. p. 265–272. Cited 3 times on pages 33, 42, and 49.

MENEGUETTE, R.; FILLHO, G.; BITTENCOURT, L.; UEYAMA, J.; VILLAS, L. A solution for detection and control for congested roads using vehicular networks. *IEEE Latin America Transactions*, v. 14, n. 4, p. 1849–1855, April 2016. ISSN 1548-0992. Cited on page 33.

HARTENSTEIN, H.; LABERTEAUX, L. P. A tutorial survey on vehicular ad hoc networks. *IEEE Communications Magazine*, v. 46, n. 6, p. 164–171, June 2008. ISSN 0163-6804. Cited on page 33.

AL-SULTAN, S.; AL-DOORI, M. M.; AL-BAYATTI, A. H.; ZEDAN, H. A comprehensive survey on vehicular ad hoc network. *Journal of Network and Computer Applications*, v. 37, p. 380 – 392, 2014. ISSN 1084-8045. Disponível em: <http://www.sciencedirect.com/science/article/pii/S108480451300074X>. Cited on page 33.

Karagiannis, G.; Altintas, O.; Ekici, E.; Heijenk, G.; Jarupan, B.; Lin, K.; Weil, T. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions. *IEEE Communications Surveys Tutorials*, v. 13, n. 4, p. 584–616, Fourth 2011. ISSN 2373-745X. Cited 2 times on pages 34 and 35.

LI, F.; WANG, Y. Routing in vehicular ad hoc networks: A survey. *IEEE Vehicular Technology Magazine*, v. 2, n. 2, p. 12–22, June 2007. ISSN 1556-6072. Cited 2 times on pages 34 and 38.

Ge, X.; Li, Z.; Li, S. 5g software defined vehicular networks. *IEEE Communications Magazine*, v. 55, n. 7, p. 87–93, July 2017. ISSN 1558-1896. Cited on page 34.

Jiang, D.; Delgrossi, L. Ieee 802.11p: Towards an international standard for wireless access in vehicular environments. In: *VTC Spring 2008 - IEEE Vehicular Technology Conference*. [S.l.: s.n.], 2008. p. 2036–2040. ISSN 1550-2252. Cited on page 36.

IEEE-SA. Ieee guide for wireless access in vehicular environments (wave) architecture. *IEEE Std 1609.0-2019 (Revision of IEEE Std 1609.0-2013)*, p. 1–106, April 2019. ISSN null. Cited on page 37.

IEEE-SA. Ieee trial-use standard for wireless access in vehicular environments (wave) - multi-channel operation. *IEEE Std 1609.4-2006*, p. 1–82, Nov 2006. ISSN null. Cited on page 37.

IEEE-SA. Ieee standard for wireless access in vehicular environments–security services for applications and management messages - amendment 1. *IEEE Std 1609.2a-2017 (Amendment to IEEE Std 1609.2-2016)*, p. 1–123, Nov 2017. ISSN null. Cited on page 37.

IEEE-SA. Ieee standard for wireless access in vehicular environments (wave) – networking services. *IEEE Std 1609.3-2016 (Revision of IEEE Std 1609.3-2010)*, p. 1–160, April 2016. ISSN null. Cited on page 37.

Chen, Q.; Jiang, D.; Delgrossi, L. Ieee 1609.4 dsrc multi-channel operations and its implications on vehicle safety communications. In: *2009 IEEE Vehicular Networking Conference (VNC)*. [S.l.: s.n.], 2009. p. 1–8. ISSN 2157-9865. Cited on page 37.

MEJRI, M. N.; BEN-OTHMAN, J.; HAMDI, M. Survey on vanet security challenges and possible cryptographic solutions. *Vehicular Communications*, v. 1, n. 2, p. 53 – 66, 2014. ISSN 2214-2096. Disponível em: <http://www.sciencedirect.com/science/article/pii/S2214209614000187>. Cited on page 37.

IEEE-SA. Ieee standard for wireless access in vehicular environments (wave)– over-the-air electronic payment data exchange protocol for intelligent transportation systems (its). *IEEE Std 1609.11-2010*, p. 1–62, Jan 2011. ISSN null. Cited on page 37.

OLARIU, S.; WEIGLE, M. C. (Ed.). *Vehicular Networks From Theory to Practice*. Chapman and Hall/CRC, 2009. Disponível em: <https://doi.org/10.1201/9781420085891>. Cited on page 38.

BAZZAN, A. L.; KLÜGL, F. Sistemas inteligentes de transporte e tráfego: uma abordagem de tecnologia da informação. *Anais das Jornadas de Atualização em Informática*, p. 2296–2337, 2007. Cited on page 38.

Jakubiak, J.; Koucheryavy, Y. State of the art and research challenges for vanets. In: *2008 5th IEEE Consumer Communications and Networking Conference*. [S.l.: s.n.], 2008. p. 912–916. ISSN 2331-9860. Cited 3 times on pages 38, 39, and 40.

MARINESCU, D. C. Chapter 5 - cloud access and cloud interconnection networks. In: MARINESCU, D. C. (Ed.). *Cloud Computing (Second Edition)*. Second edition. Morgan Kaufmann, 2018. p. 153 – 194. ISBN 978-0-12-812810-7. Disponível em: <http://www.sciencedirect.com/science/article/pii/B9780128128107000078>. Cited on page 40.

ALVES, R. d. S.; CAMPBELL, I. d. V.; COUTO, R. d. S.; CAMPISTA, M. E. M.; MORAES, I. M.; RUBINSTEIN, M. G.; COSTA, L. H. M.; DUARTE, O. C. M.; ABDALLA, M. Redes veiculares: Princıpios, aplicaçoes e desafios. 2009. Cited on page 40.

Lourenço, M.; Souza, F. S. H.; Silva, C. M.; Meneguette, R. I.; Guidoni, D. L. A hybrid v2i and v2v approach for urban traffic management in vehicular networks. In: *2019 IEEE Latin-American Conference on Communications (LATINCOM)*. [S.l.: s.n.], 2019. p. 1–6. ISSN 2330-989X. Cited 2 times on pages 42 and 46.

Guidoni, D. L.; Maia, G.; Souza, F. S. H.; Villas, L. A.; Loureiro, A. A. F. Vehicular traffic management based on traffic engineering for vehicular ad hoc networks. *IEEE Access*, v. 8, p. 45167–45183, 2020. ISSN 2169-3536. Cited 2 times on pages 44 and 49.

Barba, C. T.; Mateos, M. ; Soto, P. R.; Mezher, A. M.; Igartua, M. A. Smart city for vanets using warning messages, traffic statistics and intelligent traffic lights. In: *Proceedings of the IV IEEE Intelligent Vehicles Symposium (IV)*. [S.l.: s.n.], 2012. p. 902–907. Cited 2 times on pages 45 and 49.

ZAMBRANO-MARTINEZ, J.; CALAFATE, C.; SOLER, D.; LEMUS, L.; CANO, J.-C.; MANZONI, P.; GAYRAUD, T. A centralized route-management solution for autonomous vehicles in urban areas. *Electronics*, v. 8, p. 722, 06 2019. Cited 2 times on pages 45 and 49.

TRB. Chapter 36, travel time reliability. In: _____. *HCM 2010*. [s.n.], 2010. cap. 41, p. i–110. Disponível em: <https://trrjournalonline.trb.org/doi/abs/10.5555/9780309160773.41>. Cited 2 times on pages 47 and 76.

SCHROEDER, B. J. Part 5 - traffic operations. In: FINDLEY, D. J.; SCHROEDER, B. J.; CUNNINGHAM, C. M.; BROWN, T. H. (Ed.). *Highway Engineering*. Butterworth-Heinemann, 2016. p. 255 – 432. ISBN 978-0-12-801248-2. Disponível em: <http://www.sciencedirect.com/science/article/pii/B9780128012482000058>. Cited on page 47.

Akabane, A. T.; Immich, R.; Madeira, E. R. M.; Villas, L. A. imob: An intelligent urban mobility management system based on vehicular social networks. In: *2018 IEEE Vehicular Networking Conference (VNC)*. [S.l.: s.n.], 2018. p. 1–8. ISSN 2157-9857. Cited 2 times on pages 47 and 49.

LI, G.; HE, B.; DU, A. A traffic congestion aware vehicle-to-vehicle communication framework based on voronoi diagram and information granularity. *Peer-to-Peer Networking and Applications*, v. 11, n. 1, p. 124–138, Jan 2018. ISSN 1936-6450. Disponível em: <https://doi.org/10.1007/s12083-016-0491-y>. Cited 2 times on pages 48 and 49.

LOPEZ, P. A.; BEHRISCH, M.; BIEKER-WALZ, L.; ERDMANN, J.; FLÖTTERÖD, Y.-P.; HILBRICH, R.; LÜCKEN, L.; RUMMEL, J.; WAGNER, P.; WIESSNER, E. Microscopic traffic simulation using sumo. In: *The 21st IEEE International Conference on Intelligent Transportation Systems*. IEEE, 2018. Disponível em: <https://elib.dlr.de/124092/>. Cited on page 67.

VARGA, A.; HORNIG, R. An overview of the omnet++ simulation environment. In: *Proceedings of the 1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops*. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2008. (Simutools '08), p. 60:1–60:10. ISBN 978-963-9799-20-2. Disponível em: <http://dl.acm.org/citation.cfm?id=1416222.1416290>. Cited on page 67.

SOMMER, C.; GERMAN, R.; DRESSLER, F. Bidirectionally Coupled Network and Road Traffic Simulation for Improved IVC Analysis. *IEEE Transactions on Mobile Computing*, IEEE, v. 10, n. 1, p. 3–15, January 2011. Cited on page 67.

Cappiello, A.; Chabini, I.; Nam, E. K.; Lue, A.; Abou Zeid, M. A statistical model of vehicle emissions and fuel consumption. In: *Proceedings. The IEEE 5th International Conference on Intelligent Transportation Systems*. [S.l.: s.n.], 2002. p. 801–809. ISSN null. Cited on page 67.

OpenStreetMap contributors. *Planet dump retrieved from https://planet.osm.org* . 2017. <https://www.openstreetmap.org>. Cited on page 67.

Uppoor, S.; Fiore, M. Large-scale urban vehicular mobility for networking research. In: *2011 IEEE Vehicular Networking Conference (VNC)*. [S.l.: s.n.], 2011. p. 62–69. ISSN 2157-9857. Cited on page 83.

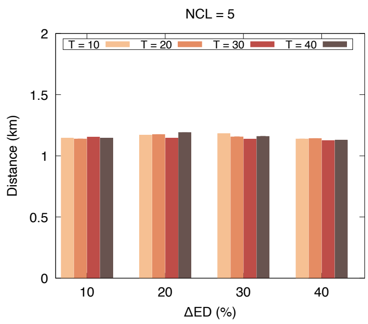
Codeca, L.; Frank, R.; Engel, T. Luxembourg sumo traffic (lust) scenario: 24 hours of mobility for vehicular networking research. In: *2015 IEEE Vehicular Networking Conference (VNC)*. [S.l.: s.n.], 2015. p. 1–8. ISSN 2157-9865. Cited on page 83.

BELLMAN, R. A markovian decision process. *Indiana Univ. Math. J.*, v. 6, p. 679–684, 1957. ISSN 0022-2518. Cited on page 83.

Appendix

APPENDIX A – Exploration Analysis

Section 5.3 shows an exploration analysis that considers only average travel time. The protocol calibration analyzed the results given a comparison between travel time and transmitted messages. However, the extensive analysis also contemplates aspects as travel distance, time loss, speed, consumption of fuel and CO2 emission. Thus, the following section exposes results for 300 and 1000 vehicles/km^2 based on one seed and a 1x1 Manhattan grid scenario.



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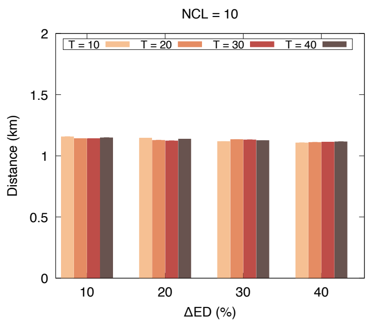

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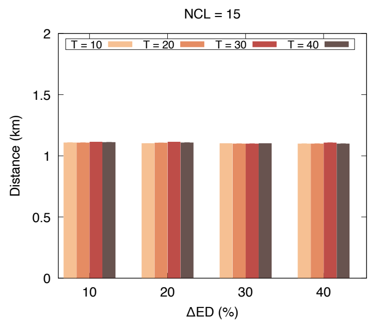

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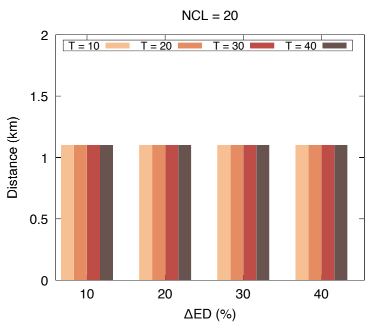

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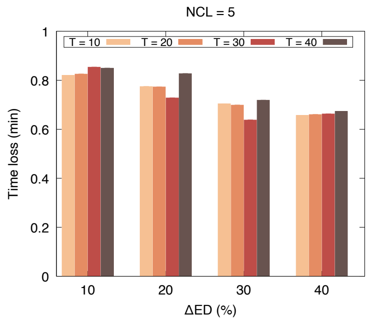
Figure 30 – Distance analysis considering 300 vehicles/km^2



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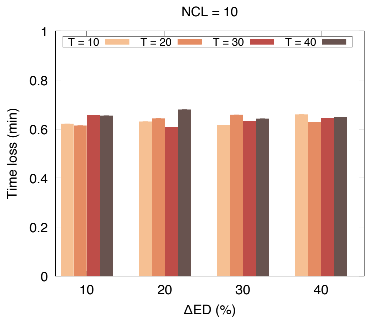

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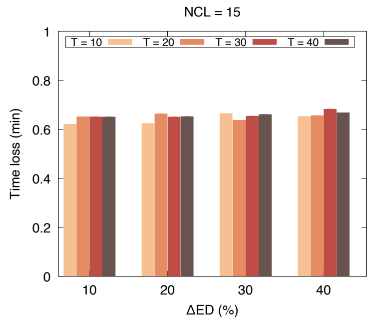

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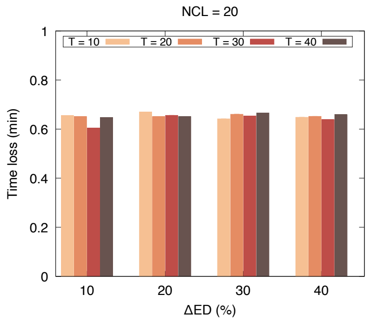

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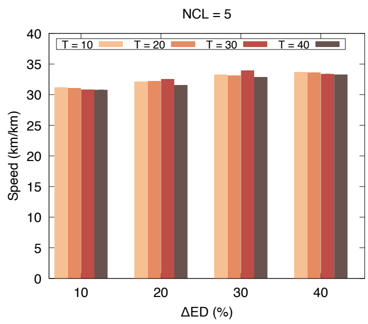
Figure 31 – Time loss analysis considering 300 vehicles/km^2



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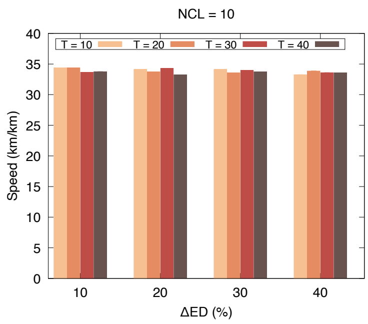

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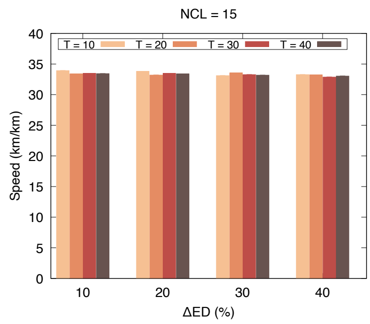

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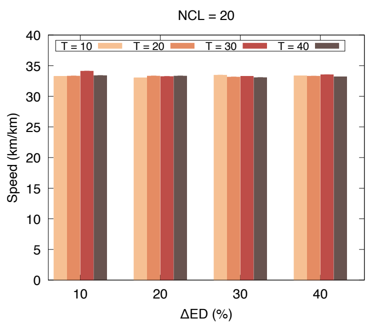

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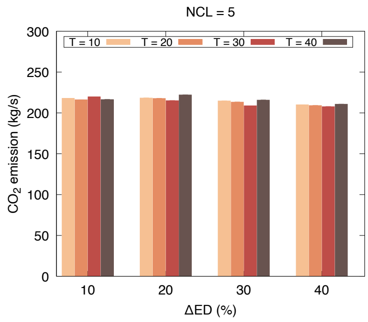
Figure 32 – Speed analysis considering 300 vehicles/km^2



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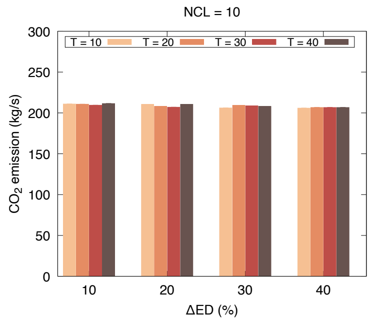

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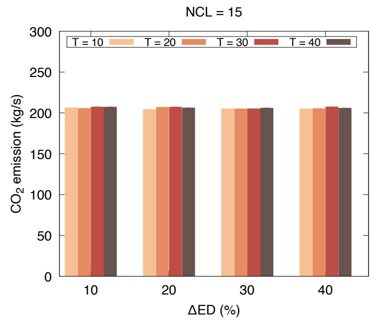

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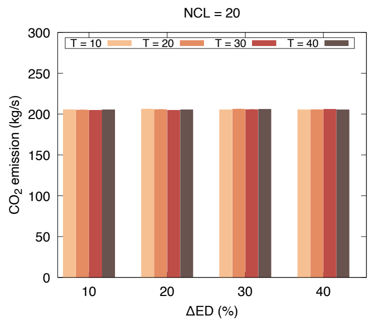

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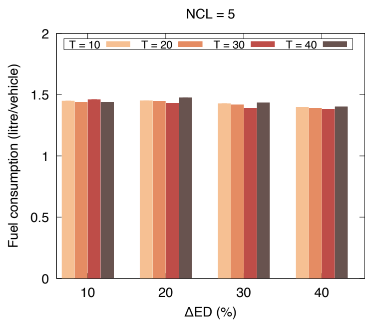
Figure 33 – CO2 analysis considering 300 vehicles/km^2



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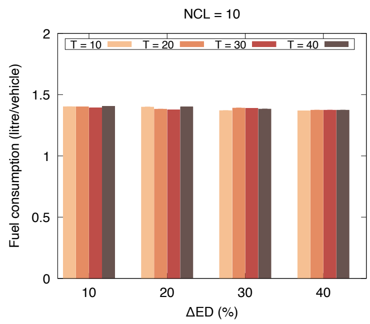

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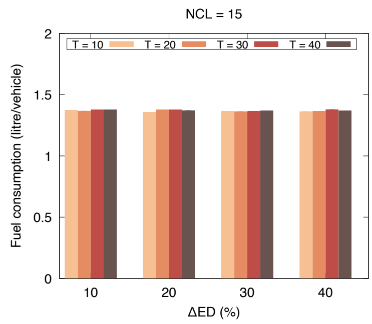

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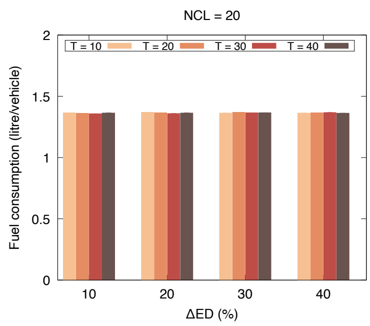

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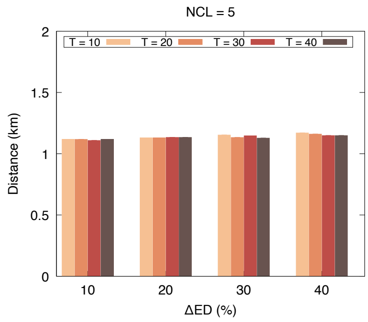
Figure 34 – Fuel analysis considering 300 vehicles/km^2



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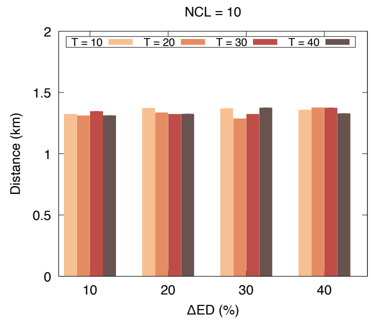

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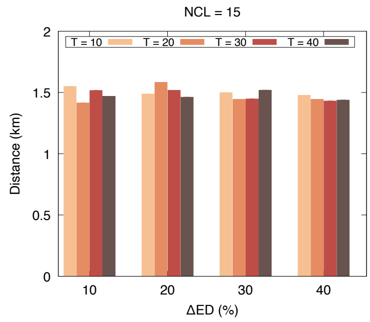

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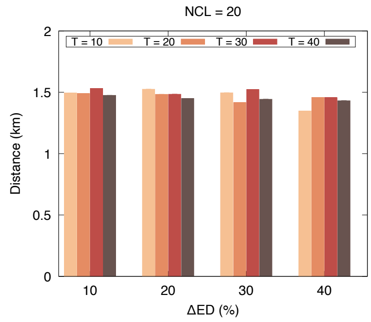

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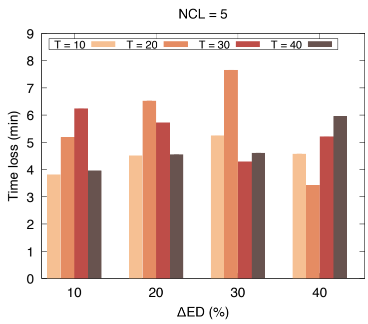
Figure 35 – Distance analysis considering 1000 vehicles/km^2



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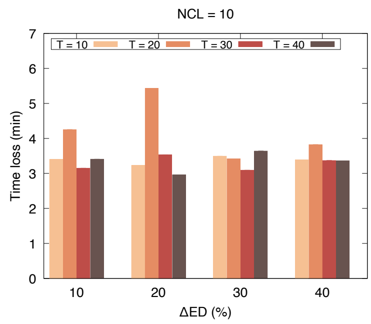

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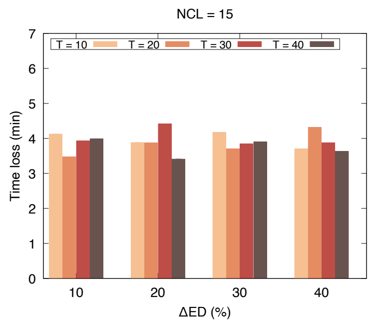

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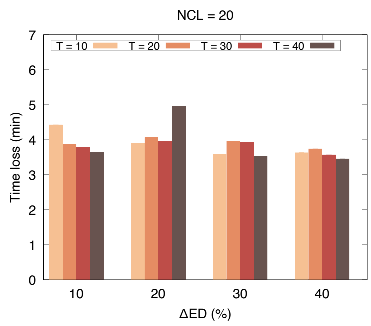

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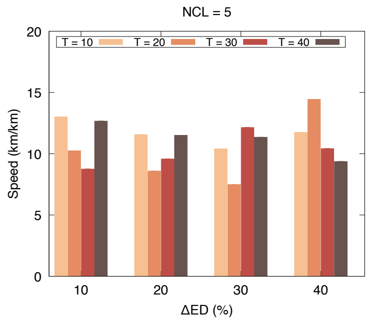
Figure 36 – Time loss analysis considering 1000 vehicles/km^2



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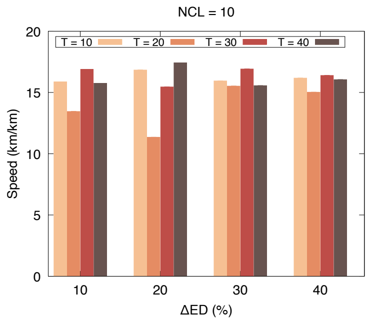

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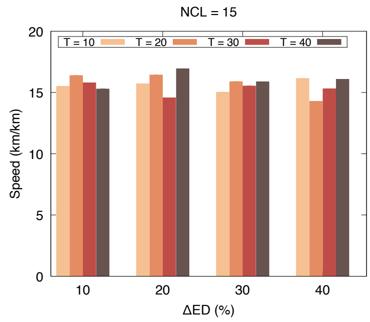

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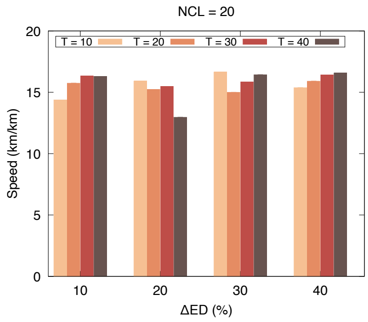

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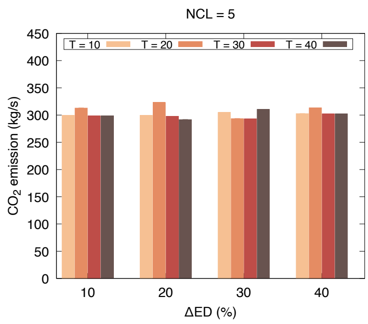
Figure 37 – Speed analysis considering 1000 vehicles/km^2



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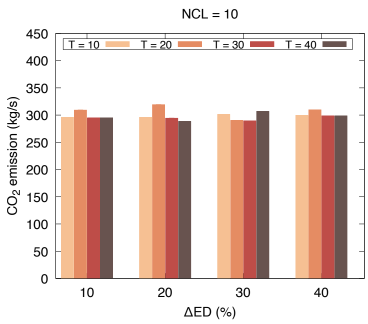

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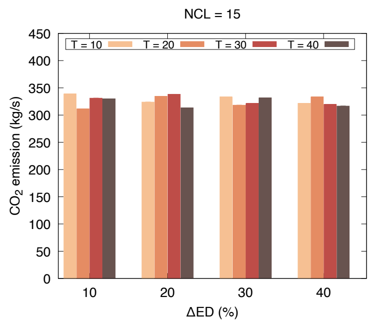

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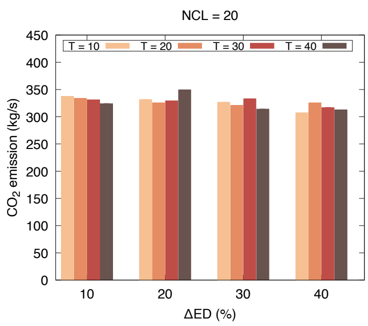

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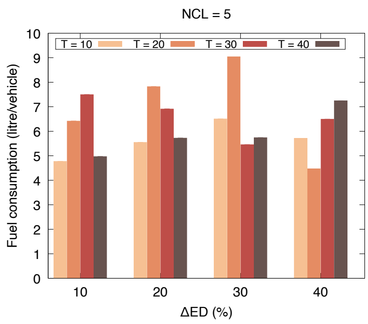
Figure 38 – CO2 analysis considering 1000 vehicles/km^2



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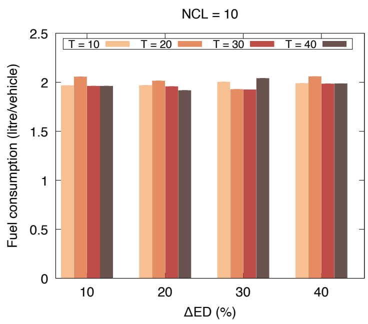

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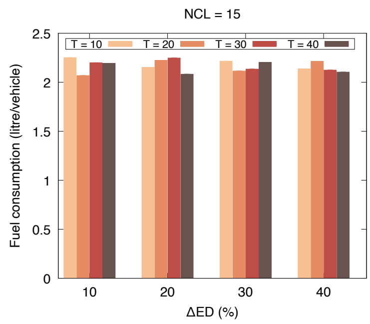

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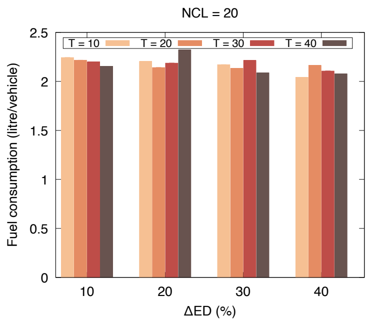

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Figure 39 – Fuel analysis considering 1000 vehicles/km^2