NATIONAL DISTANCE UNIVERSITY OF SPAIN

ARTIFICIAL INTELLIGENCE DEPARTMENT

INTELLIGENT TRAFFIC DISTRIBUTION IN CASE OF ACCIDENT BY USING VEHICULAR COMMUNICATIONS

Master's Thesis in Advanced Artificial Intelligence

Author:
Javier Barrachina Villalba

M.Sc. Advisor:
Dr. Severino Fernández Galán

Madrid, June 2013

Abstract

Currently, one of the most important factors of globalization is transportation. Road traffic is experiencing a drastic growth in recent years, thereby increasing the every day traffic congestion problems, especially in metropolitan areas.

Information Technologies and transportation infrastructure help to manage transportation systems in an accurate and effective manner. Intelligent Transportation Systems will play a leading role in our society, especially in scenarios such as warning drivers about vehicle accidents in real time, efficiently managing vehicle information required by governments and authorities, or even being able to offer drivers a variety of additional services.

In vehicular environments, wireless technologies enable real-time communication between vehicles (V2V) and between vehicles and the infrastructure (V2I). These technologies allow vehicles and traffic control systems to use information about traffic congestion in specific areas, which provides the possibility of selecting fast routes avoiding traffic jams.

A critical issue, especially in urban areas, is the occurrence of traffic accidents, since it could generate traffic jams and the emergency services arrival time can determine the difference between life or death for people involved in the accident. In this Master's Thesis, we propose and compare different systems with the aim of re-routing vehicles circulating in an urban scenario when a vehicle accident takes place, in order to reduce the emergence services arrival time. To do this, we consider two simple routing techniques and two systems based on evolutionary strategies, since the system runtime is as critical as obtaining an optimal solution. In addition, we propose a system able to estimate traffic density by using V2I communications, since traffic density is a key factor when routing vehicles.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Motivation

Currently, the number of vehicles on the roads drastically increases every year, and traffic accidents represent a serious drama in our society. Therefore, safety also acquires a special relevance when accounting for transportation systems. Governments are increasingly establishing restrictive regulations to improve safety on roads, so that current roads are designed to be safer. Moreover, the automotive industry adds new safety elements inside vehicles (e.g. airbags, stability control systems, antilock brake systems, etc.). However, the number of accidents still increases every year all over the world, being the number of fatalities also higher.

A close look at the accidents shows that many of the deaths occurred during the time between the accident and the arrival of medical assistance. The so called 'Golden hour' after a car crash is the time within which medical or surgical intervention by a specialized trauma team has the greatest chance of saving lives. If more than 60 minutes have elapsed by the time the patient arrives to the operating table, the chances of survival fall sharply. The arrival of medical help typically takes about 15 minutes, but initial access and treatment starts 25 minutes after the accident. Transportation of the injured to the hospital usually takes place 50 minutes later. Therefore, time is critical to the survival of the injured in a severe incident. Hence, any technology capable of providing a fast and efficient rescue operation after a traffic accident will increase the probability of survival of the injured, and will also reduce the injury severity [MTC+10].

In order to enable emergency services to reach the crash site in the shortest time possible, redistributing vehicular traffic in the area becomes necessary. This redistribution should benefit, as far as possible, all drivers. Therefore, we must take into account variables such as the number of junctions a vehicle will cross during its route (i. e., number of possible red lights or junctions without preference), the speed of the ways in which it is circulating, the vehicle density in a given area, etc. In particular, we want to reduce traffic density on the roads and junctions used by emergency vehicles (ambulances, fire trucks, police cars, cranes, etc.) in order to improve the emergencies' response when an accident occurs.

Intelligent Transportation Systems will play a leading role in our society, especially in scenarios such as warning drivers about vehicle accidents in real time, efficiently managing vehicle information required by governments and authorities, or even being able to offer drivers a variety of additional services. Wireless technologies, through vehicular networks, enable peer-to-peer mobile communications among vehicles (V2V), as well as communications between vehicles and infrastructure (V2I), which allow avoiding collisions among vehicles. In addition, using these technologies, crashed vehicles are able to alert nearby vehicles, as well as notify emergency services when an accident occurs. The combination of V2V and V2I communications can propel our communication capabilities. Regarding traffic safety, by adding infrastructure to vehicular networks, two benefits are provided: (i) infrastructure can provide Internet access to vehicles, allowing them to communicate with the emergency services immediately, thereby reducing notification times in case of an accident, and (ii) infrastructure access points can rebroadcast messages delivered by vehicles in low vehicle density scenarios (allowing messages to reach more vehicles).

Global Positioning System (GPS) navigation devices are used more and more in vehicles by drivers for relatively short distances and even known routes (since many of them are updated considering streets closed for construction, historical traffic, etc.). This technology calculates vehicles routes taking into account the shortest distance between two points, or the faster route considering the speed of the streets, but not contemplating the current traffic density. In addition, these systems do not consider special situations as accidents, traffic jams, or road works. For this reason, we propose as Master's Thesis research work an Intelligent Vehicle Routing System that takes into account traffic density. The main goal of this work is proposing a novel technique for 'cleaning' the route used by the emergency services as much as possible in order to reduce the time required by emergency services to perform the resume process, without significantly increasing the travel time of the rest of vehicles.

1.2 Objectives of the Master's Thesis

The first objective of this Master's Thesis is to propose an approach to reducing the emergency services arrival time when a car accident occurs, in order to improve the chances of survival for passengers involved in it. A faster rescue will increase the chances of survival and recovery for injured victims. Thereby, once the accident has occurred, it is crucial to quickly manage the rescue vehicles so that they arrive as quickly as possible to the location of the accident. This situation is more complicated in urban scenarios since the number of vehicles circulating in urban areas is higher compared to nonurban areas since urban streets and roads may have higher traffic delays during rush hours.

As the second objective of this work, we consider that the travel time of the rest of vehicles circulating in the accident area must be the lowest possible. When an accident occurs, circulation through several streets or roads may be interrupted (for instance, when the vehicles involved in the accident occupy the entire road and they can not be moved). In order to develop this system, we consider interesting to know the traffic density of the areas surrounding the accident for the purpose of redistributing traffic efficiently, since distributing traffic randomly could collapse another surrounding area. Also, we must take into account that the streets or roads along which the emergence services vehicles are circulating to reach the scene of the accident must be as empty as possible (the number of vehicles circulating on they must be the least possible), in order to not interfere with the routes of the emergency services' vehicles.

Finally, the third objective of this Master's Thesis is that our developed system must be able to obtain a valid result in the shortest time possible. This objective is very important because time is a relevant factor, since, as we mentioned above, a faster rescue will increase the chances of survival and recovery for injured victims. For this reason, we propose different possible approaches and compare them. Taking into account the obtained results, we will select the best system, in terms of vehicles travel time, emergence services arrival time, and approach runtime, since time has a special importance in these kinds of situations.

1.3 Organization of the Dissertation

This Master's Thesis dissertation is organized as follows: Chapter 2 shows how Vehicular Networks can be used in Intelligent Transportation Systems (ITS), emphasizing on how vehicular networks may improve the current emergency services response to traffic accidents. We also make an introduction to Vehicular Networks, showing their main characteristics and applications.

In Chapter 3 we present a novel solution to estimate the density of vehicles that has been especially designed for Vehicular Networks. This proposal allows improving proactive traffic congestion mitigation mechanisms to better redistribute vehicles' routes, while adapting them to the specific traffic conditions.

Chapter 4 proposes a novel infrastructure-based intelligent vehicle routing approach, specially designed to redistribute traffic in case of an accident. We also present other similar approaches and compare them in order to demonstrate that vehicle density is a very important factor to reduce the computation time, increasing the system efficiency with the aim of: (i) reducing rescue time in case of an accident, and (ii) not increasing the travel time of other vehicles significantly.

Finally, Chapter 5 presents a summary of the main results of this Thesis, along with some concluding remarks. In addition, we comment possible future research works that can derive from the work here presented.

Chapter 2

Vehicular Networks

Over the years, we have harnessed the power of computing to improve the speed of operations and increase in productivity. Also, we have witnessed the merging of computing and telecommunications. This excellent combination of two important fields has propelled our capabilities even further, allowing us to communicate anytime and anywhere, improving our work flow and increasing our life quality tremendously.

The next wave of evolution we foresee is the convergence of telecommunications, computing, wireless, and transportation technologies. Once this happens, our roads and highways will be both our communications and transportation platforms, which will completely revolutionize when and how we access services and entertainment, how we communicate, commute, navigate, in the coming future. This chapter presents an overview of the current state-of-the-art, discusses current projects, their goals, and finally highlights how emergency services and road safety will evolve with the blending of vehicular communication networks and road transportation.

2.1 Introduction

The population of the world has been increasing, with China and India being the two most densely populated countries. Road traffic has also been getting more and more congested, as a higher population and increased business activities result in greater demand for cars and vehicles for transportation. While careful city planning can help to alleviate transportation problems, such planning does not usually scale well over time with unexpected growth in population and road usage.

Modernization, migration, and globalization have also taken great tolls on road usage. Inadequacy in transportation infrastructures can cripple a nation's progress, social well-being, and economy. It can also make a country less appealing to foreign investors and can cause more pollution as vehicles spend a longer time waiting on congested roads. Increased delays can also result in road rage, which gives rise to more social problems, which are undesirable. With fuel price soaring and potential threats of fuel shortage, we are now faced with greater challenges in the field of transportation systems. In addition to this trend, technology has also impacted transportation, giving it a different outlook.

In the past, people were focused on how to build efficient highways and roads. Over time, focus shifted to mechanical and automotive engineering, in the pursuit of building faster cars to surmount greater distances. Later on, electronics technology impacted the construction of cars, embedding them with sensors and advanced electronics, making cars more intelligent, sensitive and safe to drive on. Now, innovations made so far in wireless mobile communications and networking technologies are starting to impact cars, roads, and highways. This impact will drastically change the way we view transportation systems of the next generation and the way we drive in the future. It will create major economic, social, and global impact through a transformation taking place over the next 10-15 years. Hence, technologies in the various fields have now found common grounds in the broad spectrum of the Next Generation Intelligent Transportation Systems (ITS).

In this chapter we examine the impact of future ITS technologies on road safety and emergency services. This chapter is organized as follows: Section 2.2 introduces the current advances and world trends regarding road safety, vehicular communication networks, and telematics. Section 2.3 presents the motivation of using wireless networks in vehicular environments. Section 2.4 discusses the problems related to road safety and the emergency services. The evolution of communications in emergency services when an accident occurs is described in Section 2.5. Section 2.6 presents the different issues

Table 2.1: ITS projects in Japan

Japan ITS Funded Projects	**Remarks**
AHS [mli03]	**Advanced Cruise-Assist Highway Systems** It aims at reducing traffic accidents, enhancing safety, improving transportation efficiency, as well as reducing the operational work of drivers. AHS research is being carried out in the following fields: - AHS-“i” (information) focusing on providing information. - AHS-“c” (control): vehicle control assistance. - AHS-“a” (automated cruise): fully automated driving. Its applications include obstacle detection and avoidance, speed control, driving control and man-machine interfaces.
ASV [mli03]	**Advanced Safety Vehicle** It was launched in order to transfer advanced technologies to vehicles for their greater safety. In the second phase, the extent of research has been expanded to include trucks, buses and motorcycles. Automated driving technology and basic vehicular technology areas have been added to the major safety technology field. Also, research and development will be promoted in connection with infrastructures, using two systems: autonomous type and infrastructure-employed type. This will make it possible to combine ASV with AHS.

regarding ITS and vehicular communications that we envision. In Section 2.7 we make an introduction to Vehicular Ad Hoc Networks (VANETs), showing their main characteristics and applications. Finally, Section 2.8 concludes this chapter.

2.2 Advances and Trends in Vehicular Network Technologies

Recently, there have been several projects and research efforts conducted globally to address road safety, vehicular communication networks, and telematics.

IN KOREA - The Korean Telematics Business Association was established in 2003 with the aim of boosting the telematics industry and to standardize telematic technologies and services. Its members are primarily automakers, telecommunication companies, terminal manufacturers, and content providers. Its core functions include: (a) coordinating Korean government projects related to telematics, (b) market promotion, (c) standardization efforts, and (d) international collaboration in conferences, road shows, etc.

IN JAPAN - The topics on ITS have been actively addressed by Japanese researchers and Japanese government agencies over the years. Specifically, the Japanese Ministry of Land, Infrastructure and Transport (MLIT) is the bureau of the Japanese government that decides on policies in ITS. In Japan, ITS are viewed as a new transport system that comprises an advanced information and telecommunications network for users, roads, and vehicles. Specifically, nine development areas have been identified: (a) navigation systems, (b) electronic toll collection systems, (c) assistance for safe driving, (d) optimization of traffic management, (e) efficiency in road management, (f) support for public transport, (g) efficiency in commercial vehicles, (h) support for pedestrians, and (i) support for emergency vehicle operations. Table 2.1 shows the most important ITS projects funded by the Japanese MLIT. Both projects aim to enhance safety and reduce traffic accidents while improving transportation efficiency.

IN THE USA - There are two major programs sponsored by the US DoT (Department of Transportation). The first one is the Vehicle Safety Communication (VSC) project. The second one is related to Vehicle Infrastructure Integration (VII). A VII consortium has been formed to engage key industrial players, state and local governments, as well as other partners to work on an information infrastructure for real-time communications between vehicles. The motivations for a VII program in the USA are well justified. American roadways indeed have a safety and congestion problem. In fact, in 2006, there were 6 million traffic crashes in the USA alone, injuring about 2.6 million people. Also, it was observed that a crash occurred every 5 seconds, with someone sustaining a traffic-related injury every 12 seconds. Even

Table 2.2: ITS projects in the USA

USA ITS Funded Projects	Remarks
VSC [vsc11]	**Vehicle Safety Communication** The main objectives of the VSC project are: - Estimate the potential safety benefits of vehicle safety applications. Define preliminary communications requirements for the high-priority vehicle safety applications. - Evaluate proposed DSRC standards, identify specific technical issues, present vehicle safety requirements, and secure DSRC for safety applications at real intersections. - Identify channel capacity in stressing traffic environments as a large scale deployment issue, determining that the 5.9 GHz DSRC wireless technology is potentially best able to support the communications requirements.
VII [vii11]	**Vehicle Infrastructure Integration** VII will enable safety, mobility, and commercial vehicular services and applications. It will exploit innovations in wireless communications and networking technologies, along with sensing and advanced user interfaces. When deployed, the VII network will allow drivers and travelers to access traffic conditions and routing information, receive warnings about existing or upcoming hazards, and conduct wireless commercial transactions while on-the-move.

worse, someone died in a traffic crash every 12 minutes. This death toll is major and astonishing. In addition, road congestion problems have resulted in 4.2 billion hours of travel delay, 2.9 billion gallons of gasoline fuel wasted, and a net urban congestion cost of about $80 billion (according to a 2007 report by the Texas Transportation Institute). Table 2.2 shows the most important USA ITS projects.

IN EUROPE - There are a lot of integrated projects funded by the European Commission under the EU IST 6th Framework (FP6) (2002-2006), and the EU 7th Framework (FP7) extends the program further till 2013. The White Paper on EU Transport Policy for 2010 states a key objective, i.e., 50% reduction of casualties due to road accidents by the end of 2010. Improvements on road safety are achievable by increasing the EU market penetration of Advanced Driver Assistance Systems (ADAS), currently limited by the performance and cost of sensor technologies. This is the prime focus of the European ITS research program. Tables 2.3, 2.4, 2.5, and 2.6 describe some of the most relevant ITS projects funded by the European Union. These projects cover a wide spectrum of research areas, including driver-vehicle interfaces, emergency rescue, preventive road safety, on-board sensors, pedestrian detection, intersection safety, cooperative systems and cooperative networks, maps and geographical technologies, and vehicle-to-vehicle (V2V) communications. In this chapter, we focus on how vehicular communication networks have impacted road safety, and how emergency services will evolve in the future.

2.3 Vehicular Networks: Rationale & Motivation

In the past, the automotive industry built powerful and safer cars by embedding advanced materials and sensors. With the advent of wireless communication technologies, cars are being equipped with wireless communication devices, enabling them to communicate with other cars. Such communications are not plainly restricted to data transfers (such as emails, etc.), but also create new opportunities for enhancing road safety. Some applications only require communication among vehicles, while other applications require the coordination between vehicles and the road-side infrastructure.

The applications and advantages of using vehicular communication networks for enhancing road safety and driving efficiency are diverse, which explains why research in this area has recently emerged. Vehicular communications, however, need the support of reliable link and channel access protocols. The IEEE 802.11p wireless access in vehicular environments (WAVE) [IEE10] is a standardization effort that provides a protocol suite to support vehicular communications in the 5.9 GHz licensed frequency band

Table 2.3: ITS projects in EU

EU ITS Funded Projects	**Remarks**
AIDE [aid11b]	**Adaptive Integrated Driver-vehicle Interface** The general objective is to generate knowledge and develop methodologies and human-machine interface technologies required for safe and efficient integration of ADAS (Advanced Driver Assist Systems), IVIS (In-Vehicle Information Systems) and nomad devices into the driving environment. The aims of AIDE are: - to maximize the efficiency, and hence the safety benefits, of advanced driver assistance systems - to minimize the level of workload and distraction imposed by in-vehicle information systems and nomad devices - to enable the potential benefits of new in-vehicle technologies and nomad devices in terms of mobility and comfort
AIDER [aid11a]	**Accident Information and Driver Emergency Rescue** The AIDER project's main objective is the reduction of road accident consequences by optimizing the rescue management in terms of operative time and effectiveness. AIDER vehicles will be equipped with a detection system to monitor the on-board pre- and post-crash environment. The project envisaged a kind of automotive "black box", which would continually assess a car's environment, including speed, terrain and many other factors. Should there be an accident, the box would perform a quick calculation, comparing the state of the vehicle before and after impact. This would yield important information about where the car was hit, how quickly the car stopped, and therefore how severe the accident was. The box would then alert a call center with essential details about the nature of the crash, which could be reconstructed. Since the emergency services would be contacted immediately and provided with details about the accident, they would arrive more quickly and be better prepared for specific injuries.
ATLANTIC [atl11]	**A Thematic Long-term Approach to Networking for the Telematics & ITS Community** The ATLANTIC Thematic network will operate as an Electronic Forum organized and coordinated through three geographically based network coordinators, one for each of Europe, Canada and USA. The ATLANTIC project has three parts: (1) Operation of an ITS Forum based on e-mail groups, involving key individuals in the field of Transport Telematics and Intelligent Transport Systems (ITS). The Forum sub-groups will be benchmarking the coverage, content and results of the European ITS programs against similar activities in the USA and Canada. (2) International meetings with American and Canadian partners in the project, which are self-funded. (3) Development of good practice and policy on telematics-based travel information services for cities and regions.

Table 2.4: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
PREVENT [pre11]	**Preventive and Active Safety Applications Contribute to the Road Safety Goals on European Roads** In PReVENT, a number of subprojects are proposed within clearly complementary function fields: Safe Speed and Safe Following, Lateral Support and Driver Monitoring, Intersection Safety, and Vulnerable Road Users and Collision Mitigation. The goal of Integrated Project PReVENT is to contribute to the: - Road safety goal of 50% fewer accidents by 2010 - as specified in the key action eSafety for Road and Air Transport from the European Union. - Competitiveness of the European automotive industry. - European scientific knowledge community on road transport safety. - Congregation and cooperation of European and national organizations and their road transport safety initiatives.
ADOSE [ado11]	**Reliable Application Specific Detection of Road Users with Vehicle On-board Sensors** ADOSE addresses research challenges in the area of "accident prevention through improved-sensing including sensor fusion and sensor networks". Focus is also on "increased performance, reliable and secure operation" for "new generation advanced driver assistance systems". The project is focused mainly on sensing elements and their pre-processing hardware, as a complementary project to PReVENT. Novel concepts and sensory systems will be developed based on Far Infrared cameras, CMOS vision sensors, 3D packaging technologies, ranging techniques, bio-inspired silicon retina sensors, harmonic microwave radar and tags.
INTERSAFE-2 [int11]	**Cooperative Intersection Safety** The INTERSAFE-2 project aims to develop and demonstrate a Cooperative Intersection Safety System (CISS) that is able to significantly reduce injury and fatal accidents at intersections. The novel CISS combines warning and intervention functions based on novel cooperative scenario interpretation and risk assessment algorithms. The cooperative sensor data fusion is based on advanced on-board sensors for object recognition, a standard navigation map, and information supplied over a communications link from other road users via V2V and infrastructure sensors and traffic lights via V2I.
SAFERIDER [saf11a]	**Advanced Telematics for Enhancing the Safety and Comfort of Motorcycle Riders** SAFERIDER aims to study the potential of ADAS/IVIS integration on motorcycles for the most crucial functionalities, and develop efficient and rider-friendly interfaces and interaction elements for riders' comfort and safety. SAFERIDER aims to enhance riders' safety by introducing four ADAS applications: (a) speed alert, (b) curve speed warning, (c) frontal collision warning, and (d) intersection support.

Table 2.5: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
SafeSpot [saf11b]	**Cooperative vehicles and road infrastructure for road safety** The objective of the project is to understand how intelligent vehicles and intelligent roads can cooperate to increase road safety. SafeSpot seeks to: - Use the infrastructure and the vehicles as sources and destinations of safety-related information and develop an open, flexible and modular architecture and communications platform. - Develop the key enabling technologies: ad-hoc dynamic network, accurate relative localization, dynamic local traffic maps. - Develop and test scenario-based applications to evaluate the impacts on road safety. - Define a sustainable deployment strategy for cooperative systems for road safety, evaluating also related liability, regulations and standardization aspects.
I-WAY [iwa11]	**Intelligent Cooperative Systems in Car for Road Safety** The goal of I-WAY is to develop a multi-sensorial system that can ubiquitously monitor and recognize the psychological condition of drivers as well as special conditions prevailing in the road environment. The I-WAY platform targets mainly road users, but it is a highly modular system that can be easily adapted or break up in standalone modules in order to accommodate a wide variety of applications and services in several fields of transport, thanks to its interoperability and scalable system architecture. The I-Way project is strongly committed to achieve the two strategic objectives of (a) increasing road safety, and (b) bettering transport efficiency.
COMeSafety [com11]	**Communications for eSafety** The COMeSafety Project supports the eSafety Forum with respect to all issues related to V2V and V2I communications as the basis for cooperative intelligent road transport systems. COMeSafety provides an open and integrating platform, aiming at representing the interests of all public and private stakeholders. COMeSafety acts as a broker for the consolidation and following standardization of research project results, work of the C2C-CC and the eSafety Forum. Its aims are: - Coordination and consolidation of research results and their implementation. - eSafety Forum support in case of Standardization and Frequency Allocation. - Worldwide harmonization (Japan/US/Europe). - Support the frequency allocation process. - Dissemination of the results.

Table 2.6: ITS projects in EU (Cont.)

EU ITS Funded Projects	**Remarks**
HIGHWAY [hig11]	**Breakthrough Intelligent Maps and Geographic Tools for the context-aware-delivery of E-safety and added value services** HIGHWAY combines smart real-time maps, UMTS 3G mobile technology, positioning systems and intelligent agent technology, 2D/3D spatial tools, and speech synthesis/voice recognition interfaces to provide European car drivers and pedestrians with eSafety services and interaction with multimedia and value-added-location-based services. HIGHWAY maps will help drivers facing critical driving situations.
CarTALK2000 [car11]	**Advanced driver support system based on V2V communication technologies** CarTALK2000 was established within the EU's ADASE2 (Advanced Driver Assistance Systems Europe) ITS project. Its main objectives were the development of cooperative driver assistance systems and a self-organizing ad hoc radio network as the basis for communication with the aim of preparing a future standard. It incorporated three applications: a warning system; a longitudinal control system; and a cooperative driving assistance system.
COOPERS [coo11]	**Cooperative Networks for Intelligent Road Safety** COOPERS focuses on the development of innovative telematic applications on the road infrastructure with the long term goal of a Cooperative Traffic Management between vehicle and infrastructure, thus reducing the self opening gap on telematic application development between car industry and infrastructure operators. The goal of the project is the enhancement of road safety by direct and up-to-date traffic information based on wireless communication between infrastructure and motorized vehicles on a motorway section.
CVIS [cvi11]	**Cooperative Vehicle-Infrastructure Systems** Contrarily to SafeSpot, this European project focuses on vehicle-to-infrastructure communications alone. The goals set are: - To create a unified technical solution allowing all vehicles and infrastructure elements to communicate with each other in a continuous and transparent way using a variety of media with enhanced localization. - To define and validate an open architecture and system concept for a number of cooperative system applications, and develop common core components to support cooperation models in real-life applications and services for drivers, operators, industry and other key stakeholders. - To address issues such as user acceptance, data privacy and security, system openness and interoperability, risk and liability, public policy needs, cost/benefit and business models, and roll-out plans for implementation.

(5.85-5.925 GHz).

WAVE supports both vehicle-to-infrastructure (V2I) and vehicle-to-vehicle (V2V) communications. Also, WAVE can enhance road safety and driving efficiency since it offers the required support to provide faster rescue operations, generate localized warnings of potential danger, and convey real-time accident warnings. WAVE complements satellite, WiMax, 3G, and other communications protocols by providing high data transfer rates (3-54 Mbps) in circumstances where the latency in the communication link is too high, and where isolating relatively small communication zones is important. Details about radio frequencies, modulation, link control protocols and media access can be found in [UDSAM09].

Concerning safety using vehicular networks, in [Toh07], cars can act as communication relays (routers) to form ad hoc vehicular networks via wireless communication links. Cars are restricted by the physical boundaries of the road and highways. For example, cars on one lane all travel in the same direction, keeping ample safe distance from one to another. The ability of neighboring cars to communicate wirelessly allows them to warn each other about any abnormalities or potential dangers. This, in contrast to the old way of "signaling" using visual lights, is far superior, especially when visibility is poor due to bad weather conditions. Another scenario is the ability of cars to convey accident information to other neighboring cars via V2V communications so that they can slow down and be aware of the potential danger ahead. Also, in times of road congestion, V2V communications can allow other cars further down the road to make plans to exit the highway or to seek alternate routes to their destinations, hence avoiding further congestions.

V2V communications have the following advantages: (i) allow short and medium range communications, (ii) present lower deployment costs, (iii) support short messages delivery, and (iv) minimize latency in the communication link. Nevertheless, V2V communications present the following shortcomings: (i) frequent topology partitioning due to high mobility, (ii) problems in long range communications, (iii) problems using traditional routing protocols, and (iv) broadcast storm problems [TNCS02] in high density scenarios.

Currently, there are several projects that address V2V communication issues. Wisitpongphan et al. [WTP$^+$07] quantified the impact of broadcast storms in VANETs in terms of message delay and packet loss rate, in addition to conventional metrics such as message reachability and overhead. They proposed three probabilistic and timer-based broadcast suppression techniques: (i) the weighted p-persistence, (ii) the slotted 1-persistence, and (iii) the slotted p-persistence scheme. The authors also studied the routing problem in sparse VANETs [WBM$^+$07]. In [TWB07], they proposed a new Distributed Vehicular Broadcasting protocol (DV-CAST) to support safety and transport efficiency applications in VANETs. Results showed that broadcasting in VANET is very different from routing in mobile ad hoc networks (MANET) due to several reasons such as network topology, mobility patterns, demographics, and traffic patterns at different times of the day. These differences imply that conventional ad hoc routing protocols will not be appropriate in VANETs for most vehicular broadcast applications. The designed protocol addressed how to deal with extreme situations such as dense traffic conditions during rush hours, sparse traffic during certain hours of the day (e.g., midnight to 4 am in the morning), and low market penetration rate of cars using DSRC technology. Table 2.7 shows some of the major testbeds related to ITS/VANET developed by National Labs and Universities that have been used to test and evaluate vehicular network solutions.

Concerning V2I, current research efforts include: (a) information dissemination for VANETs, especially using advanced antennas [KRS$^+$07], (b) VANET/Cellular interoperability [SRS$^+$08], and (c) WiMAX penetration in vehicular scenarios [YOCH07]. The integration of Worldwide Interoperability for Microwave Access (WiMAX) and Wireless fidelity (WiFi) technologies seems to be a feasible option for better and cheaper wireless coverage extension in vehicular networks. WiFi, under the 802.11p standard, is a good candidate to be used in V2V communications. Its weakness is short coverage. WiMAX multi-hop relay networks that employ relay stations could extend coverage and reduce the cost of deploying a vehicular infrastructure in the near future. With the emergence of new applications (Internet access, infotainment, social networking, etc.), the use of fixed infrastructure will become an attractive option [WTP$^+$07].

A prerequisite for the successful deployment of vehicular communications is to make the system secure. It is essential, for example, to make sure that critical information cannot be modified by any attacker (hacker). Recently, there has been some work dealing with security for VANETs. In [RH05], the authors provided a detailed threat analysis and devised an appropriate security architecture. They also provided a set of security protocols, and analyzed their robustness. In [CPHL07], the authors showed how to achieve efficient and robust pseudonym-based authentication. They presented mechanisms that reduce the security overhead for safety beaconing, and retain robustness for transportation safety, even

Table 2.7: ITS/VANET testbeds developed by National labs and Universities

Institution	**Remarks**
Carnegie Mellon University [cmu11]	The GM Collaborative Research Lab at Carnegie Mellon University developed the Smart Car testbed, which allows the car to recognize the driver's settings and keep him alert. It has the following features: - "Context aware", i.e. it responds to driver's needs and preferences, road and weather conditions, and information from the Internet based on demand. - It is also equipped with a "gesture interface" that allows drivers to control the car's electronics with a wave of their hand. - Built with a speech recognition system tuned to the driver's voice that connects the car to handheld computers and cell phones. - Assembled with a heads-up display for operating the radio, navigating, checking email, and the driver's schedule.
German Consortium [sim11]	A Consortium formed by automotive and telecommunication companies, the state government, and German universities is collaborating in the simTD initiative which tries to put the results of previous research projects into practice. The overall simTD test fleet comprises an internal fleet with up to 100 controlled test vehicles as well as an external fleet with approximately 300 vehicles. The internal simTD fleet of test vehicles comprises 20 core vehicles with expert drivers. 80 further vehicles are driven by persons without special training. The expert drivers will be asked to work together locally and on their own initiative to create certain scenarios. The other drivers' reaction to the respective scenario can then be used to evaluate its efficiency, safety, and acceptability of functions.
Rutgers University [rut11]	The DisCo Lab developed TrafficView, which defines a framework to disseminate and gather information about the vehicles on the road. With such a system, a vehicle's driver will be provided with road traffic information that helps driving in situations such as foggy weather, or finding an optimal route in a trip several miles long. The demonstration of the TrafficView system was performed with four vehicles, which continuously exchanged speed and location information over wireless networking technology, as they navigated across the Rutgers University campus.
Berkeley [pat11]	The California Partners for Advanced Transit and Highways (PATH) and the Department of Transportation (Caltrans) in partnership with public agencies and private industry are working in vehicle-to vehicle and vehicle-to-roadside communications on their IntelliDrive (formerly Vehicle-Infrastructure Integration, VII) testbed. IntelliDrive is a multimodal initiative that aims to enable safe, interoperable networked wireless communications among vehicles, the infrastructure, and passengers' personal communications devices.

in adverse network settings. Their proposal enabled vehicle on-board units to generate their own pseudonyms, without affecting the system security. In [YOW09], the authors suggested a method of using on-board radar to detect neighboring vehicles and to confirm their announced coordinates. They addressed position security and ways to counteract Sybil attacks.

In this Master's Thesis we focus on traffic safety applications, in order to reduce the rescue time in case of an accident (increasing the probability of survival of the injured). Specifically, using this technology together with Artificial Intelligence (AI) systems, we reduce the assistance time while maximizing the assistance quality, as well as minimizing the cost.

2.4 Road Safety and Emergency Services

Driver safety involves several factors such as understanding road conditions, having an appropriate response time towards emergencies, crash prevention procedures, etc. Overall, it is accepted that increased road safety can be achieved by exchanging relevant safety information via V2V and V2I communications, where alert information is either presented to the driver or used to trigger active safety systems (such as air bags and emergency brakes). Some of these applications will only be possible if the penetration rate of VANET-enabled cars is high enough.

A collision warning system on a vehicle needs to know the trajectories of neighboring vehicles and the configuration of the neighboring roadway. Most collision warning systems in the literature learn about the state of the neighborhood by using sensors like radar or laser vision systems.

In contrast, modern Cooperative Collision Warning (CCW) systems will construct their knowledge of the neighborhood by listening to the wireless transmissions of other vehicles. This has the advantage of a potentially inexpensive complement of on-board vehicle equipment (compared to ranging sensors, that could provide 360-degree coverage), as well as providing information from vehicles that may be occluded from direct line-of-sight of the approaching vehicle [SRS+07].

Examples of CCW applications are: (a) Forward Collision Warning (FCW), where a host vehicle uses messages from the immediate forward vehicle in the same lane to avoid forward collisions, (b) Lane Change Assistance (LCA), where a host vehicle uses messages from the adjacent vehicle in a neighboring lane to assess unsafe lane changes, and (c) Electronic Emergency Brake Light (EEBL), where a host vehicle uses messages to determine if one, or more, leading vehicles in the same lane are braking.

Cooperative Driving allows drivers to share information about traffic in order to reduce the incidence of traffic jams, minimize CO2 emissions and prevent accidents on the road. It could also help authorities by providing information about vehicles, their location, and road conditions.

2.4.1 Hazards / Accident Contributing Factors

Road hazards can involve drivers, passengers, and pedestrians on the road. On residential roads, pedestrians are vulnerable as they walk along the sides of the road. At intersections, drivers, passengers, and pedestrians are vulnerable to accidents and collisions. At sharp blends and angles, cars can lose sight of other cars coming from opposite lanes, resulting in unexpected front-end collisions. Poor environmental conditions such as bad weather can also cause accidents. Under situations of heavy rain and fog, poor visibility is the prime factor contributing to car accidents. Slippery roads can also cause cars to skid and result in accidents. Other factors such as natural disasters (e.g. earthquakes) can also result in accidents. Notice that not all environment-based accidents can be rectified or improved.

Another cause for accidents is the driver himself. Drivers who are criminals on-the-run frequently drive at high speeds to avoid police chase. They ignore other on-going vehicles and, at times, even drive in the opposite direction. Such accidents are usually catastrophic. Reckless drivers are those who are usually careless. They change lane without signaling or observing the presence of neighboring cars, resulting in accidents. Fatigued drivers are those who have exhausted themselves physically and hence become less alert while driving. They, too, contribute to accidents due to their slow response to changing road conditions.

The golden hour after a car crash is illustrated by Figure 2.1. It is the time within which medical or surgical intervention by a specialized trauma team has the greatest chance of saving lives. If more than 60 minutes have elapsed by the time the patient reaches the operating table, the chances of survival fall sharply. As shown, typical arrival of medical help takes about 15 minutes. Initial access and treatment only start 25 minutes later. Transportation of the injured to the hospital only takes place 50 minutes later. Hence, time is critical to the survival of the injured in a severe incident. Often, hurdles get in the

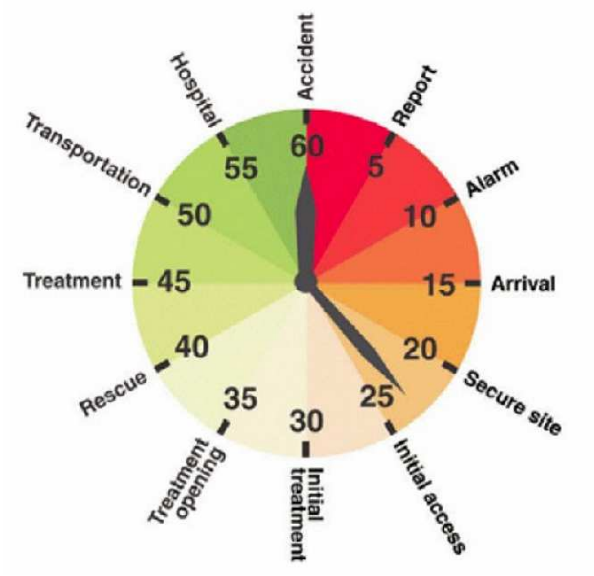


Figure 2.1: Golden hour in a car accident.

way of doctors and paramedics, dramatically slowing down the time it takes to get to a patient. Hence, any technologies capable of improving the golden hour will help to save lives.

When an accident occurs, crash detection systems can increase the protection of vehicle occupants by detecting and recognizing the type and severity of the crash, adapting protection systems to the body features and seating positions of passengers depending on the type and seriousness of the impact. Deployment of protective devices must be made in less than 5 milliseconds. Collision impact can be: (a) front impact - where front airbags are deployed and seat-belt tensioners are triggered as early as possible in co-ordination with the airbag concerned, (b) side impact - where thorax and head bags are deployed, (c) rear impact - where seat-belt tensioners are triggered even at low speeds to prevent whiplash injuries, and (d) rollover - where the rollover bar, seat-belt tensioners, and side and head airbags are triggered.

Generally, crash detection systems (CDS) can be divided into pre-crash and post-crash systems. A pre-crash system is a passive automobile safety system designed to reduce the damage caused by a collision. Most CDS use radar, and sometimes laser sensors or cameras to detect an imminent crash. Depending on the system, they may warn the driver, precharge the brakes, retract the seat belts (removing excess slack) and automatically apply partial or full braking to minimize the crash. Other experimental systems allow the vehicle to strengthen its frame just before a side-on collision [cra11], or to stop automatically before an impact [vol11]. Tables 2.8, 2.9, and 2.10 show some pre-crash systems developed by car manufacturers.

Post-crash survivability devices and systems help to minimize the chances of crash injuries or fatalities due to the secondary effects of collision, such as fire. Examples of such devices include: (a) vehicle fuel safety and isolation, (b) fire-resistant materials for vehicle interior, and (c) on-board Black-box based systems (also known as Event Data Recorder, EDR). The Black-box technology allows Automatic Crash Notification, and so it is closely related to crash notification systems such as OnStar [OnS12] or eCall [Eur09]. In such systems, cars must be equipped with a kind of black-box that automatically detects the accident when it occurs, records data obtained by in-car sensors, and sends them to the next Public Safety Answering Point (PSAP), in order to ask for help. These systems can also be used to determine the cause of the accident or to inform insurance companies. Modern black-box systems also include a built-in camera to make all the recorded information more precise and intuitive. Moreover, most systems record video for a few seconds just before and after a crash.

The National Highway Traffic Safety Administration (NHTSA) estimated that 85% of new cars would have an EDR (black box system) by 2010 [nth11].

Table 2.8: Pre-Crash developed systems by car automakers

Brand	**Remarks**
Audi	Audi has developed a system called "Pre-Sense Plus", which works in four phases. In the first phase, the system provides warning of an imminent accident, while the hazard warning lights are activated, the side windows and sunroof are closed and the front seat belts are tensioned. In the second phase, the warning is followed by light braking but strong enough to win the driver's attention. The third phase initiates autonomous partial braking at a rate of 3 m/s^2. The fourth phase decelerates the car at 5 m/s^2 followed by automatic deceleration at full braking power, roughly half a second before the projected impact. A second system called "Pre-Sense Rear" is designed to reduce the consequences of rear end collisions. Sunroof and windows are closed, seat belts are tightened in preparation for impact. The system uses radar technology and was introduced on the 2011 Audi A8.
Ford	Collision Warning with Brake Support was introduced in 2009 on the Lincoln MKS and MKT and the Ford Taurus. This system provides a warning through a Head Up Display (HUD) that visually resembles brake lamps. If the driver does not react, the system pre-charges the brakes and increases the brake assist sensitivity to maximize driver braking performance.
GM	At the end of 2005, GM announced a collision warning system which was based on vehicle-to-vehicle wireless communications. Speeds, direction, and location data, enabled the system to evaluate the level of warnings according to the information it had collected. The system is called "Sixth Sense", and it provides the information at hand and can give the driver a clear warning of another vehicle on the freeway that is either slowing down ahead or pulling across from the side. The system uses a clever mix of GPS receivers and LAN networks, and establishes communication with other vehicles within a few hundred meters.
Honda	- Collision Mitigation Brake System introduced in 2003 on the Inspire uses a radar-based system to monitor the situation ahead and provide automatic braking if the driver does not react to a warning in the instrument panel, along with a tightening of the seat belts. This was the first system to provide automatic braking. - In late-2004 Honda developed an Intelligent Night Vision System which highlights pedestrians in front of the vehicle by alerting the driver with an audible chime and visually displaying them via a HUD.

Table 2.9: Pre-Crash developed systems by car automakers (Cont.)

Brand	**Remarks**
Mercedes-Benz	- Pre-Safe system was unveiled in the fall of 2002 at the Paris Motor Show. Using Electronic Stability Programme (ESP) sensors to measure steering angle, vehicle yaw and lateral acceleration, and Brake Assist sensors to detect emergency braking, Pre-Safe can tighten seat belts, adjust seat positions and close the sunroof if it detects possible collision (including rollover). - Pre-Safe Brake introduced in the fall of 2005 co-operating with simultaneously introduced Brake Assist Plus and Distronic Plus systems provide all the functions of previous Pre-Safe system while adding a radar-based system which monitors the traffic situation ahead and provides automatic partial braking (40% or up to 0.4g deceleration) if the driver does not react to the Brake Assist Plus warnings. - In 2009, Mercedes unveiled Attention Assist which based on 70 parameters attempts to detect the driver's level of drowsiness based on the driver's driving style. This system does not actually monitor the driver's eyes. - Also, in 2009, Mercedes added a fully autonomous braking feature that will provide maximum braking at approximately 0.6 seconds before impact.
Nissan	Nissan is reportedly developing a new "magic bumper" system which raises the accelerator pedal if it senses an impending collision. Once the driver lifts off the pedal, the system then automatically applies the brakes. Infiniti offers a laser-based system for the US market that pre-pressurizes the braking system so maximum force can be applied early.
Volkswagen	The 2011 VW Touareg incorporated the innovative "Area View" which uses four cameras to detect the Touareg's surroundings and this enhances safety. Moreover, the lane assist function ensures that the vehicle does not stray from the right path; meanwhile, the side assist function warns the driver of vehicles approaching from the rear when changing lanes. Adaptive Cruise Control (ACC) with integrated Front Assist can bring the car to a stop in an emergency and can further tighten seat belts as a precautionary measure.

Table 2.10: Pre-Crash developed systems by car automakers (Cont.)

Brand	**Remarks**
Toyota	- Pre-Collision System is the very first radar-based pre-crash system which uses a forward facing millimeter-wave radar system. When the system determines a frontal collision is unavoidable, it preemptively tightens the seat belts removing any slack and pre-charges the brakes. The advanced Pre-Collision System added a twin-lens stereo camera located on the windshield and a more sensitive radar to detect for the first time smaller “soft” objects such as animals and pedestrians. A near-infrared projector located in the headlights allows the system to work at night. - In 2007, the world’s first Driver Monitoring System was introduced on the Lexus LS, using a CCD camera on the steering column; this system monitors the driver’s face to determine where the driver is looking at. If the driver’s head turns away from the road and a frontal obstacle is detected, the system will alert the driver using a buzzer and if necessary pre-charge the brakes and tighten the safety belts. - In 2008, the Toyota Crown monitors the driver’s eyes to detect the driver’s level of wakefulness. This system is designed to work even if the driver is wearing sunglasses. Toyota added a pedestrian detection feature which highlights pedestrians and presents them on an LCD display located in front of the driver. The latest Crown also uses a GPS-navigation linked brake assist function. The system is designed to determine if the driver is late in decelerating at an approaching stop sign, it will then sound an alert and can also precharge the brakes to provide optimum braking force if deemed necessary. This system works in certain Japanese cities and requires Japan specific road markings which are detected by a camera. - In March 2009 the redesigned Crown Majesta, further advanced the Pre-Collision System by adding a front-side millimeter-wave radar to detect potential side collisions primarily at intersections and when another vehicle crosses the center line. The latest version slides the rear seat upward, thus placing the passenger in a more ideal crash position if it detects a front or rear impact.
Volvo	- Volvo’s Collision Warning with Brake Support was introduced on the 2006 Volvo S80. This system provides a warning through a Head Up Display that visually resembles brake lamps. If the driver does not react, the system pre-charges the brakes and increases the brake assist sensitivity to maximize driver braking performance. - Collision Warning with Brake Assist was introduced on the 2007 Volvo S80, V70 and XC70. The system provides the same function as Collision Warning with Brake Support, but in addition, provides autonomously partial braking if the driver does not react to the brake assist functions.

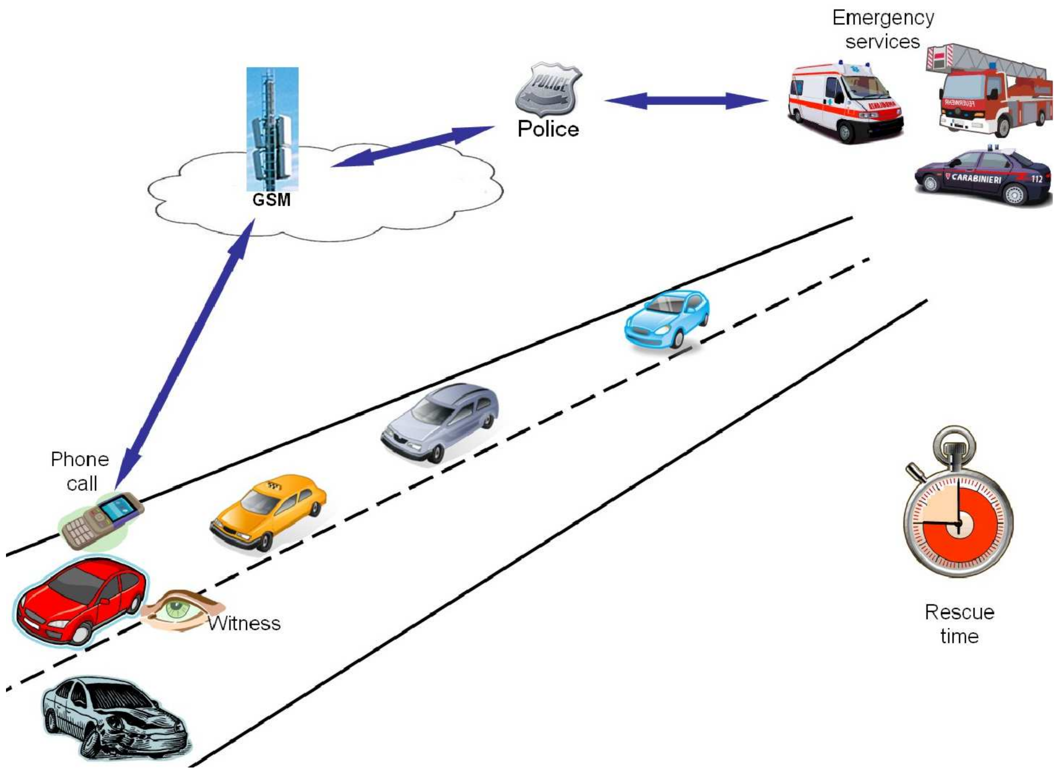


Figure 2.2: Old method of rescue using a cellular phone when an accident occurred.

2.5 Trends in Emergency Services: From Cellular to VANET-based

The demand for emergency road services has risen around the world. Moreover, changes in the role of emergency crews have occurred - from essentially transporting injured persons (to the hospital) to delivering basic treatment or even advanced life support to patients before they arrive at the hospital. In addition, advances in science and technologies are changing the way emergency rescue operates.

In times of road emergency, appropriately skilled staffs and ambulances should be dispatched to the scene without delay. Efficient roadside emergency services demand the knowledge of accurate information about the patient (adult, child, etc), their conditions (bleeding, conscious or unconscious, etc), and clinical needs. In order to improve the chances of survival for passengers involved in car accidents, it is desirable to reduce the response time of rescue teams and to optimize the medical and rescue resources needed. A faster and more efficient rescue will increase the chances of survival and recovery for injured victims. Thus, once the accident has occurred, it is crucial to efficiently and quickly manage the emergency rescue and resources.

An Automatic Crash Notification system will automatically notify the nearest emergency call center when a vehicle crashes. These call centers will determine the nature of the call and, if it is an emergency, data from vehicular sensors will allow the call center to evaluate if the vehicle has been involved in a collision. Vehicular sensors may indicate that an airbag was triggered, the mechanical impact on the vehicle, whether the vehicle did roll-over, the deceleration history and status, the number of passengers in the car, etc. Knowing the severity of emergencies and their precise locations can save lives readily while utilizing rescue resources efficiently.

The method for seeking help when an accident occurs has changed over the years. Figure 2.2 shows the old method of accident notification, where a witness of the car accident calls the police for help. Basically, the witness gives information about the location of the accident and the fatalities involved. Once the police is notified, they coordinate the rescue effort by alerting the fire department and medical services, summoning for an ambulance to the accident site quickly.

Figure 2.3 shows the current method of accident notification. When an accident occurs, a call is made to an “answering point” in order to send information about the accident and to ask for help.

eCall [ece02] is one of the most important road safety efforts made under the European Union’s

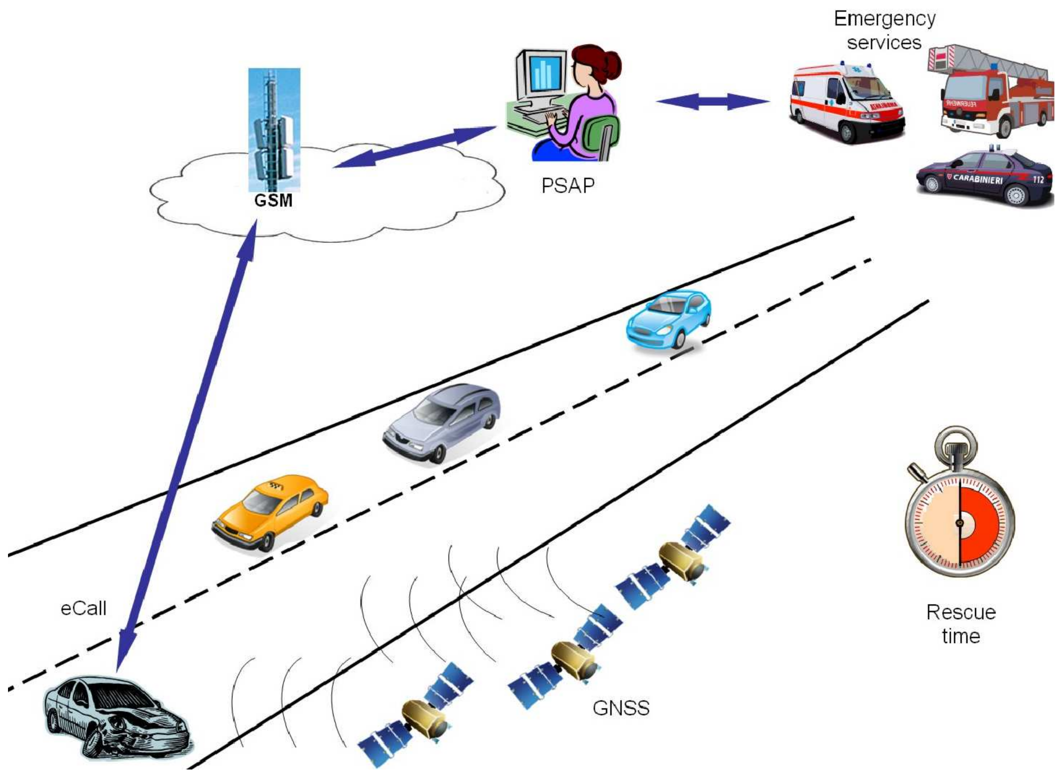


Figure 2.3: Current method of rescue when an accident occurs (e.g. eCall and OnStar).

eSafety initiative. eSafety seeks to improve road safety by fitting intelligent safety systems based on advanced electronic technologies into road vehicles. In the event of an emergency, the single European emergency number 112 can be called from all the European Union countries.

eCalls are made free of charge from fixed-line or mobile phones. eCall builds on E112 [Eur09], a location-enhanced version of 112. The telecom operator transmits the location information to the Public Safety Answering Point (PSAP), which in return must be adequately equipped with a voice-band modem detector, Minimum Set of Data (MSD) decoding capabilities, and trained operators to process this data. PSAP and emergency service chains must be capable of dealing with calls coming from an in-vehicle eCall device. They must also be able to process the MSD, including location data, which is automatically transmitted by the eCall system, even when voice communication is not possible.

The content of the MSD includes: (a) control information, (b) VIN (Vehicle Identification Number), (c) time, (d) latitude, (e) longitude, and (f) direction. The recommended transmission of the MSD between the On Board Unit in the car and the PSAP requires a parallel data transmission with voice. Whether the call is made manually or automatically, there will always be a voice connection between the vehicle and the rescue center. In this way, any car occupants capable of answering questions can provide additional details about the accident.

For eCall to work, several requirements [Eur09] must be met: Firstly, all newly manufactured cars will have to be equipped with eCall devices. In 2005, the European Commission and the automotive industry association agreed to schedule full-scale deployment of eCall service for 2009. eCall devices were made available as an option for all new cars, in September 2009.

Secondly, there is a need for the single European emergency number 112 to be operational for both fixed and mobile calls throughout the European Union. Unfortunately, not all EU member states are able to support the full 112 emergency services. Presently, the eCall system is working in 12 out of 27 EU member states.

Thirdly, emergency centers and all rescue services must be capable of processing the accident location data transmitted by eCalls. For example, ambulances must be adequately capable of receiving and processing these data. Rescue centers must be able to forward all the information to the fire brigade, hospital emergency rooms, etc. In addition, to take full advantage of the voice link to the crashed vehicle, rescue center personnel must be properly trained so as to gather critical information in several languages.

Table 2.11: eCall vs. OnStar

	eCall	OnStar
Automatic Emergency Call	✓	✓
Data Call	✓	✓
Voice Call	✓	✓
Stolen Vehicle Assistance	✗	✓
Navigation assistance	✗	✓
24 hours availability	✓	✓
Range	European Union	GM vehicles in the US
Promoter	European Union	GM
Cost	Free	Up to $300 per year

Essentially, by knowing the exact location of the crash site, response time of emergency services can be reduced by 50% in rural and 40% in urban areas. Due to this time reduction, eCall is expected to save up to 2,500 lives in the EU each year, while at the same time mitigating the severity of tens of thousands of injuries. Since eCall can also accelerate the treatment of injured people, there will be better recovery prospects for accident victims. In addition, earlier arrival at the accident scene will also translate into faster clearance of the crash site, which helps to reduce road congestion, fuel waste, and CO2 emissions. Overall, it aids in our quest for a greener and safer environment.

2.5.1 Comparison of eCall and OnStar

OnStar [OnS12] is an in-vehicle safety and security system created by General Motors (GM) for on-road assistance. Both eCall and OnStar systems are, in fact, very similar. A vehicle collision activates on-vehicle sensors, causing an emergency voice call to be initiated. Also, key information about the accident is transmitted.

Unlike eCall, OnStar provides an on-road navigation system and assistance in case the vehicle is stolen; it can also remotely unlock vehicles. Nevertheless, eCall is more ambitious since it is expected to support all brands of vehicles in the European Union region, while OnStar is only supported by GM vehicles in the US. Table 2.11 outlines the most important differences between eCall and OnStar. Future accident notification systems will be more ambitious; intelligent systems will automatically adapt the required rescue resources, allowing the rescue staff to work more efficiently, and reducing the time associated with their tasks.

2.6 A View on Future Emergency Services

In the future, our current accident notification paradigm will change with the introduction of vehicular networks. By combining V2V and V2I communications, new Intelligent Transportation Systems will emerge, capable of improving the timeliness and responsiveness of roadside emergency services. As shown in Figure 2.4, the accident information gathered can be delivered to a control unit that automatically estimates: (a) the severity of an accident, and (b) the appropriate rescue resources before summoning for emergency services.

Future emergency rescue architectures will exploit various communication technologies, such as DSRC, UMTS/HSDPA, and WAVE, empowering road users with both localized (via VANETs) and long haul (via cellular or wide area wireless data) wireless communications. By using vehicular communications, cars involved in an accident can send alerts and other important information about the accident to near-by vehicles and to the nearest wireless base station. Thereafter, an intelligent PSAP will gather this information, and channel the most critical data to the appropriate emergency services. Vehicular networks can allow faster notification of any accident occurring on the road (since sensing

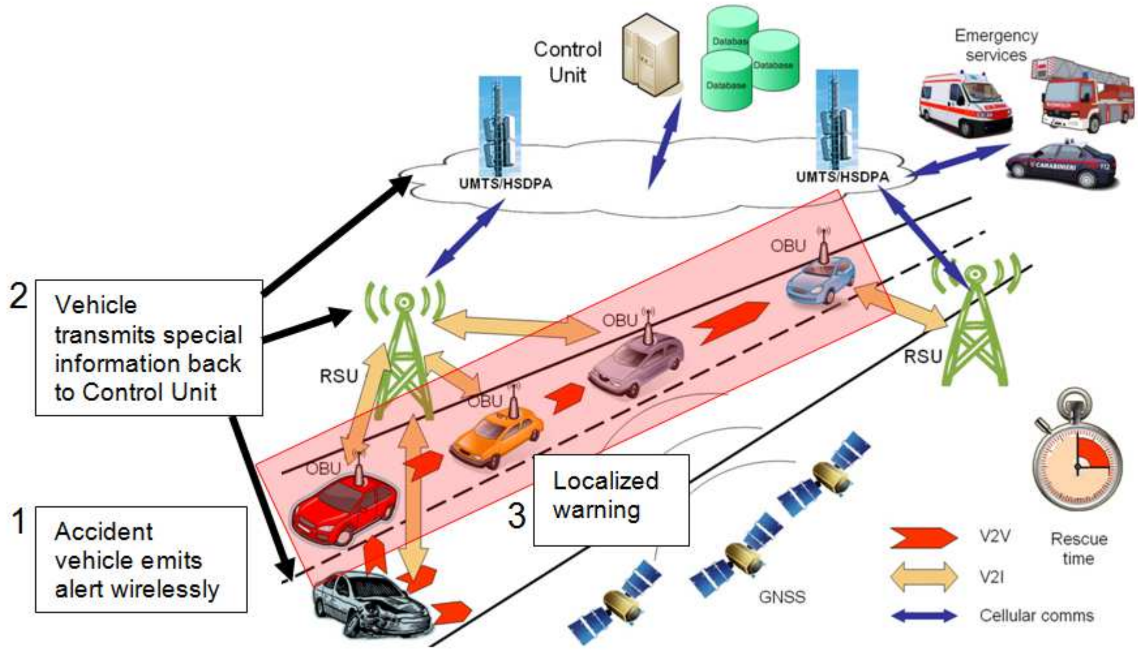


Figure 2.4: Future emergency rescue architecture combining V2I and V2V communications, combining localized alerts and warnings, special control information transmission, intelligent databases, and a Control Unit.

and propagation of incident information is done on-the-spot in real-time via multi-hop V2V communications). Surrounding vehicles will be immediately notified of the hazard, and such alerts can be further propagated via radio base stations to the core network.

Concerning technology, for any proposal to be successful, it should be compatible with the signaling protocol and air interfaces of existing implementations or standardizations. So, V2V communications should be compatible with the future 802.11p standard, while the V2I counterpart might use any of the 3/4G cellular technologies currently available. The usage of hybrid multi-wireless platforms adds robustness and reliability to the call for emergency help and rescue. In the near future, a community-based effort involving the state departments, public organizations and industry is needed to deploy the required technology and infrastructure to connect all the vehicles on the road and the emergency services.

2.7 Vehicular ad hoc Networks (VANETs)

Mobile ad hoc networks (MANETs) are a type of wireless network that does not require any fixed infrastructure. MANETs are attractive for situations where communication is required, but deploying a fixed infrastructure is impossible.

Vehicular ad hoc networks (VANETs) are a subset of MANETs, and represent a rapidly emerging research field considered essential for cooperative driving among communicating vehicles. Vehicles function as communication nodes and relays, forming dynamic networks with other near-by vehicles on the road and highways. While *Mobile ad hoc Networks* (MANETs) are mainly concerned with mobile laptops or wireless handheld devices, VANETs are concerned with vehicles (such as cars, vans, trucks, etc). Figure 2.5 shows and example of a VANET in a urban scenario, where cars communicate in a multi-hop fashion.

Wireless technologies such as *Dedicated Short Range Communication* (DSRC) [XSMK04] and the IEEE 802.11p *Wireless Access for Vehicular Environment* (WAVE) [Eic07] enable peer-to-peer mobile communication among vehicles (V2V) and communication between vehicles and the infrastructure (V2I), and are expected to be widely adopted by the car industry in the next years.

To date, many solutions regarding VANETs have been proposed and evaluated via simulation. Nevertheless, the simulation environments used to be very simplistic, so utilizing more realistic simulation environments is required.

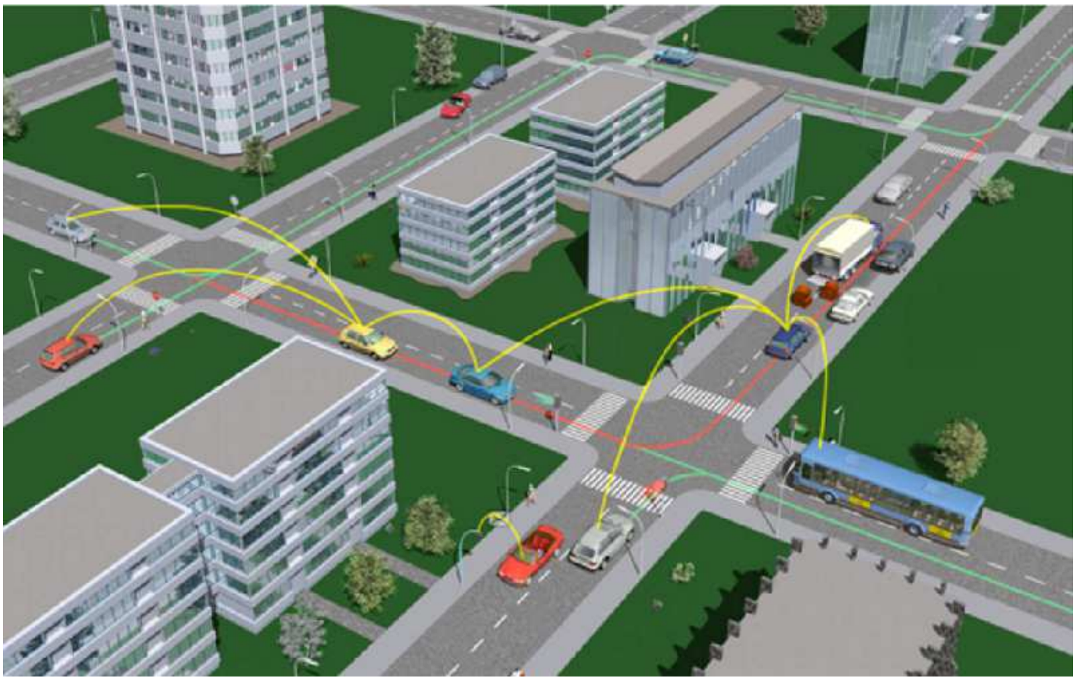


Figure 2.5: Example of a VANET.

2.7.1 Characteristics and Applications of VANETs

VANETs are characterized by: (a) trajectory-based movements with prediction locations and time-varying topology, (b) variable number of vehicles with independent or correlated speeds, (c) fast time-varying channel conditions (e.g., signal transmissions can be blocked by buildings), (d) lane-constrained mobility patterns (e.g., frequent topology partitioning due to high mobility), and (e) reduced power consumption requirements. So far, the development of VANETs is backed by strong economical interests since vehicle-to-vehicle (V2V) communication allows using wireless channels for collision avoidance (improving traffic safety), improved route planning, and better control of traffic congestion [BFW03].

The specific characteristics of Vehicular networks favor the development of attractive and challenging services and applications. These applications can be grouped together into two main different categories:

- Safety applications (see Figure 2.6), that look for increasing safety of passengers by exchanging relevant safety information via V2V and V2I communications, in which the information is either presented to the driver, or used to trigger active safety systems. These applications will only be possible if the penetration rate of VANET-enabled cars is high enough. In this thesis, we will focus on safety applications in order to reduce the number of fatalities while significantly improving the response time and the use of rescue resources.

- Comfort and Commercial applications (see Figure 2.7) that improve passenger comfort and traffic efficiency, optimize the route to a destination, and provide support for commercial transactions. Comfort and commercial applications must not interfere with safety applications [JK08].

2.8 Conclusions

Several research projects led by research institutes and car manufacturers around the world have positively impacted the future of inter-vehicle communication systems. Technologies have clearly contributed to the change in the course of actions to follow after an accident occurs, moving from a simple cellular phone call made by a witness, to the current eCall accident notification system provided in the EU.

In the near future, accident notification systems will be specially designed for post-collision rescue services. Combining V2V and V2I communications, new Intelligent Transportation Systems will emerge with the capability of improving the responsiveness of roadside emergency services, and allowing: (a)

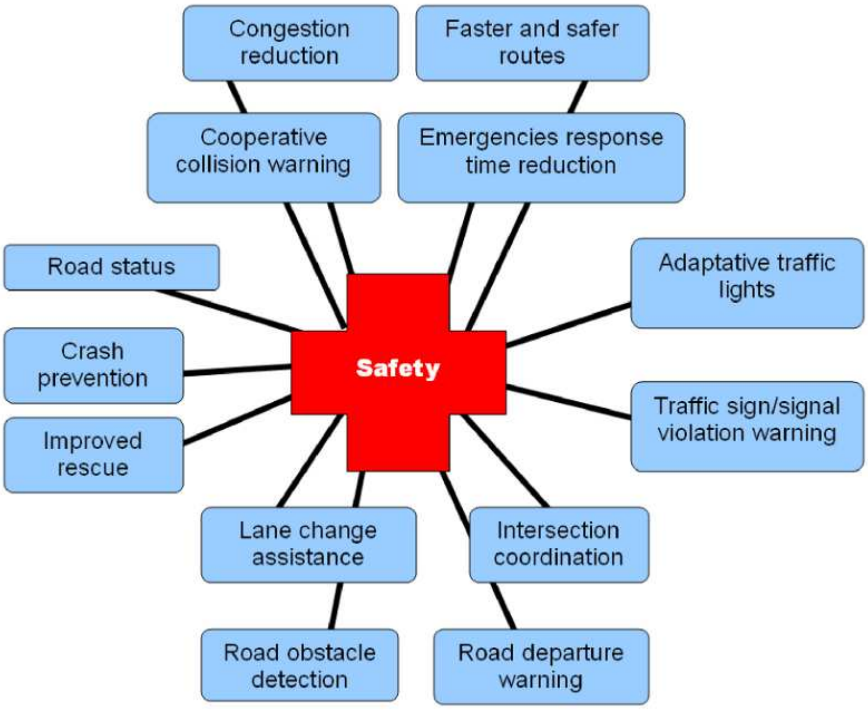


Figure 2.6: Traffic safety applications of VANETs.

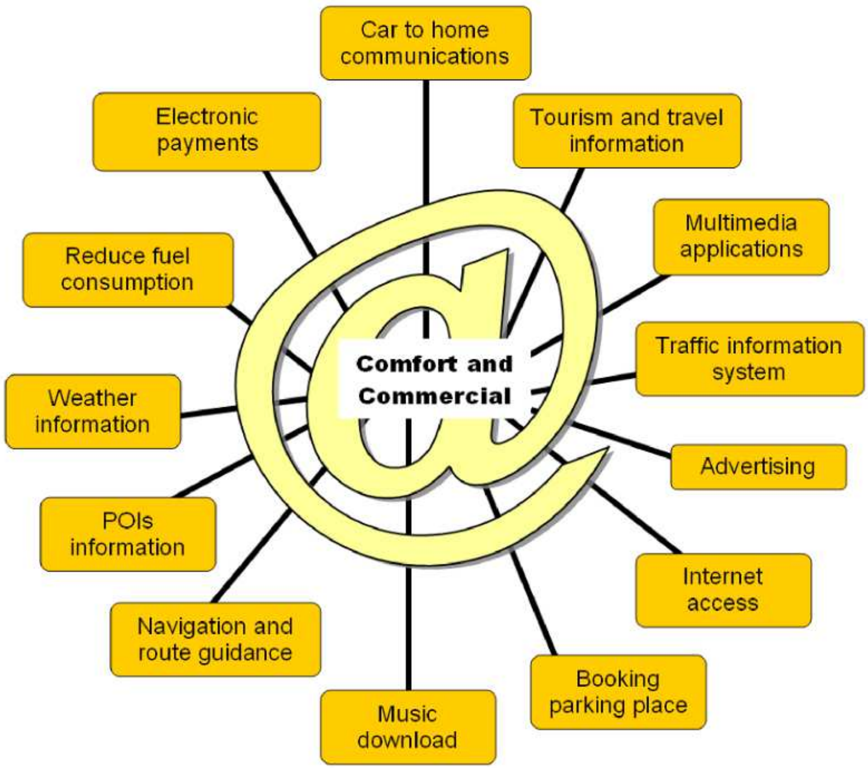


Figure 2.7: Comfort and commercial applications of VANETs.

direct communication among the vehicles involved in the accident, (b) automatic delivery of accident related data to the Control Unit, and (c) an automatic and preliminary assessment of damages based on communication and information processing.

Future ITS-based emergency services aim at achieving a low level of fatalities while significantly improving the response time and efficient use of resources.

In this chapter, we examined the impact of future ITS technologies on road safety and emergency services, and we proposed the essential information which will be disseminated by vehicles after an accident. We also presented an overview of the current state-of-the-art of the vehicular wireless technologies that will be widely adopted by industry in the next few years, and the different IEEE standards included in the WAVE architecture.

Although more work is required, the foundations are laid to deploy V2I and V2V communication systems. There are clear evidences that it will be possible for our vehicles to communicate among them, or with traffic signs, very soon. This will put at drivers' disposal a number of services that will improve traffic safety, infotainment, and reduce road congestion, wastage of fuel and CO2 emissions.

Chapter 3

A Novel V2I-based Real-Time Traffic Density Estimation System

Road traffic is experiencing a drastic increase in recent years, thereby increasing the every day traffic congestion problems, especially in metropolitan areas. Governments are making efforts to alleviate the increasing traffic pressure, being vehicular density one of the main metrics used for assessing the road traffic conditions. However, vehicle density is highly variable in time and space, making it difficult to be estimated accurately. Currently, most of the existing vehicle density estimation approaches, such as inductive loop detectors or traffic surveillance cameras, require very specific infrastructure to be installed at various locations.

In this chapter, we present a novel solution to estimate the density of vehicles that has been specially designed for Vehicular Networks. Our proposal allows Intelligent Transportation Systems to continuously estimate vehicular density by accounting for the number of beacons received per Road Side Unit (RSU), and also considering the roadmap topology where the RSUs are located. Simulation results reveal that, unlike previous proposals solely based on the number of beacons received, our approach accurately estimates the vehicular density, and therefore automatic traffic controlling systems may use our approach to predict traffic jams and introduce countermeasures. The used technical terms are explained in the following sections.

3.1 Introduction

Enhancing transportation safety and efficiency has emerged as a major objective for the automotive industry in the last decade [SCB11]. However, road traffic is experiencing a drastic increase, and vehicular traffic congestion is becoming a major problem, especially in metropolitan environments throughout the world. In particular, traffic congestion: (i) reduces the efficiency of the transportation infrastructure, (ii) increases travel time, fuel consumption, and air pollution, and (iii) leads to increased user frustration and fatigue [TKK12].

Some of the factors affecting traffic congestion are badly managed and poorly designed roads, as well as bad traffic lights sequencing [TC07]. These factors negatively affect the traffic distribution on the roads, making it possible to find extremely high congested areas where vehicles travel very slow or even get stuck.

Intelligent Transportation Systems (ITS), based on the use of Vehicular Networks (VNs), emerge as the technology that can efficiently manage information on the road, being able to offer to drivers a variety of added services such as safe, efficient, and smart driving.

In vehicular environments, wireless technologies enable peer-to-peer mobile communication among vehicles (V2V) [FGM+12b, SFS+11], and communication between vehicles and the infrastructure (V2I) [SLCG08, LL10]. Vehicles can broadcast warning messages in case of an accident, and also periodically exchange other messages (beacons) that contain information about their position, speed, or route. These messages are received not only by nearby vehicles, but also by the *Road Side Units* (RSUs), that are distributed along the infrastructure.

The specific characteristics of vehicular networks favor the development of attractive and challenging services and applications [CCH10, MCC+09]. Though traffic safety has been the primary motive for the development of these networks [STMZI+10], VNs also facilitate applications such as managing the traffic flow, monitoring the road conditions, mobile applications, environmental protection, infotainment, etc. [CLC10, BTK09, GAdP+11]. However, most of these applications could be more efficient if the protocols involved become aware of the density of vehicles at any given time, being able to adapt their behavior according to this critical factor [MBML11].

Traditionally, vehicle density has been one of the main metrics used for assessing the road traffic conditions. A high vehicle density usually indicates that the traffic is congested. However, the density of vehicles circulating in a city highly varies depending on the area and the time during the day. Thus, knowing the density of a vehicular environment is important since it allows both estimating the level of traffic congestion and improving ITS services by using the wireless channel more efficiently [SHG09].

Currently, most of the vehicle density estimation approaches are designed to use very specific infrastructure-based traffic information systems, which require the deployment of vehicle detection devices such as inductive loop detectors (systems that counts the number of vehicles passing over a sensor) or traffic surveillance cameras [TC07, BS08, THKH11]. However, these approaches are limited since they can only be aware of traffic density in a priori selected areas (i.e., the streets and junctions in which these devices are already located), making it difficult to estimate the vehicular density along a whole city. In addition, some of these approaches are not able to perform the density estimation process in real time (e.g., using cameras involves hard image treatment and analysis).

In this chapter, we present a solution to estimate traffic density on the roads that relies on the V2I communication capabilities offered by Vehicular Networks. Unlike previous works, our proposal allows ITS to continuously estimate the vehicular density in a given area by accounting for the number of beacons received per RSU, as well as the roadmap topology where the vehicles are located.

The rest of this chapter is organized as follows: Section 3.2 motivates our proposal by discussing the importance of traffic congestion. Section 3.3 reviews previous approaches related to our work, focusing on infrastructure-based solutions to estimate traffic density, and density-aware systems to avoid traffic jams. Section 3.4 details our proposal for V2I-based real-time vehicular density estimation, assessing its goodness. Additionally, we discuss the obtained results and measure the estimated error. In Section 3.5 we validate it by simulating three particular scenarios, showing that our proposed function performs well and accurately estimates the vehicular density. In Section 3.6 we compare our proposal with a beacon-based approach, where the vehicular density estimated is only based on the number of beacons received. Finally, Section 3.7 concludes this chapter analyzing our proposal and the obtained results.

3.2 Motivation

Transportation plays an important role in the economic growth and productivity of countries. When transportation systems are efficient, they provide economic and social opportunities, as well as benefits that result in positive multiplier effects such as better accessibility to markets, employment, and additional investments. On the contrary, when transport systems are deficient in terms of capacity or reliability, they can have an economic cost such as reduced or missed opportunities. Efficient transportation reduces costs, while inefficient transportation increases them [RN12]. For this reason, traffic congestion problems have been studied for a long time, mainly to relieve traffic jams and to increase transportation efficiency.

The number of vehicles in our roads is drastically increasing, specially in developing countries such as India, China, or Brazil. In addition, these vehicles tend to be concentrated on a few cities which present a large population. Traffic jams have important and negative consequences such as increasing travel time, fuel consumption, and air pollution. According to the Texas Transportation Institute in their 2010 Urban Mobility Report [DST10], congestion caused urban Americans to travel 4.8 billion hours, and to purchase an extra 3.9 billion gallons of fuel for a cost of $115 billion. On average, the yearly peak period delays caused by traffic congestion for the average commuter was 34 hours, and the cost to the average commuter has increased by 230% in only two decades. Additionally, according to the *World Health Organization*[1] (WHO), one of the most important polluting factors in the world comes from the fossil minerals combustion in vehicles.

Therefore, in the past ten years, governments have been making efforts to alleviate the increasing traffic pressure, e.g., the Chinese government is trying to strengthen the traffic infrastructure. However, the number of vehicles on the roads is growing faster, making the current road network capacity insufficient, and thereby causing the traffic congestion phenomenon to become a growing problem. Fortunately, effective traffic management, through the prediction of traffic status based on simulations, and

[1] http://www.who.int

the implementation of large-scale flow controlling methods, are effective measures for mitigating traffic jams [YLGM08].

We want to go one step farther, since we consider that a vehicular communications system which is able to estimate the traffic density in real-time could really mitigate or even solve these problems. The main objective of our work is to propose a mechanism which allows estimating the density of vehicles in a specific area by using infrastructure-based Vehicular Networks. In particular, we estimate the density, by taking into account the number of beacons received by the RSUs, and the characteristics of the roadmap topology. Hence, real-time traffic controlling systems can precisely estimate the vehicular density in a determined area, and then redirect vehicles to lower traffic density areas in order to avoid traffic jams. This could be possible by using the in-vehicle communication capabilities and navigation systems, requirements which are currently fulfilled by most of the vehicles in many countries.

3.3 Related Work

In this section we review previous works related to our proposal. In particular, we focus on: (i) infrastructure-based solutions to estimate traffic density, and (ii) density-aware systems designed to reduce traffic jam situations.

3.3.1 Infrastructure-based Solutions to Estimate Traffic Density

Despite the importance of determining vehicular density to reduce traffic congestion, so far only a few studies have explored the density estimation process.

Tyagi et al. [TKK12] considered the problem of vehicular traffic density estimation, using the information available in the cumulative acoustic signal acquired from a roadside-installed single microphone. This cumulative signal comprises several noise signals such as tire noise, engine noise, engine-idling noise, occasional honks, and air turbulence noise of multiple vehicles. The occurrence and mixture weightings of these noise signals are determined by the prevalent traffic density conditions on the road segment. Based on these learned distributions, they used a Bayes' classifier to classify the acoustic signal segments spanning a duration of 5-30 s. Using a discriminative classifier, such as a *Support Vector Machine* (SVM), obtained results are better than the obtained using a Bayes' classifier.

Tan and Chen [TC07] proposed a novel approach based on video analysis which combines an unsupervised clustering scheme called AutoClass with *Hidden Markov Models* (HMMs) to determine the traffic density state in a *Region Of Interest* (ROI) of a road. Firstly, low-level features were extracted from the ROI of each frame. Secondly, an unsupervised clustering algorithm called AutoClass was applied to the low-level features to obtain a set of clusters for each pre-defined traffic density state. Finally, four HMM models were constructed for each traffic state, respectively, with each cluster corresponding to a state in the HMM; the structure of the HMM is determined based on the cluster information.

Shirani et al. [SHG09] presented the Velocity Aware Density Estimation (VADE). In VADE, a car estimates the density of neighboring vehicles by tracking its own velocity and acceleration pattern. An opportunistic forwarding procedure, based on VADE estimation, was also proposed. In this procedure, data forwarding is done when the probability of having a neighbor is high, which dramatically reduces the probability of messages being dropped.

Maslekar et al. [MBML11] claimed that clustering has demonstrated to be an effective concept to implement the estimation of vehicular density in the surroundings. However, due to high mobility, a stable cluster within a vehicular framework is difficult to implement. In this work, they proposed a direction based clustering algorithm with a clusterhead switching mechanism. This mechanism aims at overcoming the influence of overtaking within the clusters.

Other authors use the Kalman filtering technique for the estimation of traffic density. For example, Balcilar and Sonmez [BS08] estimate traffic density based on figs retrieved from traffic monitoring cameras operated by the Traffic Control Office of Istanbul Metropolitan Municipality. To this end, they use a Kalman filter-based background estimation which can efficiently adapt itself to environmental factors such as light changes. However, this approach requires the density estimation procedures to be applied to the road areas manually marked beforehand. More recently, Anand et al. [AVS11] proposed a method that also uses the Kalman filtering technique for estimating traffic density. In particular, they propose using the flow values measured from video sequences and the travel time obtained from vehicles equipped with a the Global Positioning System (GPS). They also report density estimation using flow and Space Mean Speed (SMS) obtained from location based data, using the Extended Kalman filter technique.

All these works established the importance of vehicular density awareness for neighboring areas, but none has deepened in the analysis of the accuracy of the method used to estimate this density, or the effect of the topology in the results obtained. Moreover, the vehicular density estimation does not take place in real time, and all of them require specialized infrastructure devices.

3.3.2 Density-aware Systems Designed to Avoid Traffic Jams

Regarding the systems designed to avoid traffic congestion based on the vehicular density awareness, Hattori et al. [HHI99] simulated the traffic flow considering the capacity of the road by using a cellular automaton method. They controlled several traffic flow cases, and presented three useful results of this control method. The first one is a dispersion of traffic flow and exhaust gas, the second one is a reduction of CO gas, and the third one is an increase of the transportation efficiency.

Bedi et al. [BMD+07] proposed the *Dynamic System for Avoiding Traffic Jam* (DSATJ), inspired in *Ant Colony Optimization* (ACO) algorithms, which aims at choosing an alternative optimum path to avoid traffic jams. In their proposal, traffic jams are detected through pheromone values on edges. Their experiments were carried out with the partial road map of the North-West region of Delhi (India), to observe the performance of their approach.

Yin et al. [YJH08] presented an urban traffic congestion dynamic prediction method based on an advanced fuzzy clustering model. Additionally, they used fuzzy cluster analysis methods to analyze six different groups of relevant parameters related to traffic jams, which allow researchers to classify and rank them.

More recently, Thakur et al. [THKH11] studied the possibility of applying robust data mining and knowledge discovery techniques on traffic data gathered by on-line vehicular traffic cameras to identify potential bottlenecks. Their resulting dataset is a collection of vehicular mobility traces captured during several months from 2709 traffic webcams in ten different cities across the world (this collection consists of 7.5 Terabytes of data with 125 million vehicular figs). They also collected driving distance and time between geocoordinate pairs of street intersections for these cities, and applied spatio-temporal data mining techniques to profile these global cities. Their study helps to shed light on causes of contention in traffic jams, and provides an insight into the resolution to traffic congestion, or the possibility to plan and develop future cities.

As shown, different solutions with the aim of adopting traffic redistribution to avoid traffic congestion have been proposed. However, in this paper we propose a solution able to estimate the density of vehicles in real-time by using the communication capabilities between vehicles and RSUs. Using our system, a traffic jam can be predicted, hence allowing traffic controlling systems to anticipate their solutions.

3.4 Real-Time Vehicular Density Estimation

In this work we propose a method able to accurately estimate the density of vehicles based on the number of beacons received by RSUs and the roadmap topology. In order to find the best possible approach, we made a total of 1800 experiments. These experiments involved a wide variety of simulations over controlled scenarios, where the actual density is known. According to the results obtained, and using a regression analysis, we propose a density estimation function capable of estimating the vehicular density in any urban environment and at any instant of time. In this section we start by presenting a discussion about the most important features of the different city roadmaps. Then, we present the parameters and the methodology used in our simulations. Finally, based on the obtained results, we detail our proposed density estimation function, and estimate its error in order to assess its accuracy.

3.4.1 Features of the Cities Studied

The roadmaps used during the experiments to obtain our density estimation approach were selected in order to have different profile scenarios (i.e., with different topology characteristics).

The first step before starting the simulations was to obtain the main features of each roadmap (i.e., the number of streets, the number of junctions, the average distance of segments, and the number of lanes per street). As for the number of streets, we realized that different alternatives could be selected to obtain the number of streets of a given roadmap. Basically, they are: (i) the number of streets obtained in SUMO [KR12], where each segment between two junctions is considered a street, (ii) the number of streets obtained in *OpenStreetMap* (OSM) [Ope12], where each street has a different "name", and (iii)

Figure 3.1: Different criteria when counting the number of streets.

the number of streets according to the *Real Attenuation and Visibility* (RAV) radio propagation model, where the visibility between vehicles is taken into account when identifying the streets [MFT+12].

Figure 3.1 shows a small portion of New York City to depicting the different criteria when counting the number of streets. For example, Thames Street is considered only one street in OSM, whereas the SUMO and RAV models consider that there are two different streets instead. However, if we observe Cedar Street, the RAV visibility model and the OSM approaches consider a single street (as expected), whereas it is represented by three different streets according to SUMO, since it has three different segments. Finally, according to both the OSM and SUMO approaches, Trinity Place and Church Street are represented as two different streets, whereas the RAV model considers that only one street exists.

Table 3.1 shows the values obtained according to each criterion to count the number of streets for the cities studied. As shown, the differences between these approaches are significant (e.g., New York has 700, 827, or 257 streets when considering SUMO segments, OSM streets, or the RAV visibility approach, respectively, whereas Sydney has 1668, 315, or 872 streets, depending on the selected criterion). Therefore, it is important to decide which one to use in order to obtain accurate results. By analyzing

Table 3.1: Number of Streets obtained depending on the approach used.

City	SUMO	OSM	RAV
New York	700	827	257
Minnesota	1592	105	459
Madrid	1387	1029	628
San Francisco	1710	606	725
Amsterdam	3022	796	1494
Sydney	1668	315	872
Liverpool	3141	1042	1758
Valencia	5154	1050	2829
Rome	2780	1484	1655

Table 3.2: Map Features

Map	Streets	Junctions	avg. distance of segment (m.)	lanes/street	SJ Ratio
New York	257	500	45.8853	1.0590	0.5140
Minnesota	459	591	102.0652	1.0144	0.7766
Madrid	628	715	83.0820	1.2696	0.8783
San Francisco	725	818	72.7065	1.1749	0.8863
Amsterdam	1494	1449	44.8973	1.1145	1.0311
Sydney	872	814	72.1813	1.2014	1.0713
Liverpool	1758	1502	49.9620	1.2295	1.1704
Valencia	2829	2233	33.3653	1.0854	1.2669
Rome	1655	1193	45.8853	1.0590	1.3873

experimental results, we realized that the RAV approach better correlated with the real features of cities, since the other two are not accurate enough, or present some errors.

Table 3.2 shows the main features of each map for the cities under study. Specifically, we obtained the number of streets according to the RAV model, the number of junctions, the average distance of segments, and the number of lanes per street. We also added a column labeled as *SJ Ratio*, which represents the result of dividing the number of streets between the number of junctions, thereby indicating the roadmap complexity. As shown, the first city (New York) presents a SJ ratio of 0.5130, which indicates that it has a simple topology, whereas the last cities in the table present a greater SJ value, which indicates a more complex topology. As shown in Section 3.4.3, this aggregated factor correlates well with the obtained results.

3.4.2 Simulation Environment

All the simulations performed in this work were done using the ns-2 simulator [FV00], where the PHY and MAC layers have been modified to closely follow the IEEE 802.11p standard, which defines enhancements to 802.11 required to support ITS applications. We assume that all the nodes of our network have two different interfaces: (i) an IEEE 802.11n interface tuned at the frequency of 2.4 GHz for V2I communications, and (ii) an IEEE 802.11p interface tuned at the frequency of 5.9 GHz for V2V communications.

In terms of the physical layer, the data rate used for packet broadcasting is 6 Mbit/s, as this is the maximum rate for broadcasting in 802.11p. The MAC layer was also extended to include four different priorities for channel access. Therefore, application messages are categorized into four different *Access Categories* (ACs), where AC0 has the lowest and AC3 the highest priority.

To prove how maps affect the performance of vehicular communications, we selected nine street maps, each one representing a square area of 4 km^2. Figure 3.2 shows the topology of the maps used in the simulations.

In order to deploy RSUs in the maps, we used the Uniform Mesh deployment policy [BGF$^+$12b], that consists on distributing RSUs uniformly on the map. The advantage of this deployment policy is that it achieves a more uniform coverage area since the distance between RSUs is the same, preventing RSUs to be positioned too closely, or too sparsely. As for the mobility of the vehicles, it has been performed with *CityMob for Roadmaps* (C4R) [FGM$^+$12a], a mobility generator able to import maps directly from OpenStreetMap [Ope12], and generate ns-2 compatible traces. Table 4.3 shows the parameters used for the simulations.

To estimate our traffic density function, we evaluate the performance of a Warning Message Dissemination mechanism, where each vehicle periodically broadcasts information about itself or about abnormal situations (traffic jams, icy roads, etc.). To increase the realism of our results, we include the possibility that vehicles share accident notification messages in our simulations. In fact, we consider that vehicles can operate in two different modes: (i) warning, and (ii) normal. Vehicles in warning mode inform other vehicles about their status by sending warning messages periodically (every second). Normal mode vehicles enable the diffusion of these warning packets and, every second they also send beacons with information such as their positions, speed, etc. These periodic messages are not propagated by other vehicles. The warning messages exchanged between vehicles and RSUs are built according the *Vehicular Accident Ontology* (VEACON) [BGF$^+$12c], which provides a standard structure

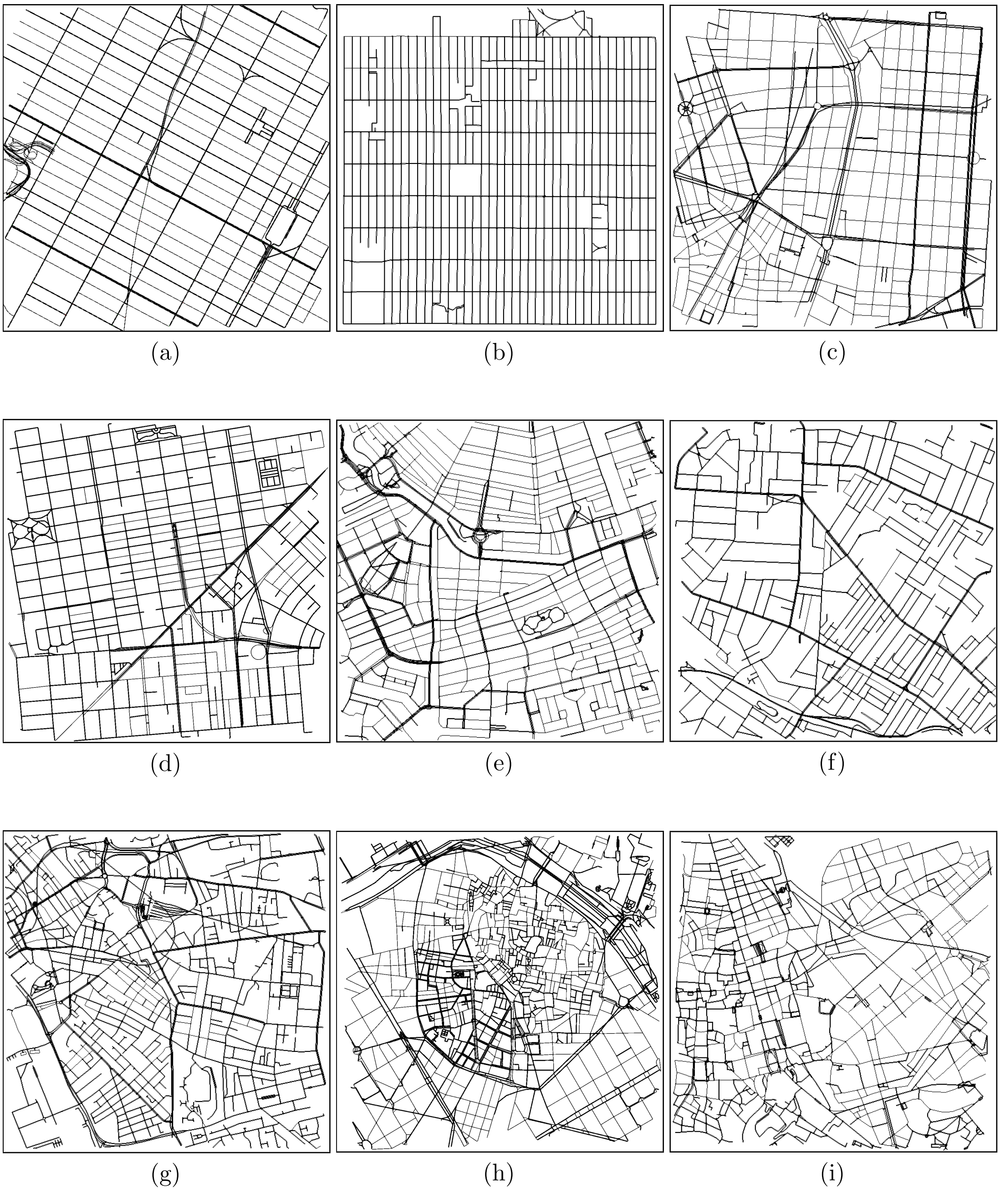


Figure 3.2: Scenarios used in our simulations. Fragments of the cities of: (a) New York (USA), (b) Minnesota (USA), (c) Madrid (Spain), (d) San Francisco (USA), (e) Amsterdam (Netherlands), (f) Sydney (Australia), (g) Liverpool (England), (h) Valencia (Spain), and (i) Rome (Italy).

Table 3.3: Parameters used for the simulations

Parameter	**Value**
roadmaps	New York, Minnesota, Madrid, San Francisco, Amsterdam, Sydney, Liverpool, Valencia, and Rome
roadmap size	$2000m \times 2000m$
number of vehicles	$[100, 200, 300...1000]$
beacon message size	$512B$
warning messages priority	$AC3$
beacon priority	$AC1$
interval between messages	1 second
number of RSUs	9
RSU deployment policy	Uniform Mesh [BGF+12b]
MAC/PHY	802.11p
radio propagation model	RAV [MFT+12]
mobility model	Krauss [KWG97]
channel bandwidth	$6Mbps$
max. transmission range	$400m$

which enables data interoperability among all the different entities involved in transportation systems.

All the results represent an average of over 20 runs with different scenarios (maximum error of 10% with a degree of confidence of 90%), and each simulation run lasted for 30 seconds.

3.4.3 Density Estimation Function

After performing the topological analysis of the studied maps, we obtained the average number of beacons received by each RSU during 30 seconds, taking into account that each vehicle sends one beacon per second, and that these messages, unlike warning messages, are not disseminated by the rest of the vehicles.

Figure 3.3 shows the results obtained for the different cities studied. As shown, the performance in New York and Minnesota in terms of number of beacons received highly differs from the rest of the cities. This is caused because New York and Minnesota have a low SJ ratio (i.e., they are simple roadmaps).

As expected, complex roadmaps (maps which have a higher SJ Ratio) present a number of beacons received lower than simple roadmaps for a similar vehicular density, since the effect that buildings have over the signal propagation is higher in complex maps. Figure 3.3 also shows that the vehicular density not only depends on the number of beacons received, but also on the SJ ratio (according to data shown in Table 3.2). Therefore, the characteristics of the roadmap will be very useful in order to accurately estimate the vehicular density in a given scenario.

After observing the direct relationship between the topology of the maps, the number of beacons received, and the density of vehicles, we proceed to obtain a function to estimate, with the minimum possible error, each of the curves shown in Figure 3.3. To this purpose, we performed a regression analysis that allowed us to find an equation offering the best fit to the data obtained through simulation. Equation 3.1 shows the density estimation function, which is able to estimate the number of vehicles per km^2 in urban scenarios, according to the number of beacons received per RSU, and the SJ ratio (i.e., streets/junctions) of the selected roadmap.

$$f(x, y) = a + b \cdot ln(x) + \frac{c}{y} + d \cdot ln(x)^2 + \frac{f}{y^2} + \frac{g \cdot ln(x)}{y} \qquad (3.1)$$

In this equation, $f(x, y)$ is the number of vehicles circulating in the studied scenario, x is the number of beacons received by each RSU, and y is the SJ ratio obtained from the roadmap. The values of the coefficients $(a, b, c, d, f, \ and \ g)$ are listed in Table 3.4. Figure 3.4 shows the 3-dimensional representation of the proposed equation.

To determine the accuracy of our proposal, we proceed to measure the estimated error. Table 3.5 shows the different types of errors when comparing our density estimation function with the values

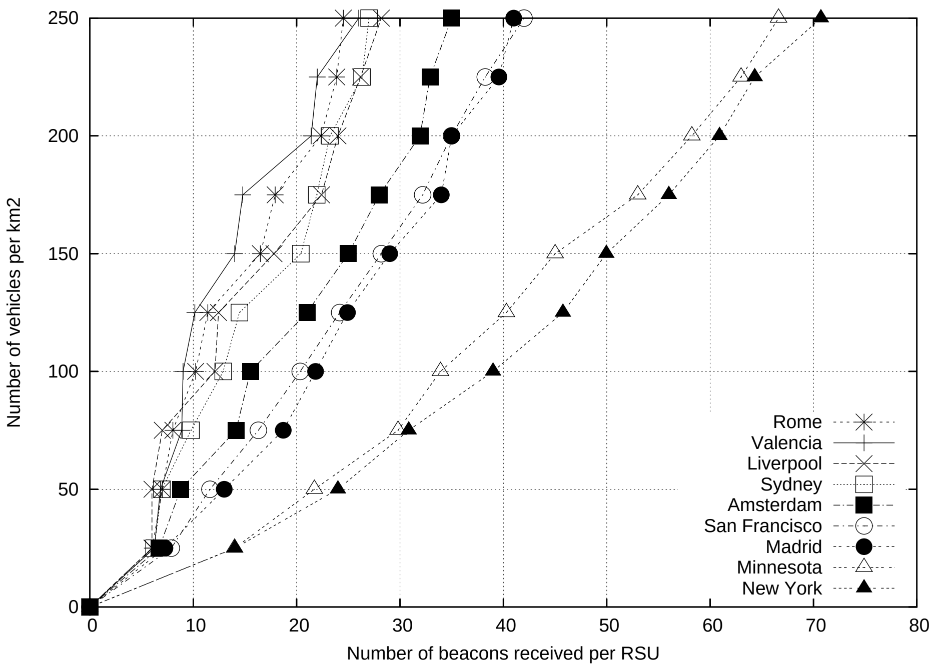


Figure 3.3: Number of vehicles per km^2 according the number of beacons received when varying the vehicular density and the roadmap.

Table 3.4: Coefficients of our Proposed Density Estimation Equation

Coeff.	**Value**
a	2.3037584774238823E+02
b	1.9069648769466475E+01
c	-4.2946130569906342E+02
d	3.1880957532509228E+01
f	1.8795302200929001E+02
g	-6.8125878716641097E+01

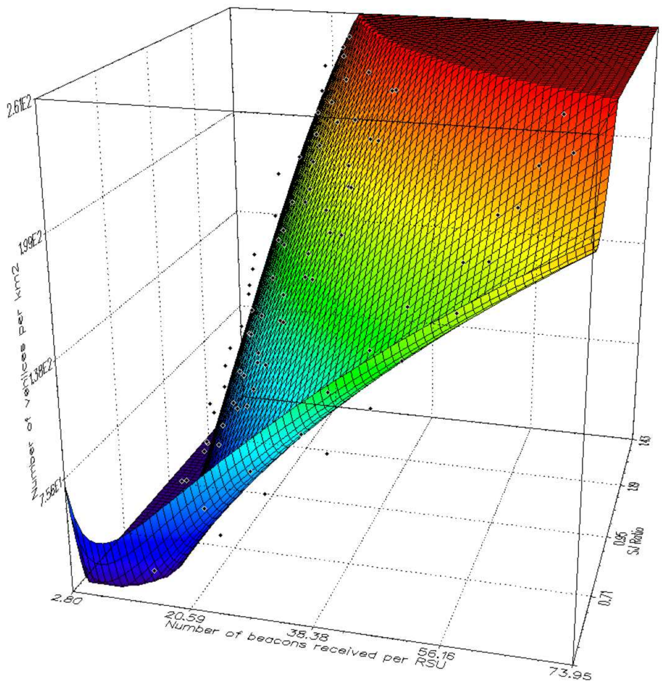


Figure 3.4: 3D representation of our density estimation function.

Table 3.5: Density Estimation Error of our Proposed Equation

Error	**Absolute**	**Relative**
Minimum	-5.399392E+01	-1.224762E+00
Maximum	4.837353E+01	1.696793E+00
Mean	2.848487E-13	3.041071E-02
Std. Error of Mean	2.422418E+00	3.542728E-02
Median	2.370528E-01	1.583324E-03

actually obtained. Note that the average relative error is of only 3.04%, which we consider that validates our proposed approach.

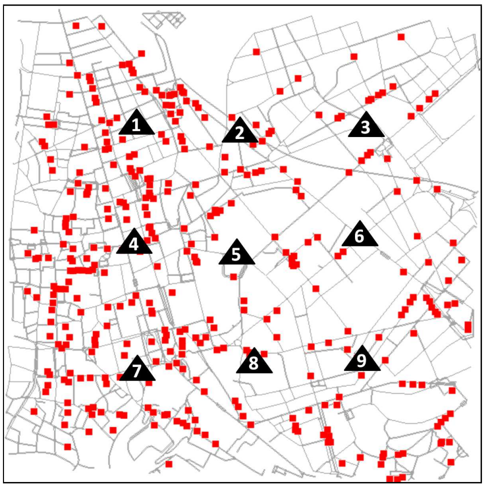
In our work, we also tested other possible functions that can be used in our vehicular density estimation approach. Equation 3.2 presents one of the alternative equations we obtained. However, in terms of accuracy, the average relative error is of 8.45%, while the first function presents a lower value (3.04%). Additionally, the Sum of Squared Errors (SSE) for the absolute error relative to this function is of 5.8344E+04, while the first function presents a lower value (4.7003E+04). Thus, we considered to use the first equation in our approach.

$$f(x, y) = a \cdot (dx + f)^b \cdot (gy + h)^c \tag{3.2}$$

3.5 Validation of our Proposal

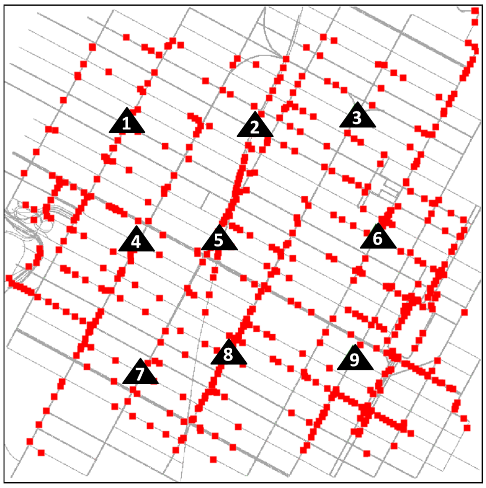
To assess our proposed density estimation function, we chose four particular cases. Specifically, we simulated: (i) a density of 100 vehicles per km^2 in Rome, the city with the highest SJ Ratio (ii) a density of 250 vehicles per km^2 in San Francisco, a city with an intermediate SJ Ratio, and (iii) a density of 200 vehicles per km^2 in New York, the city with the lowest SJ Ratio.

Figure 3.5 shows the RSU deployment strategy and the vehicles' location at the end of the simulation for the studied scenarios, whereas Table 3.6 shows the obtained results. We see that the average number of beacons received per RSU is of 8.78, 52.67, and 68.78 in Rome, San Francisco, and New York, respectively. These values obtained are highly affected by the vehicular density, as well as the roadmap topology. Note, that although the vehicular density simulated in New York is lower than the simulated



(a)

(b)



(c)

Figure 3.5: RSUs deployment and vehicles location at the end of the simulation in the cities of: (a) Rome, (b) San Francisco, and (c) New York. Solid squares represent the vehicles, and the triangles represent the RSUs.

in San Francisco, more beacons are received per RSU. This is caused by the lower SJ Ratio, since the roadmap topology of New York is simpler than that of San Francisco, thus allowing a better wireless signal propagation, as well as the reception of messages by the RSUs.

According to our proposal (i.e., applying the function shown in Equation 3.1), our system estimates a density of 103.68, 256.95, and 196.87 vehicles, respectively (see Equations 3.3, 3.4, and 3.5). Therefore, our vehicular density estimation approach accurately resembles the actual density, presenting an error of 3.68, 6.95, and 3.13 vehicles, which only represents the 3.68%, the 2.78%, and the 1.57% of the total vehicles.

$$f(x,y) = a + b \cdot ln(8.78) + \frac{c}{1.3873} + d \cdot ln(8.78)^2 + \frac{f}{1.3873^2} + g \cdot \frac{ln(8.78)}{1.3873} = 103.68 \qquad (3.3)$$

$$f(x,y) = a + b \cdot ln(52.67) + \frac{c}{0.8863} + d \cdot ln(52.67)^2 + \frac{f}{0.8863^2} + g \cdot \frac{ln(52.67)}{0.8863} = 256.95 \qquad (3.4)$$

$$f(x,y) = a + b \cdot ln(68.78) + \frac{c}{0.5140} + d \cdot ln(68.78)^2 + \frac{f}{0.5140^2} + g \cdot \frac{ln(68.78)}{0.5140} = 196.87 \qquad (3.5)$$

Table 3.6: Beacons received when simulating 250 vehicles/km^2 in San Francisco, and 200 vehicles/km^2 New York

RSU number	Rome		San Francisco		New York	
	Received beacons	% of received beacons	Received beacons	% of received beacons	Received beacons	% of received beacons
1	10	12.66	38	8.02	65	10.50
2	11	13.92	69	14.56	68	10.99
3	6	7.59	32	6.75	50	8.08
4	14	17.72	50	10.55	68	10.99
5	6	7.59	46	9.7	84	13.57
6	6	7.59	72	15.19	72	11.63
7	10	12.66	31	6.56	58	9.37
8	10	12.66	66	13.92	92	14.86
9	6	7.59	70	14.77	62	10.02
Total	**79**	**100**	**474**	**100**	**619**	**100**
Average	**8.78**	**-**	**52.67**	**-**	**68.78**	**-**

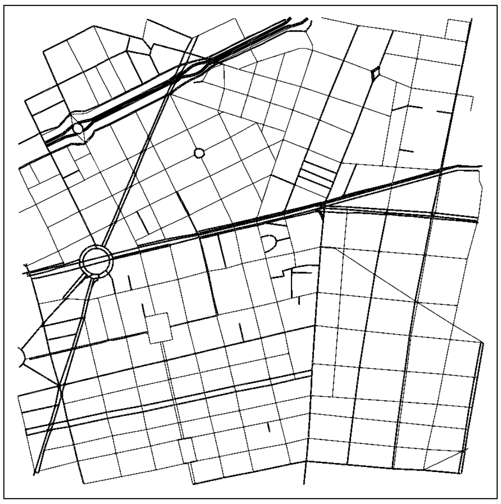


Figure 3.6: Fragment of the city of Mexico D. F. (Mexico).

In addition, we validate our proposed Density Estimation Function simulating a city which was not used to obtain it. To do this, we simulate a fragment of the city of Mexico D. F. which has a SJ Ratio of 0.7722 (see Figure 3.6). We simulated a density of 200 vehicles per km^2.

Figure 3.7 shows the RSU deployment strategy and the vehicles location at the end of the simulation for the studied example. The average number of beacons received per RSU is 47.56. According to our proposed function (see Equation 3.6), we estimate a density of 196.91 vehicles. In this example, the estimation of vehicular density obtained an error of 3.09 vehicles, which only represents the 1.55% of the total vehicles.

$$f(x,y) = a + b \cdot ln(47.56) + \frac{c}{0.7722} + d \cdot ln(47.56)^2 + \frac{f}{0.7722^2} + g \cdot \frac{ln(47.56)}{0.7722} = 196.91 \tag{3.6}$$

Moreover, using our system, we demonstrated that we are able to estimate the vehicular density in more specific areas. For example, using the data included in Table 3.6, our system can identify areas where the traffic is more congested (i.e., areas where the RSUs receive a higher percentage of beacons). For example, in the case of San Francisco, RSUs 2, 6, and 9 received a higher number of beacons compared to RSUs 1 and 7. According to these results, an automatic traffic control system could take advantage from V2I communication capabilities, adapting the vehicles' routes in order to redirect vehicles traveling in more congested areas to those areas where the RSUs receive a lower number

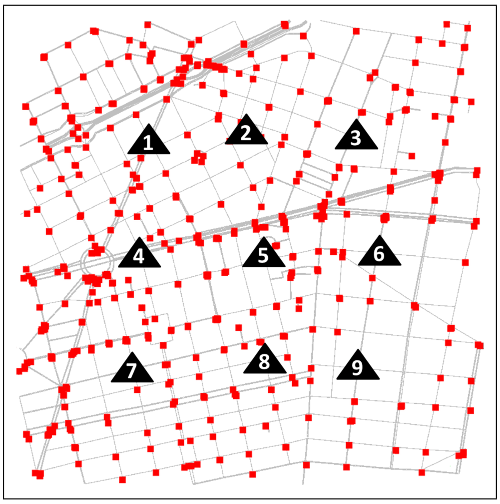


Figure 3.7: RSUs deployment and vehicles location at the end of the simulation.

of messages (i.e., less congested), thus avoiding traffic jams.

3.6 Comparing our Proposal with a Beacons-based Density Estimation Approach

Other vehicular density estimation proposals take into account just the number of beacons received (e.g., [MBML11], and [SCB11]), while omitting any data related to the map topology where the vehicles are located at. In order to assess the importance of the topology, we compared our proposal with a beacon-based approach, where the vehicular density is estimated only by using the number of beacons received. To make a fair comparison, we followed the same methodology in both approaches (i.e., we also made a regression analysis to obtain an equation capable of estimating the vehicular density, but in this case the estimation is solely based on the number of beacons received).

We tested several density estimation functions which are only based on the number of beacons received, trying to obtain the lowest value for the Sum of Squared Errors (SSE). In particular, we obtained the quintic polynomial function shown in Equation 3.7, and the logarithmic function shown in Equation 3.8.

$$f(x) = a + bx + cx^2 + dx^3 + fx^4 + gx^5 \tag{3.7}$$

$$f(x) = a + b \cdot ln(dx) + c \cdot ln(dx)^2 \tag{3.8}$$

The results confirm that our SJ Ratio function provides more accurate results, presenting a low value for the Sum of Squared Errors (i.e., 4.7003E+04), whereas the beacons-based functions present a Sum of Squared Errors value of 1.8993E+05 (for the polynomial) and 2.0161E+05 (for the logarithmic), i.e., one order of magnitude higher than our proposal.

Figure 3.8 shows a comparison of the estimated values with the simulation results obtained for the cities of Rome, San Francisco, and New York. As shown, our approach achieves a very good fit in the three cities studied, since it adjusts the estimation made, by accounting not only for the number of beacons received, but also for the features of the maps where the vehicles are located. On the contrary, those approaches that only take into account the number of beacons received are prone to provide inaccurate predictions, since they not take into account that the scenarios have different topologies. Specifically, they overestimate the number of vehicles in low density complex environments, despite being able to correctly estimate lower densities in complex maps, and higher densities in simple maps. Therefore, the advantages of using our vehicular density estimation proposal are clear in terms of accuracy.

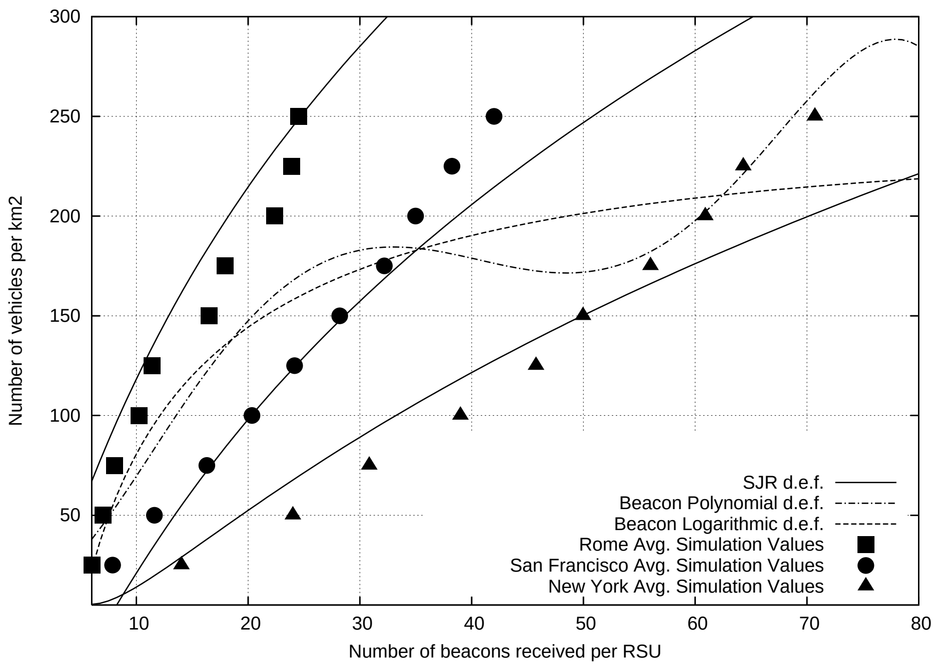


Figure 3.8: Comparison between simulated and estimated results for each density estimation function (d.e.f.).

3.7 Conclusions

In this chapter, we propose a method that allows estimating the vehicular density in urban environments at any given time by using V2I communications. Our proposal allows improving proactive traffic congestion mitigation mechanisms to better redistribute vehicles' routes, while adapting them to the specific traffic conditions.

Our vehicular density estimation algorithm takes into account not only the number of beacons received by the RSUs, but also the topology of the map where the vehicles are located. We demonstrate how our approach is able to accurately predict the vehicular density. Results show that it allows estimating the vehicular density for any given city with a high accuracy, thereby allowing governments to improve their traffic control mechanisms. Finally, we compare our proposal with respect to two different approaches that are solely based on beacons, thereby proving the high efficiency of our approach when tested in a wide variety of vehicular scenarios.

Chapter 4

Intelligent Vehicle Routing

Nowadays, traffic jams in urban areas have become a problem that keeps growing every year since the number of vehicles circulating in cities is continuously increasing. One of the most common causes producing traffic jams are vehicle accidents. Moreover, the arrival time of the emergency services could be raised through vehicles congestion. Intelligent Transportation Systems (ITS) aim at examining and reducing this problem. In this Chapter, we propose four different approaches to solve this, and compare them in order to obtain the best solution. Using V2I communications, we are able to determine the traffic density as a key factor when traffic must be redirected to reduce the emergency services arrival time and to avoid traffic jams when an accident occurs. Specifically, we propose two approaches based on Dijkstra, and two approaches based on Evolution Strategies, since, when an accident occurs, time is a critical issue and these kinds of strategies contribute to obtain an optimal solution in the shortest time.

4.1 Introduction

A close look at traffic accidents shows that many of the deaths takes place during the time elapsed between the accident occurrence and the arrival of medical assistance. The so called 'Golden Hour' after a car crash is the time within which medical or surgical intervention by a specialized trauma team has the greatest chance of saving lives. If more than 60 minutes have elapsed by the time the patient arrives to the operating table, the chances of survival fall sharply. Typical arrival of medical help takes about 15 minutes, but initial access and treatment starts 25 minutes after the accident. Transportation of the injured to the hospital usually takes place 50 minutes later. Therefore, time is critical for the survival of the injured in a severe incident, and any technology capable of providing a fast and efficient rescue operation after a traffic accident will increase the probability of survival of the injured, and reduce the injury severity [MTC+10].

Intelligent Transportation Systems (ITS) are among those newly introduced systems that promise a cure-all remedy to the ever increasing of traffic congestion [JO05]. In the near future, ITS will help the city traffic to be safer and more comfortable, redistributing traffic to avoid traffic jams [MHJ12], communicating real-time information when an accident occurs [BGF+12c], using intelligent systems for parking search [LLZS09], etc.

Cooperative vehicle systems have become an increasingly popular transportation paradigm in recent years. Wireless technologies, through vehicular networks, enable peer-to-peer mobile communications among vehicles (V2V), as well as communications between vehicles and infrastructures (V2I). Using these technologies, crashed vehicles are able to notify the emergency services about the occurrence of an accident. In addition, emergency services can redistribute traffic in real-time communicating or suggesting new routes to vehicles. These routes can be calculated using different methods as Dijkstra-based algorithms, genetic algorithms, or evolution strategies.

Evolutionary Algorithms imitate the principles of natural evolution as a method to solve parameter optimization problems. They have been successfully used to solve various types of optimization problems [GLH95], since using this kind of strategy, an optimal solution can be calculated without checking all the possible solutions. For this reason, they are widely used in real-time systems, since they can reduce the execution time drastically. Evolution Strategies are a kind of Evolutionary Algorithms with the particularity that the mutation steps are included in the chromosome. This kind of Evolutionary Algorithms obtains very good results for numerical optimization problems, specially working on continuous variables.

In this Chapter, we propose four different approaches to minimize emergency services arrival time when an accident occurs in urban scenarios, trying to solve traffic jams that could result from this special situation. In addition, we designed two of them to make use of Evolution Strategies in order to minimize the system runtime, since time is a critical factor in these situations. Then, we tested our proposed systems in three different scenarios with different topologies, with the aim of determining the best solution, taking into account the travel times of the emergency services and the rest of vehicles.

This Chapter is organized as follows: Section 4.2 reviews the related work regarding intelligent systems used to avoid traffic jams and minimize vehicle travel times. In Section 4.3 we present four different re-routing systems (i.e., Dijkstra, Density-Based Dijkstra, Evolution Strategy, and Density-Based Evolution Strategy). Section 4.4 introduces the simulation environment used to assess our proposed schemes. Section 4.5 shows the obtained results and the comparison between our proposed approaches. Finally, Section 4.6 concludes this Chapter.

4.2 Related Work

Genetic algorithms have been applied for traffic distribution in several works. Ohara et al. [ONI06] examined two routing methods to minimize the average travel time over all the vehicles running in a specific proposed model. One of these methods tried to minimize the average travel time globally through a centralized system. Since the number of combinations of vehicles routes exponentially increases as the number of vehicles grows, authors employed a genetic algorithm to search for a near-optimal route combination for all vehicles (they needed an efficient combinatorial optimization technique). In order to make their simulation, they only use a specific theoretical scenario.

Yoshikawa and Terai [YT09] discussed a route selection algorithm, particularly focused on a hybrid technique which combines genetic algorithms with the Dijkstra algorithm [Dij59] to achieve high quality route guidance. They presented a solution similar to *The Traveling Salesman Problem* [JM97]. Their proposal is based on an individual vehicle which has an order of the passing points as genes. For these simulations, they use a theoretical scenario estimating distances between nodes based on Manhattan streets distances. To develop their genetic algorithm, they only took into account route distances for each individual vehicle without using vehicle density.

Zheng and Shi [WS09] presented a mathematical model with a genetic algorithm, in order to deal with the disruption events, such as traffic jams, accidents, and alterations of road conditions, that occur in vehicle routing problems. Their work was focused on logistics problems. In particular, their algorithm found the fastest route in a theoretical scenario with a single type of logistic distribution using the same kind of vehicle for the simulations. In a real scenario there are many types of vehicles circulating at different speeds. For this reason, we consider that they should use more types of vehicles and a realistic vehicle mobility model.

More recently, Denzai et al. [DGDM12] presented an application for real-time traffic lights control in congested urban traffic, taking as input the location and route of the vehicles in the involved areas. Authors used V2I communications to receive vehicles location in order to calculate traffic density. Additionally, they developed a genetic algorithm to solve traffic jams by controlling traffic lights, due to the great complexity of the possible combination and the short time to get a response. Related to their proposed traffic density estimation system, we consider that it is not realistic since the vehicles circulating outside the infrastructure coverage area cannot communicate their position. Also, authors only consider a specific theoretical scenario.

In these studied works, authors only consider a theoretical scenario for simulations in order to verify these systems. We consider that these simulations are not realistic, since real-world roads do not follow a general pattern, especially in urban scenarios.

In other works, authors considered real scenarios to test their proposals. Collins and Muntean [CM08] presented a novel adaptive vehicle routing algorithm enabled by wireless vehicular networks. Their system was based on the client-server architecture, where clients are vehicles. They used a genetic algorithm to select the best route for each vehicle, using a fitness function taking into account road congestion, vehicle travel time, and fuel consumption. Specifically, they used four different kinds of simulations: (i) selecting the shortest route, but not varying it during the travel, (ii) each vehicle drives towards its own destination according to the route management solution, but without adaptation during the travel, (iii) each vehicle drives towards its own destination according to the route management solution with dynamic adaptation during the travel, and (iv) the hypothetical 'ideal' solution based on traffic saturation able to dynamically re-route vehicles. The only scenario used in their simulations was a fragment of the city of Boston (USA).

Sanchez-Medina et al. [SMGMRR10] developed a model for traffic signal optimization based on the combination of three key techniques: (i) genetic algorithms for the optimization task, (ii) cellular-automata-based microsimulators for evaluating every possible solution for traffic-light programming times, and (iii) a Beowulf Cluster, which is a multiple-instruction-multiple-data (MIMD) multicomputer of excellent price/performance ratio. They tested the GA with four different fitness functions: (i) number of vehicles that reach their destination point easily, (ii) mean travel time, (iii) time of occupancy and state of occupancy, and (iv) global mean speed. Authors used a traffic model based on both Krauss [KWG97], and Schadschneider and Chowdhury [SCB+99] models. However, they focused their simulations on a specific scenario, i.e., 'La Almozara' district in Zaragoza.

Other authors proposed intelligent systems for traffic distribution using real scenarios to assess their proposal. Kim et al. [SLWI05] examined the value of real-time traffic information for vehicle routing in a nonstationary stochastic network. They presented a systematic approach to aid the implementation of transportation systems integrated with real-time information technology. In particular, they developed decision-making procedures for determining the optimal driver attendance time, optimal departure times, and optimal routing policies under time-varying traffic flows based on a Markov decision process formulation. With a numerical study carried out on an urban road network in Southeast Michigan, they demonstrated advantages when using this information in terms of total cost savings and vehicle usage reduction while satisfying or improving service levels for just-in-time delivery. However, in this proposal, authors only simulated one specific scenario (i. e., Southeast Michigan). In addition, they estimated the traffic density based on historical information collected during 30 days in the most important streets of the aforementioned city. We consider traffic density varies drastically depending on many factors (time of the year, weather, holidays, etc.), therefore, a traffic density estimation based on historical information during 30 days does not represent the true real-time traffic density. We think that it is more useful to use a system able to estimate the traffic density in real-time.

From our point of view, simulating only one specific scenario is inadequate to present a vehicle routing model (even if the scenario is real since it can lead to inaccurate results). We think that simulating several different topology scenarios is necessary, since, as we demonstrated in Chapter 3, the roadmap topology significantly affects the obtained results.

On the other hand, several authors proposed traffic distribution systems by using vehicular communications. Dornbush and Joshi [DJ07] proposed a system that used a standard GPS driving aid augmented with peer-to-peer wireless communication, with the aim of informing drivers about traffic congestion. With this information, drivers could decide to change the route, but this process was not guided by any system, making the majority of drivers select the same route again. We think that a system able to automatically redirect vehicles is necessary to avoid this problem. In the same year, S. Inoue et al. [ISK07] presented an automobile control system where each driver obtains traffic information adaptively in order to alleviate traffic congestions. The proposed system used inter-vehicle ad hoc communication. Their route decision method consists on redirecting individually each vehicle to areas with lower traffic density. They proposed a system of new routes verification in order to analyze negative effects to a new route caused by a traffic congestion in another route. In their simulations, they used a simple grid theoretical scenario. Although these authors took into account the possibility of generating new traffic jams while re-routing vehicles, they did not simulate it in realistic scenarios. In addition, evaluating each possible vehicle route implies a high computational cost.

To the best of our knowledge, there are several works related to use intelligent system to avoid traffic jams. In all studied works, authors only consider a specific scenario for simulations in order to assess their proposal. We consider that only a specific scenario is not enough to validate a proposal. In addition, related proposals presented do not consider developing a system able to solve traffic jams by using a street priority scheme (based on the preference respect to the other streets in an intersection) to calculate vehicles routes. We consider that this solution may be the right one, especially when an accident occurs.

4.3 Our Proposed Vehicle Routing Systems

Since traffic jams are a critical problem in big cities nowadays, we propose an approach able to reduce the occurrence of these traffic jams, specially when an accident is the cause of congestion. To do this, we developed a system based on street priorities. The priority of one street indicates the preference of a vehicle with respect to the others when it arrives to an intersection.

Table 4.1: Features of our proposals

	Dijkstra	**Density-Based Dijkstra**	**Evolution Strategy**	**Density-Based Evolution Strategy**
One execution	✓	✓	✗	✗
Some executions	✗	✗	✓	✓
Considering traffic density	✗	✓	✗	✓

In this Section, we propose different approaches with the aim of ensuring that emergency services arrive at the place of the accident as soon as possible, whereas the rest of vehicles are not significantly affected, i. e., their travel times do not increase considerably.

In the following Subsections, we present four different vehicle routing schemes: (i) Dijkstra, (ii) Density-Based Dijkstra, (iii) Evolution Strategy, and (iv) Density-Based Evolution Strategy. Table 4.1 presents the main features of these proposed approaches. As shown, the first two proposed approaches are only based on one execution, but the second system additionally takes into account the traffic density. The other two proposed approaches are implemented via evolution strategies, and additionally by using a real-time traffic density estimation scheme in the second case.

4.3.1 Dijkstra

This system aims at obtaining the shortest route between two map positions by means of the Dijkstra algorithm [Dij59], specifically adapted to roads and streets, taking into account the length and priority of the streets. In this system, the street priority is calculated by using the number of lanes per street, assigning higher priority to the widest streets (i. e., with higher number of lanes). The main disadvantage of this system is noticeable when there is a high number of vehicles in a specific area, since it might produce traffic jams even in the widest streets. Figure 4.1 shows an example of this situation. As shown, vehicles arrive to the junction through street A. Using this system and considering the priorities shown in the figure (0.1 for street B and 0.9 for street C), the majority of vehicles continue their route through street C (90% of vehicles since this street has a greater number of lanes), collapsing it. However, street B has less traffic density which indicates that probably traffic in the street is more fluid.

This proposed system uses a static model for street priorities. That means that a priority is given to each street when a new roadmap is used as simulation scenario for the first time, and they do not change under any circumstance. This issue could generate two kind of problems when an accident occurs: (i) there could be traffic jams in determined areas of the scenario whereas other areas present very low traffic, and (ii) the streets selected as routes for the emergency services do not present low priority for the rest of vehicles in order to reduce the number of potential vehicles blocking the streets.

The main advantage of this system is the low computational cost since it does not need to know the current traffic density or the emergency service routes. When an accident occurs, this system can be applied immediately.

4.3.2 Density-Based Dijkstra

This proposed system is similar to the previous one, with the difference that, in this case, we take into account the traffic density in the area when the street priorities are calculated. To develop this method, the streets heading an area with high traffic density are penalized. When an accident occurs, the vehicles involved in it send a warning message using Vehicular Networks. When control systems are notified, they apply the vehicular density estimation approach presented in Chapter 3. In addition, the streets through which emergency services circulate to arrive at the accident site are penalized for the rest of vehicles. Specifically, in this proposed system, we do this as follows:

- *Step 1*: we prioritize streets normalizing the values 10 to 1 (see Equation 4.1). As shown, the normalized values start in 1 and end in 10 (N_{min} and N_{max}, respectively).

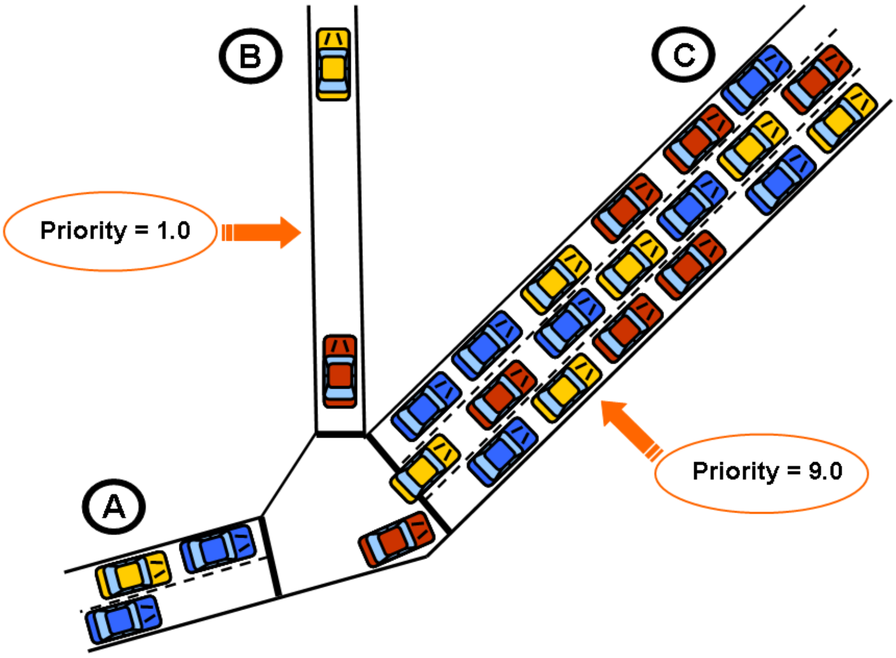


Figure 4.1: Example of traffic jam when the street priority is given by the number of lanes.

$$N_x = \frac{(P_x - P_{min}) \cdot (N_{max} - N_{min})}{P_{max} - P_{min}} + N_{min}$$
$$where:$$
$$N_{min} = 1$$
$$N_{max} = 10 \tag{4.1}$$

- *Step 2*: the normalized value of the rest of areas (N_x) is calculated by using a proportion between the minimum and the maximum traffic densities percentages, and the traffic density of the area which we want to calculate the normalized value (P_{min}, P_{max}, and P_x, respectively).
- *Step 3*: with the aim of penalizing streets with a high traffic density, we apply Equation 4.2. In this Equation, we obtain the inverse value calculated above (S_x), since a higher priority value has more priority, and we multiply this value by the number of lanes of the street (L_x).

$$S_x = (11 - N_x) \cdot L_x \tag{4.2}$$

- *Step 4*: we calculate the emergency vehicles routes.
- *Step 5*: with the aim of calculating the fastest route for the emergency services vehicle, this approach applies a simple Dijkstra algorithm for each one, calculating the shortest route between two map positions (accident site and hospital, police station, firehouse, etc.), regardless traffic density. Note that, in this case, we do not take into account the streets priority since emergency vehicles always have more priority than the rest of vehicles, regardless the street that they are circulating.
- *Step 6*: as shown in Equation 4.3, we penalize the streets through which emergency services circulate (S_{x_e}) by giving them a priority corresponding to the number of lanes (a street with four lanes has a priority of 4).

$$S_{x_e} = L_x \tag{4.3}$$

- *Step 7*: we calculate the new vehicle routes using a Dijkstra-Based algorithm taking into account the streets priorities, since the shortest path could not be the fastest path.

Equation 4.4 shows an example of street priorities calculation. As shown, we have three different areas which contain the following percentage of traffic vehicles: $P_{min} = 20\%$, $P_{max} = 50\%$, and $P_x = 30\%$ of the total of vehicles. Also, we have three streets located in the aforementioned areas with these number of lanes ($L_{min} = 3, L_{max} = 2$, and $L_x = 1$). As we have the maximum and minimum normalized values (N_{min} and N_{max}), we calculate the other street normalized value (N_x) by using Equation 4.1. Finally, we obtain the street priorities (S_{min}, S_{max}, and S_x) by using Equation 4.2, thereby obtaining street priorities of 30, 2, 7 respectively.

$$
\begin{aligned}
&P_{min} = 20, P_{max} = 50, P_x = 30 \\
&N_{min} = 1, N_{max} = 10 \\
&L_{min} = 3, L_{max} = 2, L_x = 1 \\
&N_x = \frac{(P_x - P_{min}) \cdot (N_{max} - N_{min})}{P_{max} - P_{min}} + N_{min} \\
&N_x = \frac{(30 - 20) \cdot (10 - 1)}{50 - 20} + 1 = 4 \\
&S_x = (11 - N_x) \cdot L_x \\
&S_{min} = (11 - 1) \cdot 3 = 30 \\
&S_{max} = (11 - 10) \cdot 2 = 2 \\
&S_x = (11 - 4) \cdot 1 = 7
\end{aligned}
\tag{4.4}
$$

This approach could have a delay of about 30 seconds to be applied, since the scheme needs the estimated traffic density obtained by the system present in Chapter 3 (this system needs to receive beacons during 30 seconds to estimate the traffic density). To solve this problem, control units could execute continuously the aforementioned estimation system in order to know immediately the traffic density estimation, assuming an error of non-real-time estimation with a maximum threshold of 30 seconds. Using this approximation, this system would only require calculating the emergency services routes.

4.3.3 Evolution Strategy

Evolutionary algorithms are based on Darwinian theories of evolution to explain the origin of species [ES03]. Natural selection favors those individuals competing for resources in a more effective way, i.e., better adapted to the environmental conditions. Although there are different variants of evolutionary algorithms, such as genetic algorithms, evolution strategies, evolutionary programming, and genetic programming, all of them have the same essence: an individual population generates descendants and the best individuals are selected to obtain the next generation.All evolutionary algorithms have the same methodology, presented in the Algorithm 1.

Evolution strategies are a variant of evolutionary algorithms with the following features:

- They are typically used for conditions parameter optimization.
- There is a strong emphasis on mutation for creating offspring.
- Mutation is implemented by adding some random noise drawn from a Gaussian distribution.
- Nutation parameters are changed during a run of the algorithm, achieving faster results.

Due to the high computational cost of calculating all possible combinations of street priorities to find the optimal solution, we consider interesting to apply an Evolution Strategy. Evolution Strategies

Algorithm 1 Evolutionary Algorithm Scheme

BEGIN
  INITIALIZE POPULATION
  EVALUATION
  REPEAT UNTIL (*FINISH CONDITION*) DO
    PARENTS SELECTION
    RECOMBINATION
    MUTATION
    EVALUATION
    SURVIVOR SELECTION
  END LOOP
END

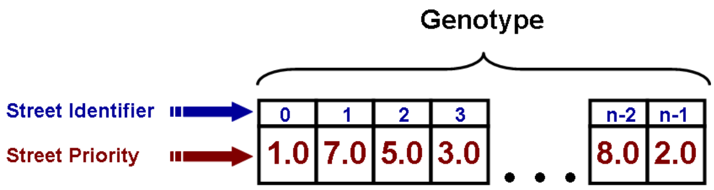


Figure 4.2: Example of genotype for street priorities.

are typically used to solve optimization problems of continuous variables. As in the previous proposed approaches, this scheme applies the Dijkstra algorithm for each emergency vehicle in order to calculate the emergency services routes. In this case we do not take into account traffic density, but we penalize the streets selected for the emergency services vehicles. Then, we calculate new routes for vehicles using a priority-based Dijkstra algorithm (with the same aims of the previously proposed system).

In the following Subsections we present the main characteristics of the Evolution Strategy used in our proposed system (i.e., definition of variables, fitness function, mutation, recombination, parents selection, and survivors selection).

4.3.3.1 Definition of Variables

An individual encodes a possible solution into a chromosome based structure (genotype) [MB05], in this case, a vector of float point numbers which contains the priority value of each street (as shown in Figure 4.2) is considered. Street priorities are randomly selected in the vectors of the initial population for each street for the first time.

4.3.3.2 Fitness Function

Selection is a process in which solutions are selected for recombination based on their fitness values. Here, fitness refers to a measure of profit, utility, or goodness to be maximized while exploring the solution space. Our system has three different fitness functions designed to minimize the arrival time for the emergency vehicles and the travel time of the rest of vehicles: (i) Fitness Function 1 gives double importance to the arrival time of emergency services (‘e’ represents emergency services vehicles, and ‘r’ represents the rest of Regular vehicles) (see Equation 4.5), (ii) Fitness Function 2 assigns same importance to both arrival times (see Equation 4.6), and (iii) Fitness Function 3 gives double importance to arrival time of the rest of vehicles (see Equation 4.7). Then, we compare these functions to determine which one obtains better results when simulating the testbed.

$$FitnessFunction1 = 2 \cdot \frac{\sum_{i_e=0}^{n_e} t_{i_e}}{n_e} + \frac{\sum_{i_r=0}^{n_r} t_{i_r}}{n_r} \tag{4.5}$$

$$FitnessFunction2 = \frac{\sum_{i_e=0}^{n_e} t_{i_e}}{n_e} + \frac{\sum_{i_r=0}^{n_r} t_{i_r}}{n_r} \tag{4.6}$$

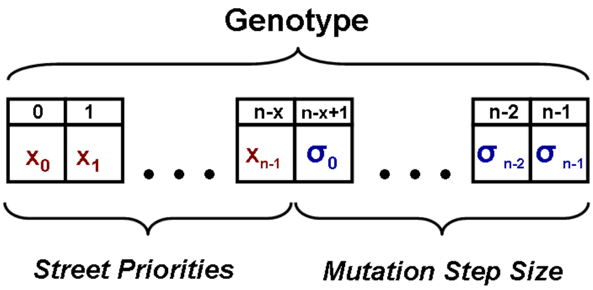


Figure 4.3: Example of genotype formed by streets priorities and mutation step sizes.

$$FitnessFunction3 = \frac{\sum_{i_e=0}^{n_e} t_{i_e}}{n_e} + 2 \cdot \frac{\sum_{i_r=0}^{n_r} t_{i_r}}{n_r} \tag{4.7}$$

4.3.3.3 Mutation

In an Evolution Strategy there is a strong emphasis on the mutation to create the offspring. Additionally, mutation is implemented by adding a random 'noise' obtained from a Gaussian distribution. Mutation parameters change during the execution of the algorithm. In our proposal, we use an Uncorrelated Mutation with n Step Sizes. The mutation mechanism applies the functions included in Equation 4.8, where σ is the mutation step size, τ is the scale parameter for the mutation step sizes, and n is the number of individuals.

$$\begin{aligned}
\sigma_i' &= \sigma \cdot e^{\tau' \cdot N(0,1) + \tau \cdot N_i(0,1)}, \\
x_i' &= x_i + \sigma_i' \cdot N_i(0,1) \\
\\
where: \\
\tau' &\propto \frac{1}{\sqrt{2n}} \\
\tau &\propto \frac{1}{\sqrt{2\sqrt{n}}}
\end{aligned} \tag{4.8}$$

Using this kind of mutation, our genotype contains values x (streets priority) and values σ (mutation step sizes), as shown in Figure 4.3.

To avoid too small standard deviations providing a negligible effect, we limit the value of the step sizes using a threshold (ε_0), i.e., $\sigma' < \varepsilon_0 \Rightarrow \sigma' = \varepsilon_0$.

4.3.3.4 Recombination

The basic scheme of recombination in Evolution Strategies requires two parents to create a child. For λ descendants, the recombination process is performed λ times. There are two variants of recombination depending on how parental alleles are recombined:

- Discrete Recombination: one of the alleles of the parents is chosen with equal probability for both parents.
- Intermediate Recombination: the parental allele values are averaged.

Furthermore, two parents can be used, randomly obtained from the population of μ individuals, for each component ($i \in \{1...n\}$) of the offspring. This is known as *Global* recombination, and the variant in which only two parents are selected for the total of components is called *Local* recombination.

In our proposed system, we apply Local Discrete Recombination, since this method is one of the most used in this kind of algorithms and it provides a good performance in most cases. As shown in Figure 4.4, each child allele is chosen with equal probability for both parents.

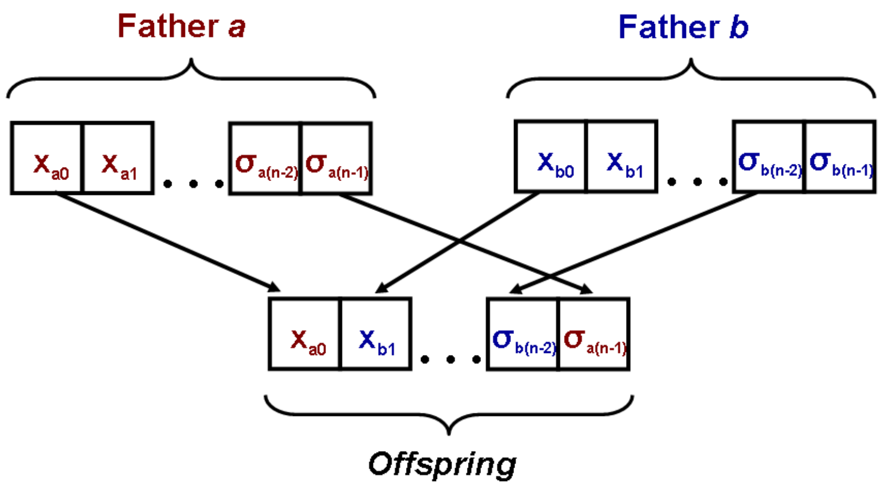


Figure 4.4: Example of local discrete recombination.

4.3.3.5 Parents Selection

The parents selection in Evolution Strategies does not depend on their fitness values. Parents are chosen randomly by using a uniform distribution from the population of μ individuals.

4.3.3.6 Survivors Selection

The Survivors Selection consists on deterministically choosing the μ best individuals, after creating λ descendants and calculating their fitness. There are two kinds of Survivor Selection:

- Selection (μ, λ): only the individuals of the offspring are considered to generate the next generation.
- Selection $(\mu + \lambda)$: survivors are selected from the union of parents and descendants.

Our proposed scheme uses Selection $(\mu + \lambda)$, since using Selection (μ, λ) descendants could produce worse results, delaying the achievement of the best solution.

4.3.4 Density-Based Evolution Strategy

This approach combines both the Density-Based Dijkstra and the Evolution Strategy schemes. The goal of this Intelligent System is to verify if using traffic density we are able to reduce our system runtime, by reducing the number of generations, since when an accident takes place, the response time has special importance. A close look at the accidents shows that many of the deaths occurred during the time between the accident and the arrival of medical assistance. For this reason, obtaining results as quickly as possible is as important as finding the optimal solution.

With the aim of reducing the system runtime, we propose an Evolution Strategy with the same characteristics as the Evolution Strategy System (presented in the previous Subsection), but in this case we do not obtain the initial population randomly. To do this, we start the strategy taking into account two different genotypes: (i) a genotype which contains street priorities based on the number of lanes, and (ii) a genotype which contains street priorities based on traffic density. The rest of individuals of the initial population are obtained recombining these two genotypes. Street priorities based on the number of lanes are obtained by squaring the number of lanes of each street, and the street priorities based on traffic density and emergency vehicles routes are obtained by using the method proposed in the Density-Based Dijkstra approach. Then, we make a first recombination with them, selecting the n best descendants in order to generate a first offspring approaching to the best solution. This improvement will make the system reach the optimal solution in less time than using a random initial population.

Figure 4.5 shows an example of the objective of this solution. As shown, initializing the population accounting for the traffic density and the number of lanes could make it possible to obtain better solutions with a lower number of offsprings, thereby reducing the system runtime. As shown, while the non-density-based system would have created x_{db} generations to obtain the y_{db} fitness value, our

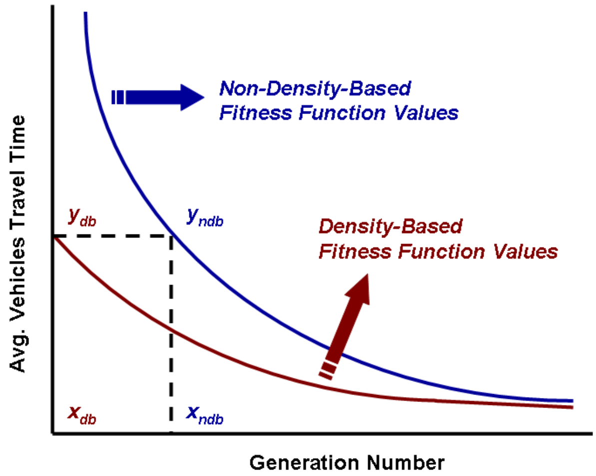


Figure 4.5: Example of fitess function values using both proposed intelligent systems (i.e., Evolution Strategy and Density-Based Evolution Strategy).

Table 4.2: Attributes of SUMO Streets

Attribute	**Description**
id	The unique id of the street
from	The id of the starting junction
to	The id of the final junction
priority	Street weight regarding the rest of the streets

density-based proposed system would obtain this value in its first generation. The initial executions would be avoided and, therefore, this approach would save crucial time.

4.4 Simulation Environment

Traffic simulation is known to be a very complex issue. One of the main reasons is due to the fact that traffic simulators must model the discrete dynamics that arise from the interaction among individual vehicles [BDS97]. The Simulation of Urban MObility (SUMO) is an open source, microscopic, continuous-space traffic simulator designed to handle large road networks, and it is mainly developed by employees of the Institute of Transportation Systems at the German Aerospace Center[1] [KR12].

SUMO mobility generator supports several mobility models, such as the Krauss mobility model [KWG97]. In addition, SUMO allows customizing a wide variety of parameters as the initial and final position of the vehicles, type of vehicles, streets maximum speed, or streets priority. Table 4.2 shows the SUMO street attributes that we use in our system. Moreover, each SUMO lane has an attribute indicating the street to which it belongs. This allows us to obtain the number of lanes of each street. We use the attributes *from* and *to* to know the heading of the street, the attribute *id* to link lanes with streets, and the attribute *priority* to implement our proposed schemes.

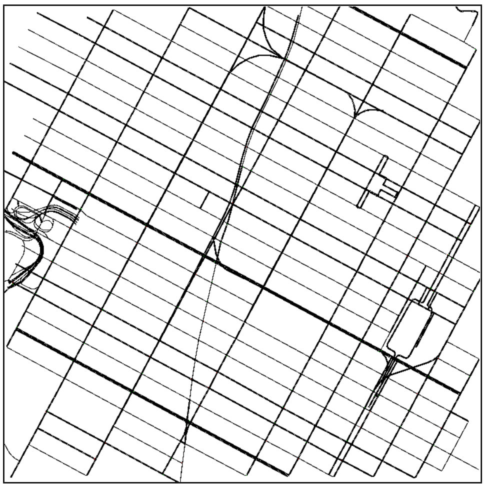
To increase the level of realism of our simulations, we use real scenarios consisting in fragments of the cities of Rome (Italy), San Francisco (USA), and New York (USA) imported directly from OpenStreetMap [Ope12]. OpenStreetMap is a project with the aims of creating and providing free geographic data, such as street and road maps. According the SJ Ratio presented in Chapter 3, these cities are examples of the roadmaps with the highest SJ Ratio, an intermediate SJ Ratio, and the lowest SJ Ratio, respectively (see Figure 4.6). So, we assess our proposal under different and representative roadmap profiles.

All simulations results consist of an average of over 100 runs with different scenarios, densities and fitness functions. Each simulation consist on vehicles circulating during 600 seconds. We simulate a car accident in the second 60. We use this first 60 seconds as a warm up to achieve a stable state and to be able to estimate traffic density with the system presented in Chapter 3. During this time, vehicles

[1] http://www.dlr.de/fs/en/desktopdefault.aspx

(a)

(b)



(c)

Figure 4.6: Scenarios used in our simulations. Fragments of the cities of: (a) Rome (Italy), (b) San Francisco (USA), and (c) New York (USA).

Table 4.3: Parameters used for the simulations

Parameter	**Value**
number of simulations	100
roadmaps	Rome, San Francisco, and New York
warm up time	60 seconds
roadmap size	$2000m \times 2000m$
number of vehicles	500 and 1000
number of collided vehicles	1
warning message size	18KB [BGF+12c]
beacon message size	$512B$
warning messages priority	$AC3$
beacon priority	$AC1$
interval between messages	1 second
RSU deployment policy	Uniform Mesh [BGF+12b]
MAC/PHY	802.11p
radio propagation model	RAV [FGM+12c]
mobility model	Krauss [KWG97]
channel bandwidth	$6Mbps$
max. transmission range	$400m$

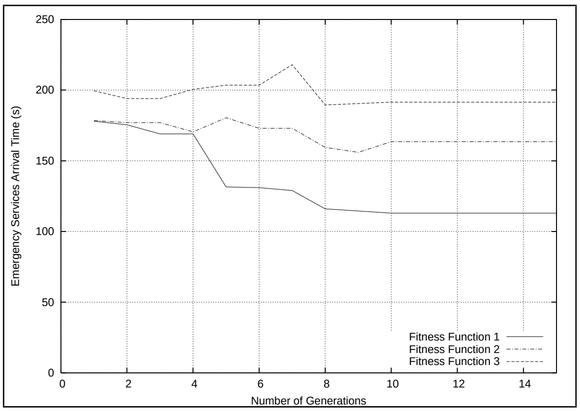
follow random routes. In the moment of the accident, we capture the specific location of all the vehicles and their target location. Then, we apply our proposed approaches to calculate the new vehicle routes, and we compare them. Additionally, we consider a non-static start and end position for the emergence vehicle, since an ambulance does not have to be always in the same place and the accident can occur in any location. Table 4.3 shows the parameters used for the simulations.

4.5 Simulation Results

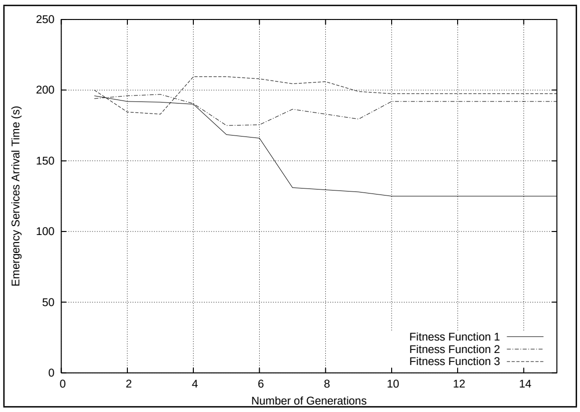
In this Section we present the simulation results of our proposed approaches and compare them. First, we show the Evolution Strategy System obtained results in order to study the number of needed generations to obtain the function convergence values. Then, we compare the Dijkstra, the Density-Based Dijkstra, and the Evolution Strategy Systems, since we demonstrate that applying an evolution strategy we obtain better results. Later, we present a comparison between Evolution Strategy and Density-Based Evolution Strategy Systems, with the aim of prove that adding traffic density information the evolution strategy obtains better results using a smaller number of generations. Finally, we study the impact on the results reducing the population size and the number of descendants, with the goal of reducing the system runtime.

4.5.1 Evolution Strategy

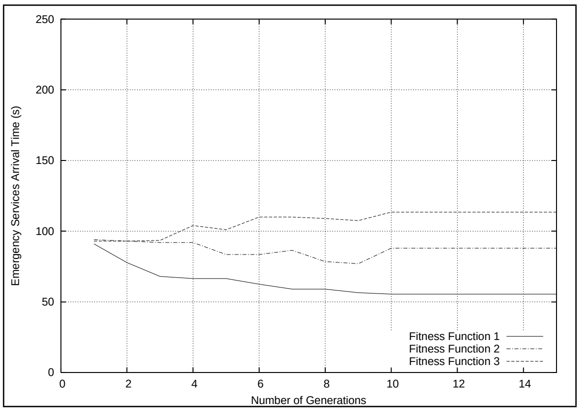
In this Subsection, we show the obtained results using our proposed Evolution Strategy and we analyze the number of generations required to obtain the function convergence value. Table 4.4 shows the parameters used for the Evolution Strategy used. Figures 4.7 and 4.8 present the obtained results. As shown, the system obtains the best emergency services arrival times when applying Equation 4.5 as a fitness function (i.e., the fitness function that gives doubled importance to the emergency services arrival time) in all simulated scenarios. Also, we can observe that using the Equation 4.7 as fitness function, our system is able to reduce travel times of the rest of vehicles, but this solution increases the emergency services arrival times. On the other hand, results indicate that applying Equation 4.6 as fitness function we reduce both times (the emergency services arrival time and the rest of vehicles travel time), but they do not decrease in the same degree as using the other two fitness functions. Since the goal of our proposal is to reduce emergency services arrival time as much as possible, we select Equation 4.5 as the best fitness function, which is able to minimize this time. In addition, as shown in Figure 4.7, using this configuration, the system obtains the function convergence values in only 10 generations as maximum.



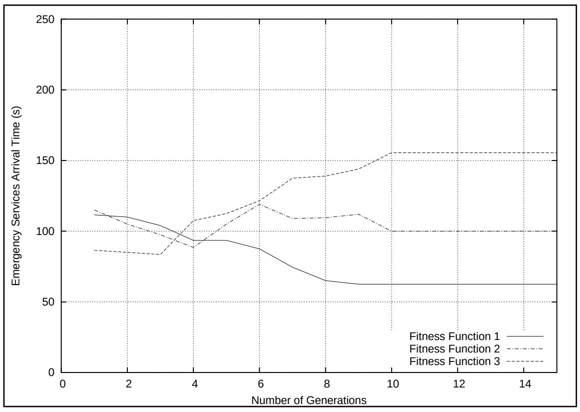
(a)



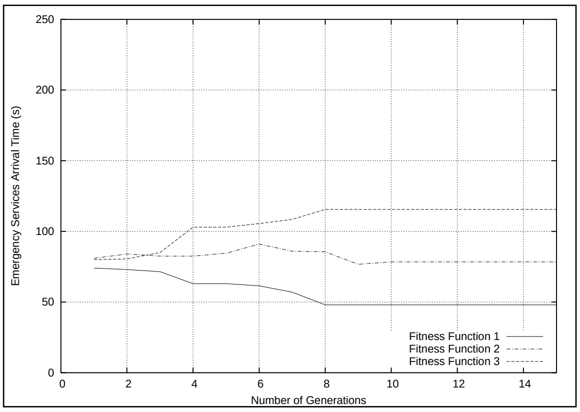
(b)



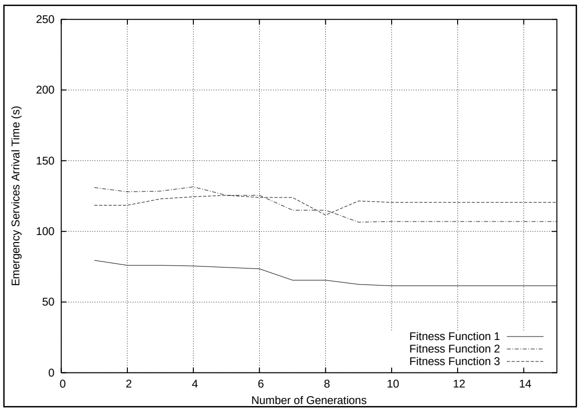
(c)



(d)

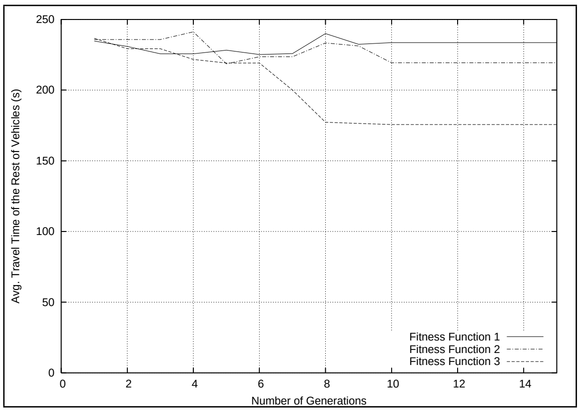


(e)

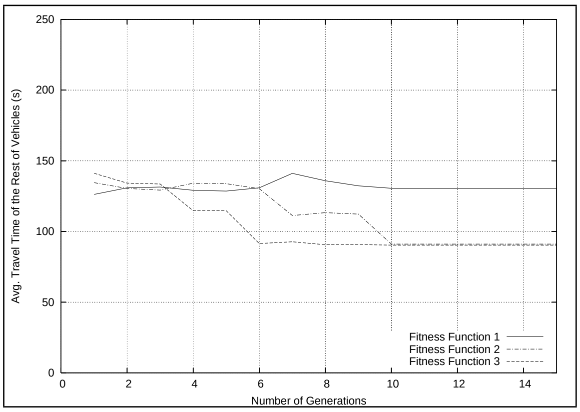


(f)

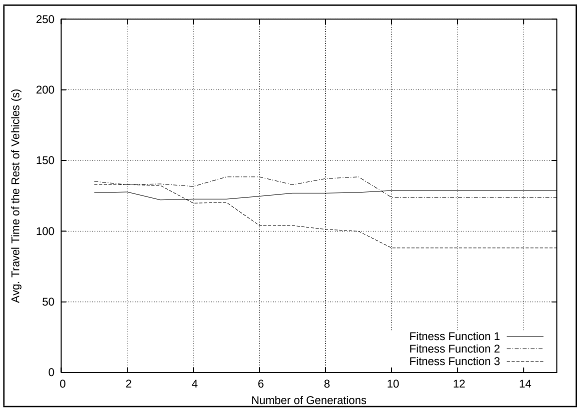
Figure 4.7: Emergency services arrival times on average after 100 simulations, using the Evolution Strategy in the scenarios of: Rome (Italy) (a) 125 vehicles/km^2, and (b) 250 vehicles/km^2, San Francisco (USA) (c) 125 vehicles/km^2, and (d) 250 vehicles/km^2, and New York (USA) (e) 125 vehicles/km^2, and (f) 250 vehicles/km^2.



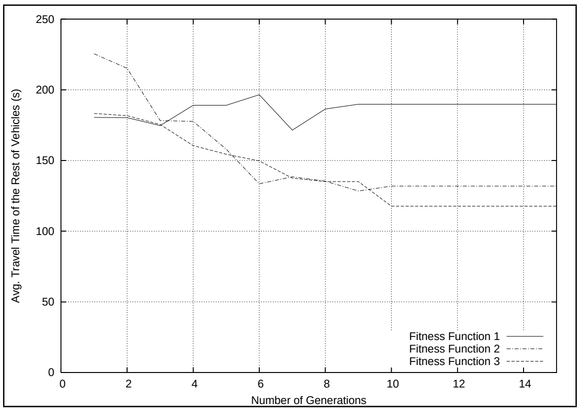
(a)



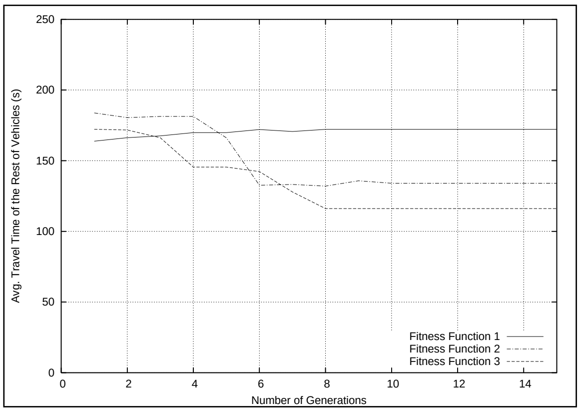
(b)



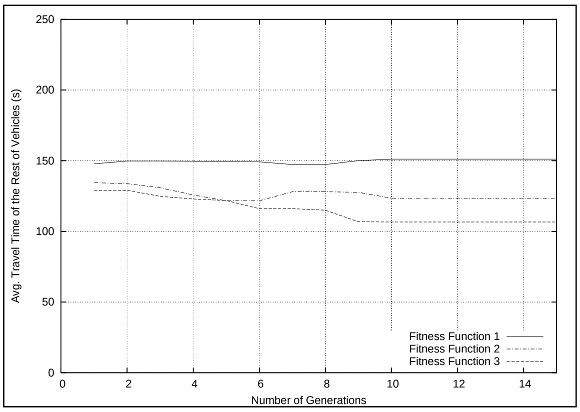
(c)



(d)



(e)



(f)

Figure 4.8: Mean travel times of the rest of vehicles on average of 100 simulations, using the Evolution Strategy in the scenarios of: Rome (Italy) (a) 125 vehicles/km^2, and (b) 250 vehicles/km^2, San Francisco (USA) (c) 125 vehicles/km^2, and (d) 250 vehicles/km^2, and New York (USA) (e) 125 vehicles/km^2, and (f) 250 vehicles/km^2.

Table 4.4: Parameters used for the Evolution Strategy

Parameter	Value
number of simulations	100
population number	5
number of descendants	10
number of generations	20
fitness function	Equations 4.5, 4.6, and 4.7
mutation	Uncorrelated Mutation with n Step Sizes
recombination	Local Discrete
parents selection	Randomly
survivors selection	$(\mu + \lambda)$

Table 4.5: Simulation Obtained Results

Scenario	Vehicles/km^2	Dijkstra		Density-Based Dijkstra		Evolution Strategy	
		Vehicles Avg. t.	Emgcy. Serv. t.	Vehicles Avg. t.	Emgcy. Serv. t.	Vehicles Avg. t.	Emgcy. Serv. t.
Rome	125	222.91	190	205.09	162	233.59	113
	250	112.27	209	109.01	159	130.54	125
San Francisco	125	112.02	92.5	106.86	82.5	128.74	55.5
	250	148.08	126	145.14	82.5	189.81	62.5
New York	125	151.43	68	134.04	60.5	172.19	48
	250	143.46	83.5	126.61	78.5	151.14	61.5

4.5.2 Dijkstra, Density-Based Dijkstra, and Evolution Strategy Comparison

For the purpose of knowing which one is the best system, we analyze the results obtained with the configuration proposed in the previous Subsection (i. e., 10 number of generations, and Equation 4.5 as the fitness function), since they were the best parameter values when using the Evolution Strategy.

As shown in the aforementioned Table, using Density-Based Dijkstra system we decrease all studied times compared with the application of Dijkstra system. Concretely, we reduce emergency services travel times an average of 16.84% (i. e., 19.33% in Rome, 22.67% in San Francisco, and 8.51% in New York). Also, we reduce the rest of vehicles travel time an average of 6.79% (i.e., 5.45% in Rome, 3.3% in San Francisco, and 11.61% in New York).

On the other hand, Evolution Strategy significantly reduces emergency services arrival time, but increases the rest of vehicles travel time. Specifically, this system reduces emergency services travel times an average of 37.81% (40.36% in Rome, 45.2% in San Francisco, and 27.88% in New York). However, this system increases the rest of vehicles travel time an average of 13.87% (10.53% in Rome, 21.55% in San Francisco, and 9.53% in New York). Although this intelligent system increases the rest of vehicles travel time (a maximum of 28.18%), it can significantly reduce the emergency services travel time (a minimum of 26.35%).

4.5.3 Comparison Between Evolution Strategy and Density-Based Evolution Strategy Systems

In this Subsection we compare our two proposed intelligent algorithms (i.e., Evolution Strategy and Density-Based Evolution Strategy). Simulations were performed using the parameters showed in Table 4.5, but, in order to simplify the comparison, we only simulate our systems using the Equation 4.5 as a fitness function, since, according to Subsection 4.5.1, this Equation allows obtaining better results. As shown in Figure 4.9, the results obtained applying Density-Based Evolution Strategy system are better than Evolution Strategy. Also, we can observe that the Density-Based approach system obtains smaller emergency services arrival times with a smaller number of generations.

In addition, we compare the Density-Based Evolution Strategy system results with the obtained when using the Dijkstra system. As shown in Table 4.6, we reduce emergency services travel times an

Table 4.6: Simulation Obtained Results

Scenario	**Vehicles/km^2**	**Dijkstra**		**Density-Based Evolution Strategy**	
		Vehicles Avg. t.	**Emgcy. Serv. t.**	**Vehicles Avg. t.**	**Emgcy. Serv. t.**
Rome	125	222.91	190	249.36	89
	250	112.27	209	126.51	93
San Francisco	125	112.02	92.5	120.21	43.5
	250	148.08	126	169.38	53.5
New York	125	151.43	68	171.06	31
	250	143.46	83.5	157.44	43.5

Table 4.7: Parameters used for the Density-Based Evolution Strategy System

Parameter	**Value**
number of simulations	100
population number	5 and 3
number of descendants	10 and 5
number of generations	20
fitness function	Equation 4.5
mutation	Uncorrelated Mutation with n Step Sizes
recombination	Local Discrete
parents selection	Randomly
survivors selection	$(\mu + \lambda)$

average of 54.33% (53.58% in Rome, 55.26% in San Francisco, and 51.16% in New York). However, this system increases the rest of vehicles travel time an average of 11.49% (12.27% in Rome, 10.85% in San Francisco, and 11.36% in New York. Although this intelligent system increases the rest of vehicles travel time (a maximum of 14.39%), it can significantly reduce the emergency services arrival time (a minimum of 47.9%).

Since one of the most important goal of our dissertation is reducing the emergency services travel times, the Density-Based Evolution Strategy system is the best of all proposed. Once again, we demonstrate that the traffic density is a key factor for distributing vehicles.

4.5.4 Density-Based Evolution Strategy System Reducing Population and Number of Descendants

As stated above, emergency services arrival time is a critical factor when an accidents occurs. Simulations performed by the system require a high computational cost, increasing its application time. Hence, reducing the necessary simulations would decrease the system action time which directly affects the emergency services needed time to arrive to the accident location. For this reason, in this Subsection we test our best proposed system reducing the population size and the number of descendants. Table 4.7 present the parameters used in this simulations. As shown, we reduce the number of populations individuals from 5 to 3, and the number of descendants from 10 to 5. Note that we only use the Density-Based Evolution Strategy system applying only the Equation 4.5 as a fitness function, since we obtained the best results using this configuration.

Figure 4.10 shows the obtained results. As can be seen, reducing the number of population individuals and descendants, the emergency services arrival time increases: 27.68% in Rome, 27.5% in San Francisco, and 34.21% in New York. This is due to we generate a smaller number of possible population individuals in each generation, thereby restricting the probability to achieve better individuals.

Although the system could obtain more quickly the function convergence values reducing populations individuals and descendants number (i.e., smaller number of generations), results are worse. Therefore, we consider that our approach operates better with 5 individuals population and 10 descendants.

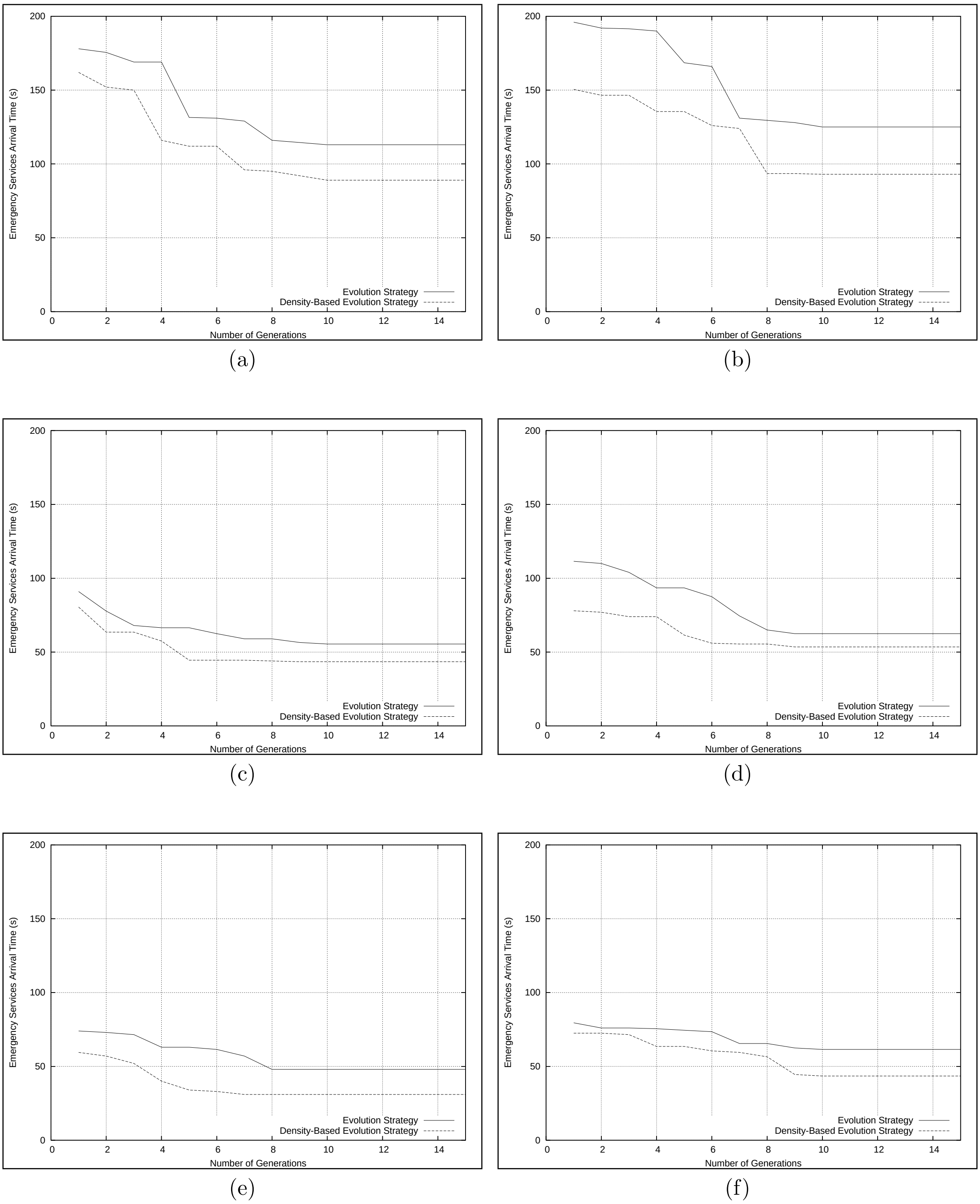
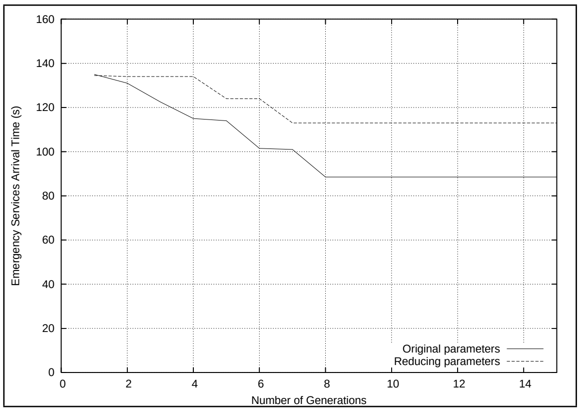
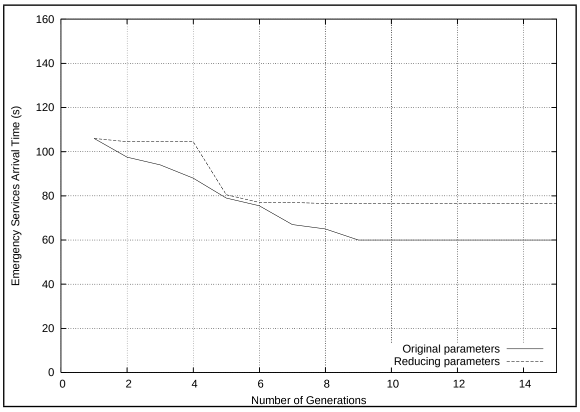


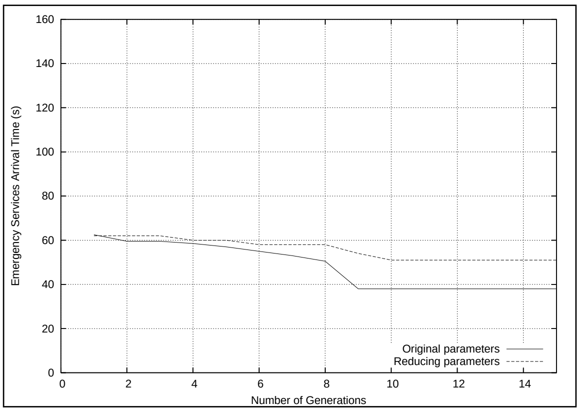
Figure 4.9: Evolution Strategy and Density-Based Evolution Strategy systems emergency services arrival times on average after 100 simulations in the scenarios of: Rome (Italy) (a) 125 vehicles/km^2, and (b) 250 vehicles/km^2, San Francisco (USA) (c) 125 vehicles/km^2, and (d) 250 vehicles/km^2, and New York (USA) (e) 125 vehicles/km^2, and (f) 250 vehicles/km^2.



(a)



(b)



(c)

Figure 4.10: Emergency services arrival times simulating 250 vehicles/km^2 varying the number of population individuals and descendants numbers in the scenarios of: (a) Rome (Italy), (b) San Francisco (USA), and (c) New York (USA).

4.6 Conclusions

In this Chapter, we propose four different approaches to reduce the emergency services arrival time when an accident occurs, trying to avoid traffic jams that could result from this special situation. Specifically, we present two systems based on Evolution Strategies which obtain a sub-optimal solution in a reduced time. Moreover, we demonstrate that traffic density is a key factor to distribute traffic in an efficient manner.

Our proposals have been tested in three different scenarios with different topologies and traffic densities. Results show that the best solution is to combine an Evolution Strategy with the traffic density information collected at the time of the accident, which is used to initialize the population. The improvement obtained with this approach reduces the emergency services arrival time a minimum of 47.9%, increasing the travel time of the rest o vehicles only a 14.39% at worst, compared to other algorithms that obtain an improvement of 5.99% (Density-Based Dijkstra), and 26.35% (Evolution Strategy), respectively.

Chapter 5

Conclusions, Publications and Future Work

5.1 Conclusions

Throughout this Master's thesis several novel contributions have been made to the area of Intelligent Transportation Systems. The main goal of this dissertation is to design a system to reduce the emergency services arrival time when an accident occurs, since time is a critical issue in these situations.

With the aim of knowing traffic density in real time, we present an approach able to accurately estimate it by using V2I communications. Our vehicular density estimation algorithm takes into account not only the number of beacons received by the RSUs, but also the topology of the map where the vehicles are located. The proposed approach presents an average relative error of 3.04%.

Finally, we present and compare four different traffic distribution systems with the objective of reducing the emergency services arrival time when an accident occurs. We demonstrate that combining Artificial Intelligence, specifically Evolution Strategies, with traffic density information, our system is able to obtain a sub-optimal solution in a reduced time. In particular, we reduce the emergency services arrival time in 47.9% in the worst case, using a maximum of 10 generations.

Results show that using our novel proposal, we improve the emergency services arrival time a minimum of 47.9%, while increasing the travel time of the rest o vehicles only in 14.39% at worst. Applying our system when an accident occurs, emergency services could save more lives, since the time elapsed from the moment of the accident and the time when injured passengers receive medical assistance is notably reduced. Moreover, our approach does not generate new traffic jams caused by traffic redirection.

5.2 Publications

The research work related to this Master's thesis has resulted in 9 publications (3 of them still under revision); among them, we have 4 journal articles (all of them indexed by the Journal Citation Reports (JCR) database or the SCImago Journal Country Rank (SJR)), and 5 conference papers (4 of them indexed by the Computer Science Conference Ranking or the Computing Research and Education (CORE) lists). We now proceed by presenting a brief description of each of them.

5.2.1 Publications Related to this Master's Thesis

[BFG+13b] J. Barrachina, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "I-VDE: A Novel Approach to Estimate Vehicular Density by Using Vehicular Networks", in *The 12th International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW 2013)*, Wroclaw, Poland, July 2013.

Road traffic is experiencing a drastic increase in recent years, thereby increasing the every day traffic congestion problems, especially in cities. Vehicle density is one of the main metrics used for assessing the road traffic conditions. Currently, most of the existing vehicle density estimation approaches, such as inductive loop detectors or traffic surveillance cameras, require infrastructure-based traffic information systems to be installed at various locations. In this paper, we present

I-VDE, a solution to estimate the density of vehicles that has been specially designed for Vehicular Networks. Our proposal allows Intelligent Transportation Systems to continuously estimate the vehicular density by accounting for the number of beacons received per Road Side Unit, as well as the roadmap topology. Simulation results indicate that our approach accurately estimates the vehicular density, and therefore automatic traffic controlling systems may use it to predict traffic jams and introduce countermeasures.

The International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW) is one of the most important conferences related to wireless and mobile computing. According to the Computing Research and Education (CORE) list[1], it is classified as CORE B.

[BFG+13a] J. Barrachina, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Assessing Vehicular Density Estimation Using Vehicle-to-Infrastructure Communications", in *The Fourteenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM)*, Madrid, Spain, June 2013.

Vehicle density is one of the main metrics used for assessing the road traffic conditions. In this paper, we present a solution to estimate the density of vehicles that has been specially designed for Vehicular Networks. Our proposal allows Intelligent Transportation Systems to continuously estimate the vehicular density by accounting for the number of beacons received per Road Side Unit, as well as the roadmap topology. Simulation results indicate that our approach accurately estimates the vehicular density, and therefore automatic traffic controlling systems may use it to predict traffic jams and introduce countermeasures.

The International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM) is one of the most important symposium related to wireless and mobile computing. According to the Computing Research and Education (CORE) list, it is classified as CORE A.

In addition, we have sent the following papers which are still under revision and pending of acceptance.

[BGF+13c] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Reducing Emergence Services arrival time by using Vehicular Communications and Evolution Strategies", in *Expert Systems with Applications*, 2013.

Nowadays, traffic jams in urban areas have become a problem that keeps growing every year since the number of vehicles circulating in cities is continuously increasing. One of the most common causes producing traffic jams are vehicle accidents. Moreover, the arrival time of the emergency services could be raised through vehicles congestion. Intelligent Transportation Systems (ITS) aim at examining and reducing this problem. In this paper, we propose four different approaches to solve this, and compare them in order to obtain the best solution. Using V2I communications, we are able to determine the traffic density as a key factor when traffic must be redirected to reduce the emergency services arrival time and to avoid traffic jams when an accident occurs. Specifically, we propose two approaches based on Dijkstra, and two approaches based on Evolution Strategies, since, when an accident occurs, time is a critical issue and these kinds of strategies contribute to obtain an optimal solution in the shortest time.

Expert Systems With Applications is a refereed international journal whose focus is on exchanging information relating to expert and intelligent systems applied in industry, government, and universities worldwide. According to the latest Journal Citation Reports list (JCR, 2011), this magazine has an impact of 2.203, being in position 22 of 111 (Q1) in the category COMPUTER SCIENCE, ARTIFICIAL INTELLIGENCE.

[BGF+13a] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A V2I-based Real-Time Traffic Density Estimation System", in *Computer Networks*, 2013.

Road traffic is experiencing a drastic increase in recent years, thereby increasing the every day traffic congestion problems, especially in metropolitan areas. Governments are making efforts to alleviate the increasing traffic pressure, being vehicular density one of the main metrics used for assessing the road traffic conditions. However, vehicle density is highly variable in time and space, making it difficult to be estimated accurately. Currently, most of the existing vehicle

[1] http://www.core.edu.au/

density estimation approaches, such as inductive loop detectors, or traffic surveillance cameras, require very specific infrastructure to be installed on the road. In this paper, we present a novel solution to accurately estimate the density of vehicles in urban scenarios. Our proposal, that has been specially designed for Vehicular Networks, allows Intelligent Transportation Systems to continuously estimate vehicular density by accounting for the number of beacons received per Road Side Unit (RSU), and also considering the roadmap topology where the RSUs are located. Simulation results reveal that, unlike previous proposals solely based on the number of beacons received, our approach accurately estimates the vehicular density, and therefore our approach can be integrated within automatic traffic controlling systems to predict traffic jams, and thus introducing countermeasures.

Computer Networks is an international journal providing a publication vehicle for complete coverage of all topics of interest to those involved in the computer communications networking area. According to the latest Journal Citation Reports list (JCR, 2011), this magazine has an impact of 1.200, being in position 16 of 50 (Q2) in the category COMPUTER SCIENCE, HARDWARE & ARCHITECTURE.

[BGF+13b] J. Barrachina, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Redistributing traffic routes in case of an accident by combining VNs and AI", in *IEEE International Conference on Tools with Artificial Intelligence (ICTAI)*, Washington DC, USA, November 2013.

A critical issue, especially in urban areas, is the occurrence of traffic accidents, since it could generate traffic jams and the emergency services arrival time can determine the difference between life or death for people involved in the accident. In this paper, we propose two different approaches to solve this, and compare them in order to obtain the best solution. Using V2I communications, we are able to determine the traffic density as a key factor when traffic must be redirected to reduce the emergency services arrival time and to avoid traffic jams when an accident occurs. Specifically, we propose a traffic re-routing approach based on Dijkstra, and an approach based on Evolution Strategies, which allows to obtain a sub-optimal solution in a short time.

The annual IEEE International Conference on Tools with Artificial Intelligence (ICTAI) provides a major international forum where the creation and exchange of ideas related to artificial intelligence are fostered among academia, industry, and government agencies. According to the Computing Research and Education (CORE) list, it is classified as CORE B.

5.2.2 Other Related Publications

[BGF+13d] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Road Side Unit Deployment: A Density-Based Approach", in *IEEE Intelligent Transportation Systems Magazine*. September 2012.

Currently, the number of vehicles increases every year, raising the probability of having accidents. When an accident occurs, wireless technologies enable vehicles to share warning messages with other vehicles by using vehicle to vehicle (V2V) communications, and with the emergency services by using vehicle to infrastructure (V2I) communications. Regarding vehicle to infrastructure communications, Road Side Units (RSUs) act similarly to wireless LAN access points, and can provide communications with the infrastructure. Since RSUs are usually very expensive to install, authorities limit their number, especially in suburbs and areas of sparse population, making RSUs a precious resource in vehicular environments. In this paper, we propose a Density-based Road Side Unit deployment policy (D-RSU), specially designed to obtain an efficient system with the lowest possible cost to alert emergency services in case of an accident. Our approach is based on deploying RSUs using an inverse proportion to the expected density of vehicles. The obtained results show how D-RSU is able to reduce the required number of RSUs, as well as the accident notification time.

The IEEE Intelligent Transportation Systems Magazine is sponsored by the IEEE Intelligent Transportation Systems Society. According to the SCImago Journal & Country Rank[2] (SJR), this magazine has an impact of 0.581, being in position 4 of 33 (Q1) in the category AUTOMOTIVE ENGINEERING.

[2]http://www.scimagojr.com/

[BGF+12c] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "VEACON: a Vehicular Accident Ontology Designed to Improve Safety on the Roads", in *Journal of Network and Computer Applications*. Vol. 35, pp. 1891-1900, Elsevier. 2012. Available at: http://dx.doi.org/10.1016/j.jnca.2012.07.013

Vehicles are nowadays provided with a variety of new sensors capable of gathering information about themselves and from their surroundings. In a near future, these vehicles will also be capable of sharing all the harvested information, with the surrounding environment and among nearby vehicles over smart wireless links. They will also be able to connect with emergency services in case of accidents. Hence, distributed applications based on Vehicular Networks (VNs) will need to agree on a common understanding of context for interoperability, and, therefore, it is necessary to create a standard structure which enables data interoperability among all the different entities involved in transportation systems. In this paper, we focus on traffic safety applications; specifically, we present the VEhicular ACcident ONtology (VEACON) designed to improve traffic safety. Our ontology combines the information collected when an accident occurs, and the data available in the General Estimates System (GES) accidents database. We assess the reliability of our proposal using both realistic crash tests, held in the facilities of Applus+ IDIADA in Tarragona, Spain, and vehicular network simulations, based on the ns-2 simulation tool. Experimental results highlight that both nearby vehicles and infrastructure elements (RSUs) are correctly notified about an accident in just a few seconds, increasing the emergency services notification effectiveness.

The Journal of Network and Computer Applications welcomes research contributions, surveys and notes in all areas relating to computer networks and applications thereof. According to the latest Journal Citation Reports list (JCR, 2011), this magazine has an impact of 1.065, being in position 21 of 50 (Q2) in the category COMPUTER SCIENCE, HARDWARE ARCHITECTURE.

[BGF+12b] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "D-RSU: A Density-Based Approach for Road Side Unit Deployment in Urban Scenarios", in *International Workshop on IPv6-based Vehicular Networks (Vehi6), collocated with the 2012 IEEE Intelligent Vehicles Symposium*, Alcalá de Henares, Spain, pp. 1-6, 3 June 2012.

Currently, the number of vehicles in the roads increases every year, raising the probability of having accidents. When an accident occurs, wireless technologies enable vehicles to share warning messages with other vehicles by using vehicle to vehicle (V2V) communications, and with the emergency services by using vehicle to infrastructure (V2I) communications. Regarding vehicle to infrastructure communications, Road Side Units (RSUs) act similarly to a wireless LAN access point and can provide communications with the infrastructure. Since RSUs are usually very expensive to install, authorities limit their number, especially in suburbs and areas of sparse population, making RSUs a precious resource in vehicular environments. In this paper, we propose a Density-based Road Side Unit deployment policy (D-RSU), specially designed to obtain an efficient system with the lowest possible cost to alert emergency services in case of an accident. Our approach reduces the required number of RSUs, as well as the accident notification time.

The International Workshop on IPv6-based Vehicular Networks (Vehi6) is collocated with the IEEE Intelligent Vehicles Symposium, which is the premier annual forum sponsored by the IEEE Intelligent Transportation System Society (ITSS).

[BGF+12a] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "CAOVA: A Car Accident Ontology for VANETs", in *IEEE Wireless Communications and Networking Conference (WCNC)*, Paris, France, pp. 1864-1869, April 2012. Available at http://dx.doi.org/10.1109/WCNC.2012.6214089

In a near future, vehicles will be provided with a variety of new sensors capable of gathering information from their surroundings. These vehicles will also be capable of sharing the harvested information via Vehicular Ad hoc NETworks (VANETs) with nearby vehicles, or with the emergency services in case of an accident. Hence, distributed applications based on VANETs will need to agree on a common understanding of context for interoperability, and therefore, it is necessary to create a standard structure which enables data interoperability among all the different entities involved in transportation systems. In this paper, we focus on traffic safety; specifically, we present a Car Accident lightweight Ontology for VANETs (CAOVA). The instances of our ontology are filled with: (i) the information collected when an accident occurs, and (ii) the data available in the General Estimates System (GES) accidents database. We assess the reliability of our proposal in two different ways: one via realistic crash tests, and the other one using a network simulation framework.

IEEE Wireless Communications and Networking Conference (WCNC) is the world premier wireless event that brings together industry professionals, academics, and individuals from government agencies and other institutions to exchange information and ideas on the advancement of wireless communications and networking technology. According to the Computing Research and Education (CORE) list, it is classified as CORE A. Additionally, Google Scholar considers this conference as one of the top twenty most important publications within the Computer Networks Wireless Communication area (see http://scholar.google.es/citations?view_op=top_venues&hl=esvq= eng_computernetworkswirelesscommunication).

5.3 Future Work

In the development of this Master's Thesis several issues emerged which deserve further scrutiny in a future. In this Section we present the ones we consider most relevant.

When vehicular networks start to be implemented in real environments, intelligent vehicles (network nodes) will coexist with non-intelligent vehicles. In this situation, our proposed systems might not operate correctly. Hence, we consider necessary to study the percentage of necessary intelligent vehicles, in order to achieve a proper function of our systems.

On the other hand, we assessed our proposed Intelligent Traffic Density-Based Routing System in only three different scenarios. Although these scenarios are representative, since they have different topology profiles, we contemplate the possibility of performing more testbeds in other different scenarios with the aim of finding a connection between the scenario topologies and the improvements obtained of the travel times.

Finally, we consider interesting to adapt our Intelligent Traffic Density-Based Routing System for other unpredictable situations, as floods, fires, or fallen obstacles on the road, which could obstruct some of the streets.

Bibliography

[ado11] Reliable Application Specific Detection of Road Users with Vehicle On-board Sensors, 2011. Available at http://www.adose-eu.org/.

[aid11a] Accident Information and Driver Emergency Rescue, 2011. Available at http://www.ika.rwth-aachen.de/pdf_eb/gb6-21e_aider.pdf.

[aid11b] Adaptive Integrated Driver-vehicle Interface, 2011. Available at http://www.aide-eu.org/.

[atl11] ATLANTIC - A Thematic Long-term Approach to Networking for the Telematics and ITS Community, 2011. Available at http://www.trg.soton.ac.uk/archive/its/atlantic.htm.

[AVS11] R.A. Anand, L. Vanajakshi, and S.C. Subramanian. Traffic density estimation under heterogeneous traffic conditions using data fusion. In *IEEE Intelligent Vehicles Symposium (IV)*, pages 31–36, Jun. 2011.

[BDS97] S. Benjaafar, K. Dooley, and W. Setyawan. Cellular automata for traffic flow modeling. Technical report, Center for Transportation Studies University of Minnesota, 1997.

[BFG+13a] J. Barrachina, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. Assessing Vehicular Density Estimation Using Vehicle-to-Infrastructure Communications. In *The Fourteenth International Symposium on a World of Wireless, Mobile and Multimedia Networks (IEEE WoWMoM)*, June 2013.

[BFG+13b] J. Barrachina, M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. I-VDE: A Novel Approach to Estimate Vehicular Density by Using Vehicular Networks. In *The 12th International Conference on Ad Hoc Networks and Wireless (ADHOC-NOW 2013)*, July 2013.

[BFW03] M. Bechler, W.J. Franz, and L. Wolf. Mobile Internet access in FleetNet. In *Verteilten Systemen KiVS 2003*, Feb. 2003.

[BGF+12a] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. CAOVA: A Car Accident Ontology for VANETs. In *IEEE Wireless Communications and Networking Conference (WCNC)*, pages 1864–1869, April 2012. Available at http://dx.doi.org/10.1109/WCNC.2012.6214089.

[BGF+12b] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. D-RSU: A Density-Based Approach for Road Side Unit Deployment in Urban Scenarios. In *International Workshop on IPv6-based Vehicular Networks (Vehi6), collocated with the 2012 IEEE Intelligent Vehicles Symposium*, pages 1–6, Jun. 2012.

[BGF+12c] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. VEACON: A Vehicular Accident Ontology designed to improve safety on the roads. *Journal of Network and Computer Applications*, 35(6):1891–1900, Nov. 2012.

[BGF+13a] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. A V2I-based Real-Time Traffic Density Estimation System. *Expert Systems with Applications*, 2013.

[BGF+13b] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. Redistribute traffic in case of an accident combining VNs and AI. In *IEEE International Conference on Tools with Artificial Intelligence (ICTAI)*, Nov. 2013.

[BGF+13c] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. Reducing Emergence Services arrival time by using Vehicular Communications and Evolution Strategies. *Expert Systems with Applications*, 2013.

[BGF+13d] J. Barrachina, P. Garrido, M. Fogue, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. Road Side Unit Deployment: A Density-Based Approach. *IEEE Intelligent Transportation Systems Magazine*, 2013.

[BMD+07] P. Bedi, N. Mediratta, S. Dhand, R. Sharma, and A. Singhal. Avoiding traffic jam using ant colony optimization - a novel approach. In *International Conference on Computational Intelligence and Multimedia Applications*, volume 1, pages 61–67, Dec. 2007.

[BS08] M. Balcilar and A.C. Sonmez. Extracting vehicle density from background estimation using Kalman filter. In *23rd International Symposium on Computer and Information Sciences (ISCIS '08)*, pages 1–5, Oct. 2008.

[BTK09] K.E. Bekris, K.I. Tsianos, and L.E. Kavraki. Safe and distributed kinodynamic replanning for vehicular networks. *Mobile Networks and Applications*, 14(3 SPEC. ISS.):292–308, 2009.

[car11] Advanced driver support system based on V2V communication technologies, 2011. Available at `http://www.cartalk2000.net/`.

[CCH10] H.-C. Chao, Y.-S. Chen, and Y.M. Huang. Advanced and applications in vehicular ad hoc networks. *Mobile Networks and Applications*, 15(1):1–3, 2010.

[CLC10] P.-Y. Chen, J.-W. Liu, and W.-T. Chen. A fuel-saving and pollution-reducing dynamic taxi-sharing protocol in VANETs. In *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*, pages 1–5, Sept. 2010.

[CM08] K. Collins and G.-M. Muntean. An adaptive vehicle route management solution enabled by wireless vehicular networks. In *IEEE 68th Vehicular Technology Conference (VTC)*, pages 1–5, Sept. 2008.

[cmu11] GM Collaborative Research Lab, 2011. Available at `http://gm.web.cmu.edu/`.

[com11] Communications for eSafety, 2011. Available at `http://www.comesafety.org/`.

[coo11] Cooperative Networks for Intelligent Road Safety, 2011. Available at `http://www.coopers-ip.eu/`.

[CPHL07] G. Calandriello, P. Papadimitratos, J.P. Hubaux, and A. Lioy. Efficient and robust pseudonymous authentication in VANET. In *Fourth ACM international workshop on Vehicular ad hoc networks, VANET '07*, pages 19–28, 2007.

[cra11] Crash-predicting car can brace itself for impact, 2011. Available at `http://www.newscientist.com/article/dn13973-crashpredicting-car-can-brace-itself-forimpact.html`.

[cvi11] Cooperative Vehicle-Infrastructure Systems, 2011. Available at `http://www.cvisproject.org/`.

[DGDM12] H. Dezani, L. Gomes, F. Damiani, and N. Marranghello. Controlling traffic jams on urban roads modeled in Coloured Petri net using Genetic Algorithm. In *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pages 3043–3048, Oct. 2012.

[Dij59] E. W. Dijkstra. A note on two problems in connexion with graphs. *Numerische Mathematik*, 1:269–271, 1959.

[DJ07] S. Dornbush and A. Joshi. Streetsmart traffic: Discovering and disseminating automobile congestion using vanet's. In *IEEE 65th Vehicular Technology Conference, 2007. (VTC)*, pages 11–15, Apr. 2007.

[DST10] T. L. David Schrank and S. Turner. TTIs 2010 urban mobility report powered by INRIX traffic data. *Texas Transportation Institute, The Texas A&M University System*, Dec. 2010.

[ece02] European Commission eSafety Initiative, 2002. Available at `http://ec.europa.eu/information_society/activities/esafety/in-dex_en.htm`.

[Eic07] S. Eichler. Performance evaluation of the IEEE 802.11p WAVE communication standard. In *Proceedings of the Vehicular Technology Conference (VTC-2007 Fall), Baltimore, MD, USA*, Sept. 2007.

[ES03] E. Eiben and J. E. Smith. *Introduction to Evolutionary Computing*. Springer-Verlag, 2003.

[Eur09] European Commission. Information Society and Media. eCall - saving lives through in-vehicle communication technology, 2009. Available at `http://www.esafetysupport.org/en/ecall_toolbox/media_centre/press_coverage.htm`.

[FGM+12a] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. A Realistic Simulation Framework for Vehicular Networks. In *5th International ICST Conference on Simulation Tools and Techniques (SIMUTools 2012), Desenzano, Italy*, pages 37–46, March 2012.

[FGM+12b] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. An adaptive system based on roadmap profiling to enhance warning message dissemination in VANETs. *IEEE/ACM Transactions on Networking*, 2012.

[FGM+12c] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni. Evaluating the impact of a novel message dissemination scheme for vehicular networks using real maps. *Transportation Research Part C: Emerging Technologies*, 25:61–80, Dec. 2012.

[FV00] K. Fall and K. Varadhan. ns notes and documents. The VINT Project. UC Berkeley, LBL, USC/ISI, and Xerox PARC, Feb. 2000. Available at http://www.isi.edu/nsnam/ns/ns-documentation.html.

[GAdP+11] A. J. Gonzalez, J. Alcober, R. M. de Pozuelo, F. Pinyol, and K. Z. Ghafoor. Context-aware multimedia service composition using quality assessment. In *IEEE International Conference on Multimedia and Expo (ICME)*, pages 1–6, Jul. 2011.

[GLH95] G.W. Greenwood, C. Lang, and S. Hurley. Scheduling tasks in real-time systems using evolutionary strategies. In *Proceedings of the Third Workshop on Parallel and Distributed Real-Time Systems*, pages 195–196, Apr. 1995.

[HHI99] Y. Hattori, T. Hashimoto, and S. Inoue. A study for the traffic flow control considering the capacity of the road by cellular automaton method. In *IEEE International Conference on Systems, Man, and Cybernetics (SMC '99)*, volume 4, pages 569–573, 1999.

[hig11] HIGHWAY - Breakthrough intelligent maps and geographic tools for the context-aware delivery of e-safety and added-value services, 2011. Available at `http://www.transport-research.info/web/projects/project_details.cfm?id=20403&pa-ge=contact`.

[IEE10] IEEE 802.11 Working Group. IEEE Standard for Information Technology – Telecommunications and information exchange between systems – Local and metropolitan area networks –Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 6: Wireless Access in Vehicular Environments. Jul. 2010.

[int11] Cooperative Intersection Safety, 2011. Available at `http://www.intersafe-2.eu/public/`.

[ISK07] S. Inoue, K. Shozaki, and Y. Kakuda. An automobile control method for alleviation of traffic congestions using inter-vehicle ad hoc communication in lattice-like roads. In *IEEE Globecom Workshops*, pages 1–6, Nov. 2007.

[iwa11] Intelligent Cooperative Systems in Car for Road Safety, 2011. Available at `http://www.iway-project.eu/`.

[JK08] J. Jakubiak and Y. Koucheryavy. State of the art and research challenges for VANETs. In *Consumer Communications and Networking Conference (CCNC)*, pages 912–916, Jan. 2008.

[JM97] D.S. Johnson and L.A. McGeoch. The travelling salesman problem: A case study in local optimization. In *Local Search in Combinatorial Optimization. Wiley*, pages 215–310, 1997.

[JO05] D. Jawad and K. Ozbay. The cost behavior of intelligent transportation systems over time. In *IEEE Intelligent Transportation Systems*, pages 1039–1044, Sept. 2005.

[KR12] D. Krajzewicz and C. Rossel. Simulation of Urban MObility (SUMO). Centre for Applied Informatics (ZAIK) and the Institute of Transport Research at the German Aerospace Centre, 2012. Available at http://sumo.sourceforge.net/index.shtml.

[KRS+07] S. Kaul, K. Ramachandran, P. Shankar, S. Oh, M. Gruteser, I. Seskar, and T. Nadeem. Effect of antenna placement and diversity on vehicular network communications. In *4th Annual IEEE Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON'07)*, pages 112–121, 2007.

[KWG97] S. Krauss, P. Wagner, and C. Gawron. Metastable states in a microscopic model of traffic flow. *Physical Review E*, 55(5):5597–5602, 1997.

[LL10] Y.-B. Lin and Y.-C. Lin. WiMAX location update for vehicle applications. *Mobile Networks and Applications*, 15(1):148–159, 2010.

[LLZS09] R. Lu, X. Lin, H. Zhu, and X. Shen. Spark: A new vanet-based smart parking scheme for large parking lots. In *INFOCOM 2009, IEEE*, pages 1413–1421, Apr. 2009.

[MB05] D. Mester and O. Bräysy. Active guided evolution strategies for large-scale vehicle routing problems with time windows. *Computers & Operations Research*, 32(6):1593–1614, 2005.

[MBML11] N. Maslekar, M. Boussedjra, J. Mouzna, and H. Labiod. A stable clustering algorithm for efficiency applications in VANETs. In *7th International Wireless Communications and Mobile Computing Conference (IWCMC)*, pages 1188–1193, Jul. 2011.

[MCC+09] F. J. Martinez, J.-C. Cano, C. T. Calafate, P. Manzoni, and J. M. Barrios. Assessing the feasibility of a VANET. In *ACM Workshop on Performance Monitoring, Measurement and Evaluation of Heterogeneous Wireless and Wired Networks (PM2HW2N 2009, held with MSWiM)*, pages 39–45. ACM New York, NY, USA, 2009.

[MFT+12] F. J. Martinez, M. Fogue, C. K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni. Computer simulations of VANETs using realistic city topologies. *Wireless Personal Communications*, pages 1–25, 2012.

[MHJ12] J. Ma, X. Huang, and Y. Jiang. Applicable research of urban road traffic congestion based on rough set theory and genetic algorithm. In *World Automation Congress (WAC)*, pages 1–4, Jun. 2012.

[mli03] ITS Handbook Japan, 2002-2003. Available at `http://www.mlit.go.jp/road/ITS/index/indexHBook.html`.

[MTC+10] F. J. Martinez, C. K. Toh, J.-C. Cano, C. T. Calafate, and P. Manzoni. Emergency services in future intelligent transportation systems based on vehicular communication networks. *IEEE Intelligent Transportation Systems Magazine*, 2(2):6–20, summer 2010.

[nth11] National Highway Traffic Safety Administration (NTHSA), 2011. Available at `http://www.nhtsa.dot.gov/`.

[ONI06] K. Ohara, Y. Nojima, and H. Ishibuchi. Comparison between Centralized Global Optimization and Distributed Local Optimization for Traffic Jam Avoidance. In *Proc. of 2006 Genetic and Evolutionary Computation Conference Late Breaking Papers*, page 6p CD ROM, Jul. 2006.

[OnS12] OnStar by GM. OnStar Web Site, 2012. Available at `http://www.onstar.com`.

[Ope12] OpenStreetMap. Collaborative project to create a free editable map of the world, 2012. Available at http://www.openstreetmap.org.

[pat11] California Partners for Advanced Transit and Highways, 2011. Available at `http://www.path.berkeley.edu/`.

[pre11] Preventive and Active Safety Applications Contribute to the Road Safety Goals on European Roads, 2011. Available at `http://www.prevent-ip.org/`.

[RH05] M. Raya and J.-P Hubaux. The security of vehicular ad hoc networks. In *3rd ACM workshop on Security of ad hoc and sensor networks*, pages 11–21, 2005.

[RN12] J. P. Rodrigue and T. Notteboom. The Geography of Transport Systems, 2012. Available at http://people.hofstra.edu/geotrans.

[rut11] Disco Lab - Rutgers University, 2011. Available at `http://discolab.rutgers.edu/traffic/index.htm`.

[saf11a] Advanced Telematics for Enhancing the Safety and Comfort of Motorcycle Riders, 2011. Available at `http://www.saferider-eu.org/`.

[saf11b] Cooperative vehicles and road infrastructure for road safety, 2011. Available at `http://www.safespot-eu.org/`.

[SCB+99] A. Schadschneider, D. Chowdhury, E. Brockfeld, K. Klauck, L. Santen, and J. Zittartz. *Traffic and Granular Flow: Social, Traffic, and Granular Dynamics*. Springer-Verlag, 1999.

[SCB11] R. Stanica, E. Chaput, and A. Beylot. Local density estimation for contention window adaptation in vehicular networks. In *IEEE 22nd International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pages 730–734, Sept. 2011.

[SFS+11] W. Sun, T. Fu, Y. Su, F. Xia, and J. Ma. ODAM-C: An Improved Algorithm for Vehicle Ad Hoc Network. In *International Conference on Internet of Things (iThings/CPSCom) and 4th International Conference on Cyber, Physical and Social Computing*, pages 152–156, Oct. 2011.

[SHG09] R. Shirani, F. Hendessi, and T.A. Gulliver. Store-carry-forward message dissemination in vehicular ad-hoc networks with local density estimation. In *IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall)*, pages 1–6, Sept. 2009.

[sim11] Safe and Intelligent Mobility. Test Field Germany, 2011. Available at `http://www.simtd.de/`.

[SLCG08] F. Soldo, R. Lo Cigno, and M. Gerla. Cooperative synchronous broadcasting in infrastructure-to-vehicles networks. In *Fifth Annual Conference on Wireless on Demand Network Systems and Services (WONS)*, pages 125–132, Jan. 2008.

[SLWI05] K. Seongmoon, M.E. Lewis, and C.C. White III. Optimal vehicle routing with real-time traffic information. *IEEE Transactions on Intelligent Transportation Systems*, 6(2):178–188, Jun. 2005.

[SMGMRR10] J.J. Sanchez-Medina, M.J. Galan-Moreno, and E. Rubio-Royo. Traffic Signal Optimization 'La Almozara' District in Saragossa Under Congestion Conditions, Using Genetic Algorithms, Traffic Microsimulation, and Cluster Computing. *IEEE Transactions on Intelligent Transportation Systems*, 11(1):132–141, Mar. 2010.

[SRS+07] R. Sengupta, S. Rezaei, S. E. Shladover, D. Cody, S. Dickey, and H. Krishnan. Cooperative Collision Warning Systems: Concept Definition and Experimental Implementation. *Intelligent Transportation Systems*, 11(3):143–155, 2007.

[SRS+08] R. Sengupta, S. Rezaei, S. E. Shladover, D. Cody, S. Dickey, and H. Krishnan. Cross-layer-based adaptive vertical handoff with predictive rss in heterogeneous wireless networks. *IEEE Transactions on Vehicular Technology*, 57(6):3679–3692, 2008.

[STMZI+10] J. Santa, R. Toledo-Moreo, M. A. Zamora-Izquierdo, B. Ubeda, and A. F. Gomez-Skarmeta. An Analysis of Communication and Navigation Issues in Collision Avoidance Support Systems. *Transportation Research Part C. Emerging Technologies*, 18(3):351–366, 2010.

[TC07] E. Tan and J. Chen. Vehicular traffic density estimation via statistical methods with automated state learning. In *IEEE Conference on Advanced Video and Signal Based Surveillance (AVSS)*, pages 164–169, Sept. 2007.

[THKH11] G.S. Thakur, P. Hui, H. Ketabdar, and A. Helmy. Spatial and temporal analysis of planet scale vehicular imagery data. In *IEEE 11th International Conference on Data Mining Workshops (ICDMW)*, pages 905–910, Dec. 2011.

[TKK12] V. Tyagi, S. Kalyanaraman, and R. Krishnapuram. Vehicular traffic density state estimation based on cumulative road acoustics. *IEEE Transactions on Intelligent Transportation Systems*, 13(3):1156–1166, Sept. 2012.

[TNCS02] Y.C. Tseng, S.Y. Ni, Y.S. Chen, and J.P. Sheu. The broadcast storm problem in a mobile ad hoc network. *Wireless Networks*, 8:153–167, 2002. DOI: 10.1023/A:1013763825347.

[Toh07] C.-K. Toh. Future Application Scenarios for MANET-Based Intelligent Transportation Systems. In *Future Generation Communication and Networking (FGNC'07)*, pages 414–417, 2007.

[TWB07] O.K. Tonguz, N. Wisitpongphan, and F. Bai. Broadcasting in VANET. In *INFOCOM MOVE Workshop, Anchorage, Alaska*, pages 7–12, May. 2007.

[UDSAM09] R. A. Uzcategui, A. J. De Sucre, and G. Acosta-Marum. WAVE: a tutorial - [topics in automotive networking]. *IEEE Communications Magazine*, 47(5):126–133, May 2009. Available at `http://dx.doi.org/10.1109/MCOM.2009.4939288`.

[vii11] Vehicle Infrastructure Integration, 2011. Available at `http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/NRD/Multi-media/PDFs/Public%20Paper/SAE/2006/Carter_Vehicle_Infra-structure_Integration.pdf`.

[vol11] Volvo S60 Concept drives itself in stop-start traffic, 2011. Available at `http://www.gizmag.com/volvo-s60-concept-drives-itself-in-stop-start-traffic/10582/`.

[vsc11] Vehicle Safety Communications - Applications VSC-A, 2011. Available at `http://www.nhtsa.dot.gov/staticfiles/DOT/NHTSA/NRD/Multi-media/PDFs/Crash%20Avoidance/2009/811073.pdf`.

[WBM+07] N. Wisitpongphan, F. Bai, P. Mudalige, V. Sadekar, and O.K. Tonguz. Routing in sparse vehicular ad hoc networks. *IEEE Journal on Selected Areas in Communications*, 25(8):1538–1556, Oct. 2007.

[WS09] Z. Wang and J. Shi. A model for urban distribution system under disruptions of vehicle travel time delay. In *Second International Conference on Intelligent Computation Technology and Automation (ICICTA)*, volume 3, pages 433–436, Oct. 2009.

[WTP+07] N. Wisitpongphan, O.K. Tonguz, J.S. Parikh, P. Mudalige, F. Bai, and V. Sadekar. Broadcast storm mitigation techniques in vehicular ad hoc networks. *IEEE Wireless Communications*, 14:84–94, 2007.

[XSMK04] Q. Xu, R. Sengupta, T. Mak, and J. Ko. Vehicle-to-vehicle safety messaging in DSRC. In *Proceedings of the 1st ACM international workshop on Vehicular ad hoc networks, Philadelphia, PA, USA*, Oct. 2004.

[YJH08] Z. Yin, W. Junli, and L. Huapu. A study on urban traffic congestion dynamic predict method based on advanced fuzzy clustering model. In *International Conference on Computational Intelligence and Security (CIS '08)*, volume 2, pages 96–100, Dec. 2008.

[YLGM08] Z. Ye, J. Limin, C. Guoqiang, and G. Min. Approach and application of transportation state analysis. In *Fourth International Conference on Networked Computing and Advanced Information Management (NCM '08)*, volume 2, pages 260–265, Sept. 2008.

[YOCH07] K. Yang, S. Ou, H.-H. Chen, and J. He. A Multihop Peer-Communication Protocol With Fairness Guarantee for IEEE 802.16-Based Vehicular Networks. *IEEE Transactions on Vehicular Technology*, 56(6):3358–3370, 2007.

[YOW09] G. Yan, S. Olariu, and M.C Weigle. Providing VANET security through active position detection. *Computer Communications*, 31(12):2883–2897, Jul. 2009.

[YT09] M. Yoshikawa and H. Terai. Car navigation system based on hybrid genetic algorithm. In *2009 WRI World Congress on Computer Science and Information Engineering*, volume 5, pages 62–65, Apr. 2009.