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Design and Evaluation of a Traffic Safety System based on Vehicular Networks for the Next Generation of Intelligent Vehicles

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DESIGN AND EVALUATION OF A TRAFFIC SAFETY SYSTEM BASED ON VEHICULAR NETWORKS FOR THE NEXT GENERATION OF INTELLIGENT VEHICLES

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COMPUTER SCIENCE AND SYSTEM ENGINEERING DEPARTMENT

Design and Evaluation of a Traffic Safety System based on Vehicular Networks for the Next Generation of Intelligent Vehicles

Thesis submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Computer Science

Manuel Fogué Cortés

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Teruel, September 2012

To my family and my girlfriend,
for their patience and support.

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I have traveled a long way until I arrived where I am today. I have been in different places, at different times, with different people. And finally, I came back to the place where everything started. Even if it could be hard to believe, Teruel still exists and offers lots of things, more than it could seem at first sight.

The situation was not easy when I finished my Computer Science Degree. The economy had just started to fall into recession, and finding a job would not be as simple as I initially thought. So, why not trying in the place where my academic life started? I decided to talk with Dr. Francisco J. Martínez about the possibility to work at the Escuela Universitaria Politécnica de Teruel at that moment. Then, Dr. Martínez and his wife, Dr. Piedad Garrido, accepted to be my advisors as a Ph.D. student. There were lots of doubts, and we were not sure about almost anything, but there was potential. I knew we could do something good, and nearly three years after that, I am finishing my Thesis and I am very proud of all the process followed. My advisors have helped so much during this time, it is difficult to think I could have reached so far without their invaluable support.

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Abstract

The integration of telecommunication technologies into the automotive industry is a fact that will change, within a relatively short time, the way we travel today. The different vehicles on the road will be able to exchange information through *Vehicular Ad Hoc Networks* (VANETs), which opens a new world of possibilities due the tremendous potential of this technology. From new entertainment and passenger comfort applications, through mechanisms to reduce the consumption, to tools that will increase road safety. Among all these possibilities, this thesis focuses on improving road safety, having a direct impact on the reduction of road casualties by making use of *Intelligent Transport Systems* (ITS).

The first step to achieve our goal lies in obtaining an efficient dissemination of warning messages about potentially dangerous situations on the road. However, the assessment of techniques developed for vehicular networks involves a high cost and complexity, since the nodes are able to move at high speeds and it is difficult to obtain representative results. This is why simulation has become the most useful tool for researchers in this field. In order to improve this process, we developed a framework that uses mobility scenarios in real cities to simulate the exchange of messages between nodes represented by vehicles. This framework allowed us to develop and evaluate a protocol for warning message dissemination that selects the nodes in charge of the retransmission based on the topology of the current scenario. In addition, we demonstrate that the street layout (roadmap) where the diffusion takes place is one of the most influential factors regarding the efficiency of the dissemination process, and thereby performing an adaptation of the broadcast scheme to the map allows reducing the notification time and increases the number of vehicles that are informed about the dangerous situation.

Our dissemination algorithms are part of a broader architecture, called e-NOTIFY, which starting from the installation of On-Board Units (OBUs) in vehicles, is able to detect traffic accidents, report them to the authorities, and inform the emergency services. However, to achieve a full automation of this process, thereby reducing the time to assist the injured people involved, it is necessary to rely on artificial intelligence techniques. Our proposal makes use of the information provided by vehicular networks to: (i) estimate the severity of the accident and the injuries of the people affected, and (ii) determine the optimal set of resources that should be sent to the crash site. The development and evaluation of a prototype proved the feasibility of the system and how it could help to reduce casualties on the road.

Resumen

La integración de las tecnologías de la telecomunicación a la industria automovilística es un hecho que cambiará, en un plazo relativamente corto, la forma en que viajamos. Los diferentes vehículos en la carretera serán capaces de intercambiar información mediante redes vehiculares ad hoc (VANETs), abriendo un nuevo mundo de posibilidades debido al tremendo potencial de esta tecnología. Desde nuevas aplicaciones de entretenimiento y comfort, pasando por reducir el consumo, hasta herramientas que aumentarán la seguridad. De entre estas posibilidades, este trabajo se centra en la mejora de la seguridad vial, repercutiendo en la reducción de víctimas mediante sistemas inteligentes de transporte (ITS).

El primer paso para conseguir nuestro objetivo reside en conseguir una diseminación eficiente de los mensajes de alerta sobre situaciones potencialmente peligrosas en la carretera. Sin embargo, la evaluación de técnicas desarrolladas para redes vehiculares conlleva un gran coste y complejidad, ya que los nodos se mueven a gran velocidad y es complicado obtener resultados representativos. Así, la simulación se ha convertido en la herramienta más útil para los investigadores de este campo. Por esto, se ha desarrollado un entorno que parte de escenarios de movilidad en ciudades reales hasta la simulación del intercambio de mensajes entre los vehículos. Este marco de trabajo nos ha permitido desarrollar y evaluar un protocolo de diseminación de mensajes de alerta que selecciona los nodos encargados de la retransmisión basándose en la topología del escenario. Además, hemos demostrado que la disposición de las calles es uno de los factores que afectan en mayor medida a la eficiencia de la diseminación, y realizar una adaptación del esquema de difusión al mapa en cuestión consigue reducir el tiempo de notificación y la proporción de vehículos que no son informados de la situación peligrosa.

Nuestros algoritmos de diseminación se encuadran dentro de una arquitectura más amplia, denominada e-NOTIFY, que usando unidades de a bordo (OBUs) instaladas en los vehículos, es capaz de detectar accidentes de tráfico, notificarlos a las autoridades, y avisar a los servicios de emergencia. No obstante, para automatizar este proceso, con la consiguiente reducción del tiempo de asistencia, es necesario apoyarse en técnicas de inteligencia artificial. Nuestra propuesta hace uso de la información proporcionada mediante redes vehiculares para: (i) estimar la gravedad del accidente y de las heridas de las personas afectadas, y (ii) determinar el conjunto de recursos óptimo que debería enviarse al lugar del accidente. El desarrollo y evaluación de un prototipo ha demostrado la factibilidad del sistema, y cómo podría ayudar a reducir el número de víctimas en la carretera.

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Chapter 1

Motivation, Objectives and Organization of the Thesis

1.1 Motivation

A massive deployment of devices with wireless capabilities has been prominent during the last decade. Nevertheless, during the next few years, this trend is expected to become even more pronounced. Most of the wireless networks available nowadays are infrastructure-based. However, users may not always want to communicate using an infrastructure due to security, costs, or bandwidth constraints.

In vehicular environments, wireless technologies such as *Dedicated Short Range Communication* (DSRC) [QRTJ04] and IEEE 802.11p *Wireless Access for Vehicular Environment* (WAVE) [IEE10] enable peer-to-peer mobile communication among vehicles (V2V) and communication between vehicles and the infrastructure (V2I). V2V communications allow the transmission of small messages to improve traffic safety. V2I communications, in contrast, allow users to access higher level applications usually related to infotainment. We think that the combination of V2V and V2I communications can propel our communication capabilities even further, allowing us to communicate anytime and anywhere, improving the future Intelligent Transportation Systems (ITS) and increasing our life quality tremendously.

The specific characteristics of vehicular networks favor the development of attractive and challenging services and applications. In this thesis we focus on safety applications. Specifically, we aim to improve traffic safety by using vehicular networks. To that end, we will develop efficient warning message dissemination mechanisms for vehicular networks, decreasing the notification time for the vehicles potentially affected by dangerous situations on the road. We will make use of computer simulations to assess our proposals, since deploying and testing real Vehicular Ad Hoc Networks (VANETs) involves high cost and intensive labor. In addition, we will propose an architecture to use the information collected by collided vehicles to automatically estimate the severity of the accidents, and decide the most adequate rescue team for its assistance. This would noticeably reduce the reaction time when facing a traffic accident, thus increasing the survival chances for the people affected.

1.2 Objectives of the Thesis

The first objective of this thesis is to propose a system for reducing the Emergency Services Responsiveness. 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. In this thesis we want to propose efficient warning message dissemination protocols that would reduce the time since the occurrence of the accident until it is correctly received and processed by the authorities. We also want to study the factors that affect warning dissemination in a higher degree, in order to use them in our advantage to increase the efficiency of the dissemination process.

The second objective of this thesis is to develop a complete architecture giving support to the notification, processing, and assistance of traffic accidents through vehicular networks. It would be interesting to build a prototype that could be tested in a real environment to evaluate the feasibility of the system and its mass implantation in the automotive industry.

The third objective is to develop intelligent algorithms allowing the automatic processing of the information received using our system. The entity in charge of handling notifications should be able to estimate the severity of the accident based on the data collected by the vehicles that participated in the collision. Hence, it would be helpful to know the damages in the vehicle, and also the injuries of the different passengers, to adapt the emergency operative to send to the crash site. Historical data from past accidents could be in handy for this task, using them to build prediction models for unknown accidents.

Finally, as the fourth objective of the thesis, we want to use the information collected from the accident, and the estimations made by the intelligent algorithms, to determine the sanitary resource sets that should be included included in the rescue team assigned to the notified accident. We have to develop a resource model to be used in traffic accidents, and an appropriate allocation policy. We must take into account different factors affecting the optimal selection, such as arrival time, cost, and balanced resource usage. We should select the different resources provided by the available health care center based on our preferences towards one objective or another.

After describing our distinct objectives in detail, we proceed by making a joint evaluation of all the previous proposals, obtaining a clear picture of the overall improvements achieved.

1.3 Organization of the Thesis

This thesis is organized as follows: in Chapter 2 we show 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 Ad Hoc Networks (VANETs), showing their main characteristics and applications.

Chapter 3 presents our realistic simulation framework, built to obtain more accurate and meaningful results when simulating vehicular environments. Specifically, we have designed and implemented Citymob for Roadmaps (C4R), a mobility generator for vehicular networks, and we have introduced several enhancements to the ns-2 [FV00], a widely used network simulator. All these enhancements allow simulating vehicular networks using real maps, while reducing the time required to prepare the simulated scenarios.

In Chapter 4 we determine which are the key factors when simulating VANETs in realistic urban environments. Our purpose is to determine what are the key factors affecting *Warning Message Dissemination* (WMD) in order to concentrate on such parameters, thus reducing the amount of simulation time required when evaluating traffic safety applications for VANETs.

Chapter 5 presents the *enhanced Message Dissemination based on Roadmaps* (eMDR), a novel scheme specially designed to increase the percentage of informed vehicles and reduce the notification time; at the same time, it mitigates the broadcast storm problem in real urban scenarios. To further improve this technique, in Chapter 6 we propose the Profile-driven Adaptive Warning Dissemination Scheme (PAWDS), a scheme that uses a mapping technique based on adapting the dissemination strategy according to both the characteristics of the street area where the vehicles are moving, and the density of vehicles in the target scenario.

Chapter 7 is dedicated to our prototype architecture called e-NOTIFY, a novel proposal designed to increase the chances of survival for passengers involved in car accidents. This chapter also includes information about the parts that form the system, and the different experiments performed during its validation in a real crash test.

In Chapter 8, we propose an intelligent algorithm which is able to automatically estimate the severity of traffic accidents based on the concept of data mining and knowledge inference. Our system uses historical data from previous accidents occurred in very different situations, whereas it only considers the most relevant variables that can characterize their severity.

Chapter 9 presents our approach to the sanitary resources allocation problem in traffic accidents. Our proposal is based on the use of multi-objective genetic algorithms, and it is able to generate a list of optimal solutions accounting for the specific policy of the decision-making entity.

Finally, in Chapter 10 we present a summary of the main results of this thesis, along with some concluding remarks. We also include a list of the publications related to the thesis, and we comment on 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 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 de-

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.

velopments areas have been identified: (a) navigation systems, (b) electronic toll collection (ETC) 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. 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

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.

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, onboard 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 (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 com-

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 (text, audio, images, real-time video, voice/graphics) 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 that relays information about accidents ahead, break-downs and congestion; a longitudinal control system; and a cooperative driving assistance system that supports merging and weaving.
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.

munication 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,

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.

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 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 thesis we focus on traffic safety applications, in order to reduce the number of accidents, or reduce the rescue time in case of an accident (increasing the probability of survival of the injured). Specifically, (i) we improve the warning message broadcast effectiveness in safety applications for vehicular networks, (ii) we are able to automatically estimate the severity of traffic accidents for better assist people injured in traffic accidents, and (iii) using this technology together with Artificial Intelligence (AI) systems, we reduce the assistance time while maximizing the assistance quality, minimizing the cost, minimizing the penalty for overuse of resources, as well as balancing the resource deployment.

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 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.

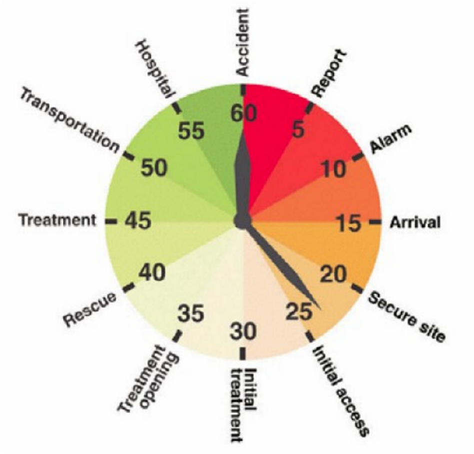


Figure 2.1: Golden hour in a car accident.

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

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.

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) estimates that 85% of new cars will have an EDR (black box system) by 2010 [nth11].

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.

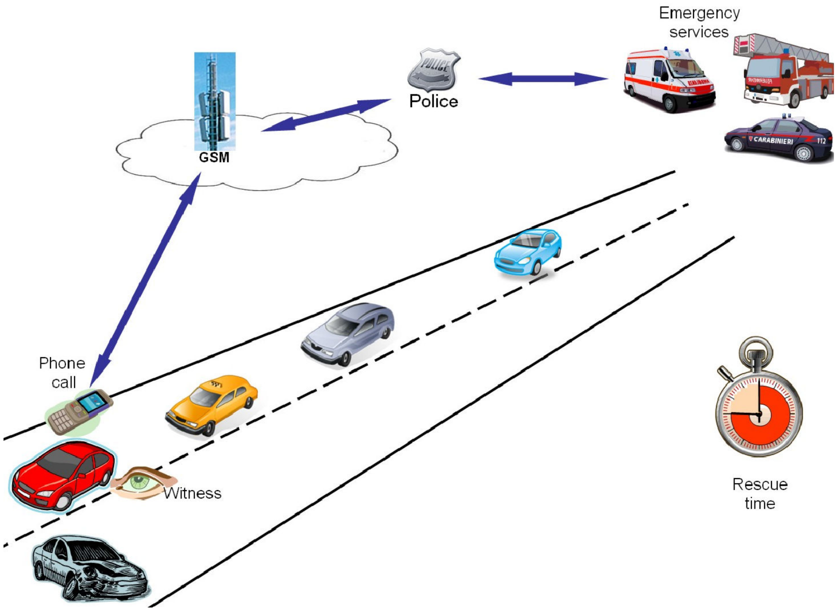


Figure 2.2: Old method of rescue using a cellular phone when an accident occurred.

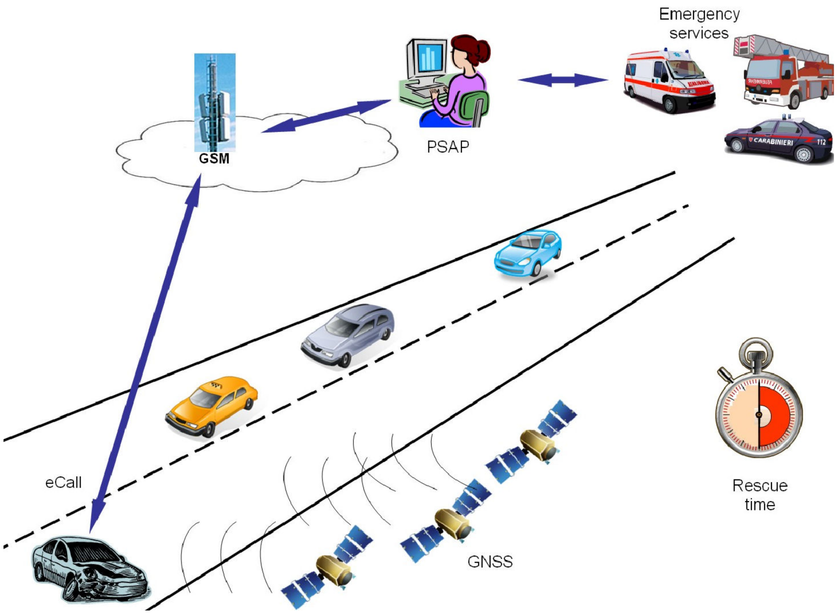


Figure 2.3: Current method of rescue when an accident occurs (e.g. eCall and OnStar).

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

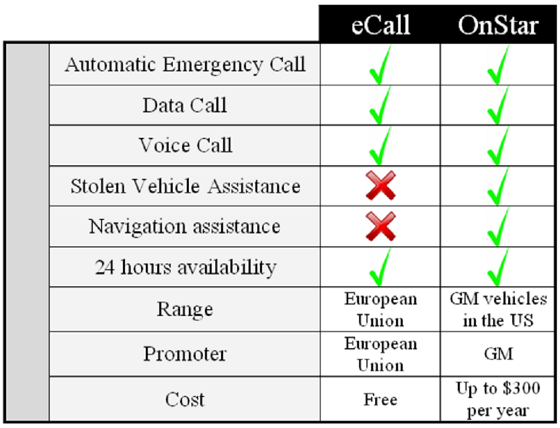
For eCall to work, several requirements [Eur09] must be met: Firstly, all newly manufactured cars will have to be equipped with eCall devices. In 2005, the European Commission and the automotive industry association agreed to schedule full-scale deployment of eCall service for 2009. eCall devices were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

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.

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

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 (CU) 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 intelli-

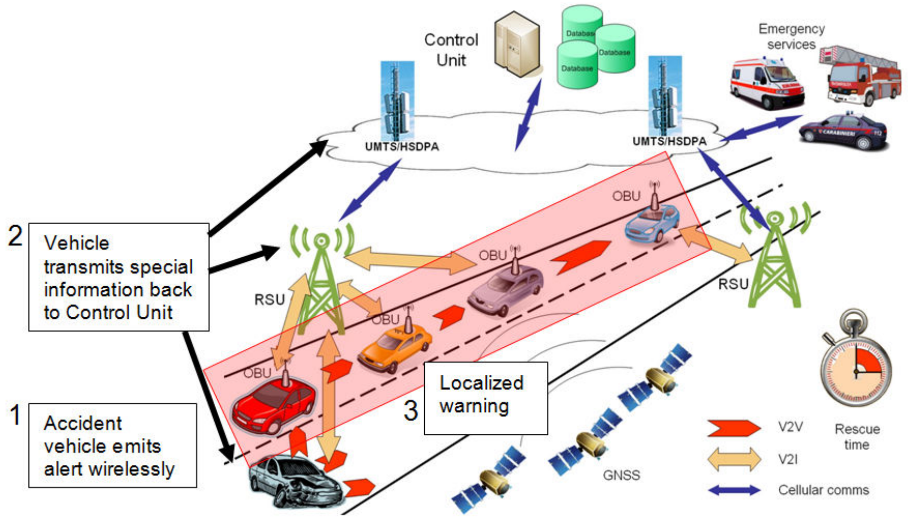


Figure 2.4: Future emergency rescue architecture combining V2I and V2V communications, combining localized alerts and warnings, special control information transmission, intelligent databases, and a Control Unit.

gent 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 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

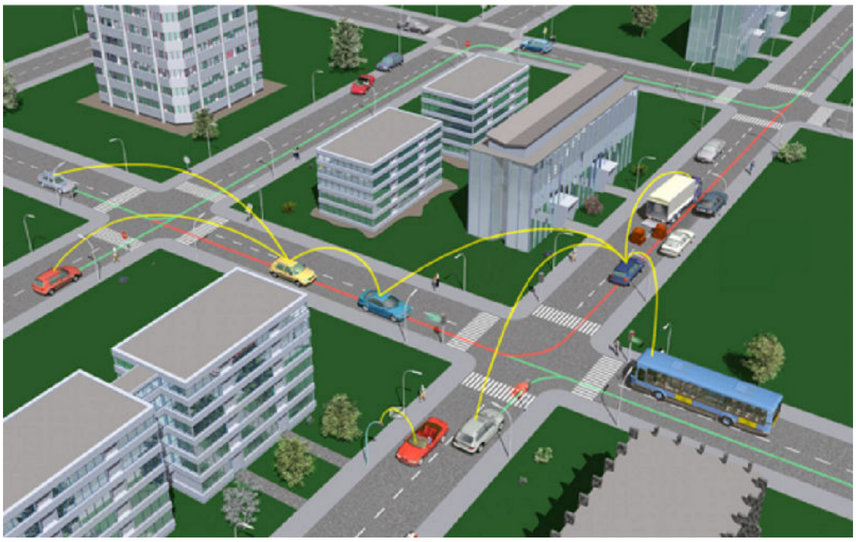


Figure 2.5: Example of a VANET.

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) [QRTJ04] 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.

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].

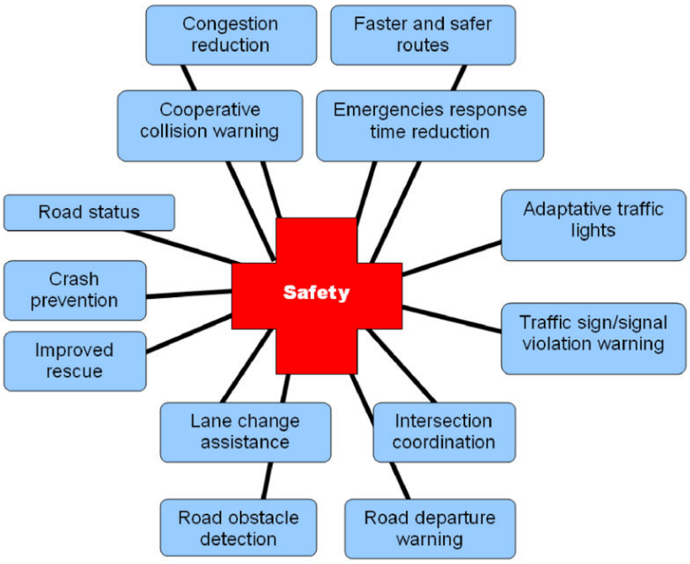


Figure 2.6: Traffic safety applications of VANETs.

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 in 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 Summary

Several research projects led by research institutes and car manufacturers around the world have positively impacted the future of *Inter-Vehicle Communication* (IVC) 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

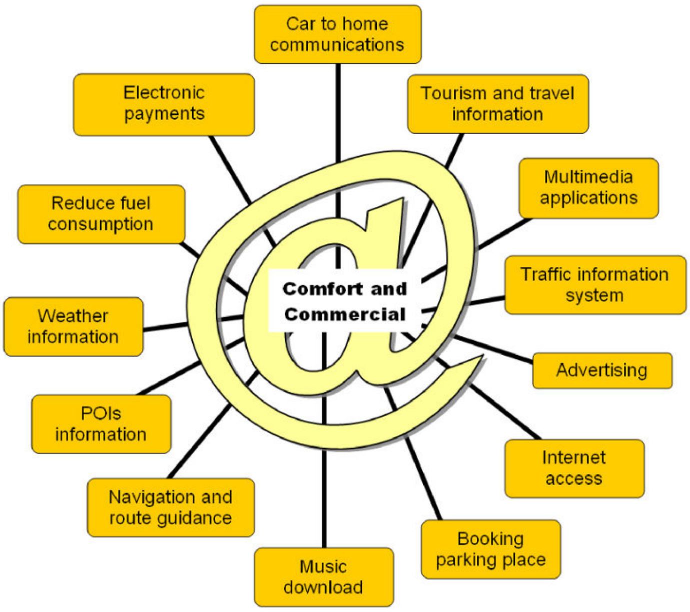


Figure 2.7: Comfort and commercial applications of VANETs.

call made by a witness, to the current eCall accident notification system provided in 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) 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 examine the impact of future ITS technologies on road safety and emergency services, and we propose 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 realistic simulation framework for Vehicular Networks

Research in *Vehicular Networks* (VNs) has found in simulation the most useful method to test new algorithms and techniques. This is mainly due to the high cost of deploying such systems in real scenarios. When simulating vehicular environments, two different issues must be addressed: mobility and wireless communications. Regarding mobility, several mobility pattern generators have been proposed so far. However, all of them present important drawbacks from the point of view of reproducing realistic mobility over real roadmaps. As for the wireless communications, ns-2 has become one of the most widely used network simulators for wireless communications researchers. However, simulating VNs requires using environments behaving as realistically as possible, and ns-2 presents some deficiencies that make it difficult to obtain accurate vehicular simulations.

In this chapter, we present a realistic simulation framework which combines vehicular mobility over real roadmaps and ns-2 optimizations to obtain more accurate and meaningful results when simulating vehicular environments.

3.1 Introduction

Deploying and testing Vehicular Networks (VNs) involves high cost and manpower, since realistic testbeds may require using vehicles moving at high speeds and integrated wireless devices to support communication among them. Moreover, obtaining representative scenarios to evaluate the operation of a VN system could become a complex matter as these systems are usually large and heterogeneous, and they depend on the behavior of the surrounding vehicles. Hence, relying on simulation is an useful methodology prior to actual implementation [SCB11].

One of the important issues when creating a vehicular simulation environment is to correctly model how vehicles move, providing an accurate and realistic vehicular mobility description at both macroscopic and microscopic levels. Regarding other features, such as using real topologies, or the effect of radio signal absorption due to obstacles, they are rarely included, and, therefore, obtained results are far from being realistic.

Unlike other previous works, we seek to fully address the peculiarities of vehicular mobility and urban radio transmission, especially when buildings interfere with radio signal propagation. With this purpose, we developed a more accurate and realistic vehicular simulation framework by improving the process to obtain both: (i) realistic mobility traces, and (ii) accurate radio propagation models. Our approach offers a solution that allows integrating real roadmaps into the simulation process, while obtaining more accurate and meaningful results.

VN simulations are greatly dependent on the simulated environment. The position and effect of the obstacles that could interfere with the radio signal, as well as the presence and behavior of other vehicles, produce notable differences in the obtained results [MFC$^+$10b]. In addition, the topology of the map used to constrain vehicle movement is a key factor [FGM$^+$11b].

In this chapter we present a complete simulation framework specially designed to simulate vehicular networks, in order to assess novel proposals. Specifically, we have designed and implemented Citymob for Roadmaps (C4R), a mobility generator for vehicular networks. Moreover, we have introduced several enhancements to ns-2 [FV00], a widely used network simulator. All these enhancements allow simulating vehicular networks using real maps while reducing the time required to prepare the simulated scenarios. Compared to other similar proposals, such as VERGILIUS [GSPG10], Veins [SYGD08], or TraNS [PRL$^+$08], our vehicular simulation framework accounts for the effect of obstacles (e.g. buildings) in radio signal propagation when using the IEEE 802.11p in real urban maps.

The rest of the chapter is organized as follows: Section 3.2 introduces the problem of modeling mobility when simulating vehicular networks. Section 3.3 presents our Citymob for Roadmaps (C4R) mobility generator. Section 3.4 shows the limitations of ns-2 when simulating vehicular scenarios. In Section 3.5 we elaborate on the enhancements we developed for the ns-2 simulator. Section 3.6 presents some similar simulation tools currently available. Finally, Section 3.7 concludes this chapter.

3.2 Modeling mobility in Vehicular Networks

A critical issue in VN simulation studies is the need for a mobility model reflecting the real behavior of vehicular traffic. Vehicular mobility generators are needed to increase the level of realism in VN simulations. They use previously defined mobility models to generate realistic vehicular mobility traces to be used as an input for a network simulator. The inputs of the mobility generator include the road model and the scenario parameters (i.e., maximum vehicular speed, rates of vehicle arrivals and departures, etc). The output of the trace details the location of each vehicle at every time instant for the entire simulation time, along with their mobility profiles. Examples are VanetMobiSim [HFFB06], SUMO [KHRW02], FreeSim [Fre08], CityMob [MCCM08] and STRAW [str08].

A wide variety of mobility models has been proposed for vehicular simulations. They try to closely represent the movement patterns of users. The Simulation of Urban MObility (SUMO) mobility generator supports several mobility models, such as the Krauss mobility model [KWG97] with some modifications to allow multi-lane behavior [KHRW02], and the Wagner mobility model [Wag06].

The Krauss model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor. The Wagner model, unlike most driving models which assume an instantaneous or even delayed reaction of the driver to the surrounding situation, considers two important features of human driving and of human actions in general. Firstly, humans usually plan ahead, and secondly, the type of control that humans apply is not continuous, but discrete in time: they act only at certain moments in time.

Saha and Johnson [SJ04] modeled vehicular traffic with a random mobility of vehicles over real road topologies extracted from the maps of the US Census Bureau TIGER database. In that work, vehicles select one point over the graph as their destination, and then compute the shortest path to get there. The edges sequence is obtained by weighting the cost of traveling on each road at its speed limit, and the traffic congestion.

Choffnes et al. [CB05] designed STRAW, a street mobility model that models real traffic conditions by incorporating a simple car-following model with traffic control to introduce vehicular congestion. STRAW relies on street plans to build a roadmap for the specified target region. It also provides at least one lane in each direction on which vehicles can move.

Mahajan et al. [MPGW06] presented three different models: (i) *Stop Sign Model* (SSM), (ii) *Probabilistic Traffic Sign Model* (PTSM), and (iii) *Traffic Light Model* (TLM). The main difference between these models is basically the algorithm used to reproduce stop signs. All roads are modeled as bidirectional roads; SSM and PTSM assume a single lane in each direction of every road, whereas TLM provides the option for modeling multiple lanes.

Our proposal provides some of the aforementioned mobility models (see Section 3.3.1), including our Downtown Model which makes it possible to account for areas with different vehicle densities since, in a real town, traffic is not uniformly distributed; instead, there are downtowns or points of interest that may attract vehicles, or points that repel vehicles (e.g., residential areas when people go to work).

3.3 C4R: CityMob for Roadmaps

In this section we present our novel mobility pattern generator for vehicular networks called Citymob for Roadmaps (C4R)[1], a software which allows simulating vehicular traffic in different locations using real maps. C4R has been implemented using the Java programming language, and it is distributed under the GNU/GPL license.

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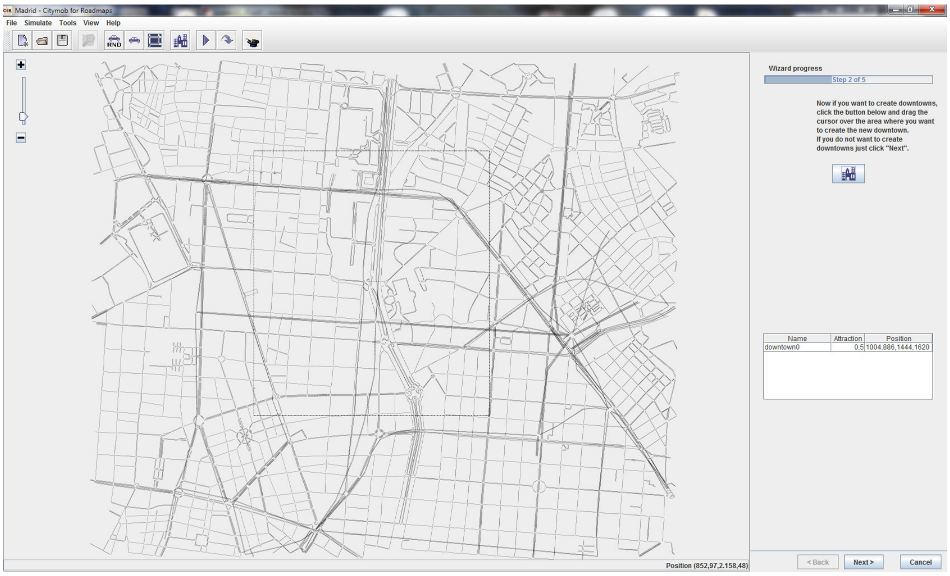
[1] `C4R's` source code is available at http://www.grc.upv.es/software/



Now if you want to create downtowns, click the button below and drag the cursor over the area where you want to create the new downtown.
If you do not want to create downtowns just click "Next".

Name	Attraction	Position
downtown0	0,5	1004,886,1444,1620

Position (852,97,2.158,48)

Figure 3.1: Downtown definition (Step 2 out of 5 of the C4R wizard).

3.3.1 C4R's features

C4R has been proposed to simulate more realistic vehicular scenarios based on real roadmaps from all over the world. C4R relies on both the OpenStreetMap [osm09] tool to get the real roadmaps, and SUMO [KHRW02] to generate the vehicles and their movements within these scenarios. *OpenStreetMap* (OSM) is a collaborative project to create a free editable map of the world, which is being built largely from scratch, and released with an open content license. The Simulation of Urban MObility (SUMO) is an open source, microscopic, space-continuous traffic simulator designed to handle large road networks.

The functionality provided by C4R is twofold: it constrains vehicle movements to the streets defined in the roadmap, and it limits their mobility according to the vehicular congestion and traffic rules. C4R has the following features:

- Ease of use. Unlike other previously proposals, users can generate several mobility traces from scratch in just a few minutes. This process, which is necessary to test and validate every novel scientific proposal, usually took us several hours, even for simple scenarios.

- Highly portable system (MAC, Windows and Linux compatibility) since it has been implemented in Java.

- It is possible to work with real maps from all over the world imported from OpenStreetMap. They can be selected graphically or by manually providing the coordinates. By using a digital roadmap as input, C4R obtains the topology of roads and their speed limits. The speed limit is assigned according to the road types defined in its map database. The traffic lights are also modeled by C4R automatically.

- Users can easily change the number of simulated vehicles.
- C4R distinguishes among different types of vehicles (cars, trucks, taxis, etc.) which usually have different mobility characteristics, hence increasing the level of realism of the simulations.
- Vehicle routes can be defined either by the user or randomly.
- Attraction and repulsion points in the roadmap can be defined graphically or by providing the coordinates manually.
- Vehicles movements are defined according to the selected mobility model. C4R provides the following mobility models: (Krauss [KWG97], Krauss modified [KHRW02], Wagner [Wag06], Kerner [Ker98], *Intelligent driver model* (IDM) [THH00], and the Downtown model [MCCM08]).
- It is possible to visualize simulations. Users can rapidly visualize mobility traces once they are generated.
- C4R allows users to obtain multiple ns-2 compatible mobility traces at once.
- All the necessary steps in the trace creation process can be taken using a user-friendly wizard (see Figure 3.1), making the use of C4R very simple. We only have to execute the wizard and follow the five steps required, i.e., (1) obtain real roadmap data, (2) define the attraction or repulsion points if they are required, (3) insert vehicles into the scenario, (4) select a mobility model from the different available ones, and (5) indicate the simulation time and the number of traces desired.

Table 3.1 presents the minimum system requirements to run our C4R application. The minimum capacity of the hard disk could be greater for some tasks. In some circumstances, when working with big maps and many vehicles, the trace file size could be greater than 5 GB, but this is unusual.

3.3.2 C4R's parameters

C4R can be tuned by the user in order to adapt the different possibilities to the user needs. In this subsection we review some of the most important parameters available in our C4R tool.

- **Attraction rate**. As previously mentioned, traffic is not uniformly distributed; there are special areas that may attract or repel vehicles. Users can assign different rates to the attraction/repulsion areas. Values near 0 will define repulsion points, and values near 1 will define attraction points.

Table 3.1: C4R System Requirements

Component	**Minimum requirements**
Processor	Pentium IV
Hard disk	1 GB
RAM	512 MB
Screen resolution	1024×768
Platform	MAC/Linux/Windows
Java runtime version	Java 6 SE
SUMO version	0.11.1
Internet connection	56K connection

- **Downtown rate**. Using this parameter, the user can define the probability for a vehicle to be within an attraction/repulsion area, and the probability of traveling to/from this area.

- **Departure (in seconds)**. It is the time when the vehicles are deployed in the scenario. The user can deploy different vehicles at different time instants.

- **Maximum simulation time (in seconds)**. It is the total duration of the simulation.

- **Number of traces**. One important aspect when simulating novel proposals is to launch several executions with different generated mobility scenarios in order to obtain reasonable confidence intervals, thus increasing the reliability of the obtained results. Hence, researchers usually need to generate several different traces from the same roadmap. C4R makes it possible; users only need to define the required number of traces.

Additionally, there is another set of parameters that can be tuned for the different mobility models available:

- **Acceleration**, which defines the maximum acceleration of the vehicles. By default, it is set to 1.4 m/s^2.

- **Deceleration**, which defines the maximum deceleration of the vehicles. By default, it is set to 2 m/s^2.

- **Sigma**, which indicates the driver's imperfection (between 0 and 1). By default, it is set to 0.5. This parameter is only used in the Krauss and modified Krauss models.

- **Tau**, which defines the driver's reaction time. By default, it is set to 0.3 s. This parameter is used in all models except the IDM model.

- **k**. This parameter is only used in the Kerner model, and defines the vehicle density measured in vehicles per kilometer. By default, it is set to 20 vehicles/km.

- **Phi**. This parameter is only used in the Kerner model, and defines the flow rate measured in vehicles per time interval.

- **Headway**, which sets the desired time headway to the vehicle in front. This parameter is only used in the IDM model. By default, it is set to 1.5 s.

- **MinGap**, which expresses the minimum net distance that is kept even at a complete stand-still in a traffic jam. This parameter is only used in the IDM model. By default, it is set to 2 m.

3.3.3 Qualitative Comparison of Mobility Generators

Table 3.2 presents a summary of some of the most widely used vehicular mobility generators focusing on their main characteristics. We have grouped the comparison parameters into five different categories: (a) Software characteristics, (b) Map types, (c) Mobility models supported, (d) Traffic models implemented, and (e) Trace formats supported.

As shown, Freesim exhibits good software characteristics but it is limited in other functions. VanetMobiSim, SUMO, CityMob, STRAW and C4R all have good software features and traffic model support. However, only VanetMobiSim provides excellent trace file support. C4R is excellent in software features, mobility, and traffic model support. Regarding map types and traces, C4R is clearly oriented to simulate real maps in the ns-2 simulator. Its most important feature is allowing to generate realistic mobility traces graphically (using real maps), easily (by means of the wizard), and quickly (in only a few minutes).

3.3.4 Quantitative Comparison of Mobility Generators

To evaluate the realism and effectiveness of existing VANET mobility generators, we performed the simulation of a generic *Warning Message Dissemination* (WMD) protocol on ns-2 over SUMO, VanetMobiSim, and C4R traces. WMD protocols are useful when an accident occurs since they can help to prevent new accidents (by warning other vehicles about the accident), and alleviate congestion [MCC+09].

Figure 3.2 shows the simulated topology for the map layout, and Table 3.3 shows the simulation parameters used. As shown, C4R is the only mobility generator which includes the Downtown mobility model; it considers that there is an area where the density of vehicles is slightly higher (as the downtown in the cities usually presents higher traffic densities). SUMO and VanetMobiSim use the Krauss model, and the IDM with Lane Changes, respectively. The rest of parameters are the same for the three mobility generators.

The performance metrics we measured include: (i) the percentage of vehicles receiving the warning messages, (ii) the warning notification time, which is the time required by vehicles to receive the warning messages, and (iii) the number of packets received per vehicle. Each simulation run lasted for 450 seconds. In order to achieve a stable state, we only collect data after the first 60 seconds. Since the performance results are highly related to the scenarios, and due to the

Table 3.2: A comparison of the studied mobility generators

	VanetMobiSim	**SUMO**	**FreeSim**	**CityMob**	**STRAW**	**C4R**
Opensource	✓	✓	✓	✓	✓	✓
Console	✗	✓	✗	✓	-	✗
GUI	✓	✓	✓	✓	✓	✓
Available examples	✓	✓	✓	✗	-	✓
Continuous development	✗	✓	-	✓	✗	✓
Wizard	✗	✗	✗	✗	✗	✓
Real	✓	✓	✓	✗	✓	✓
User defined	✓	✓	✗	✗	-	✗
Random	✓	✓	✗	✓	✗	✗
Manhattan	✗	✗	✗	✓	✗	✗
Voronoi	✓	✗	✗	✗	✗	✗
Random Way-Point	✓	✓	✗	✓	✗	✓
STRAW	✗	✓	✗	✗	✓	✓
Manhattan	✗	✓	✗	✓	✗	✗
Downtown	✗	✗	✗	✓	✗	✓
Krauss model	✗	✓	✗	✗	✗	✓
Wagner model	✗	✓	✗	✗	✗	✓
Kerner	✗	✓	✗	✗	✗	✓
IDM	✓	✓	✗	✗	✗	✓
Multilane roads	✓	✓	-	✓	✓	✓
Lane changing	✓	✓	-	✓	✓	✓
Separate directional flows	✓	✓	-	✓	✓	✓
Speed constraints	✓	✓	✓	✓	✓	✓
Traffic signs	✓	✓	-	✓	✓	✓
Intersections management	✓	✓	-	✗	-	✓
Large road networks	-	✓	-	✓	✓	✓
Collision free movement	-	✓	-	✓	-	✓
Different vehicle types	✗	✓	✗	✓	-	✓
Hierarchy of junction types	✗	✓	✗	✗	-	✓
Route calculation	✓	✓	✓	✗	✓	✓
Ns-2 trace support	✓	✗	✗	✓	✗	✓
GloMoSim support	✓	✗	✗	✗	✗	✗
Qualnet support	✓	✗	✗	✗	✗	✗
SWANS support	✗	✗	✗	✗	✓	✗
XML-based support	✓	✗	✗	✗	✗	✗

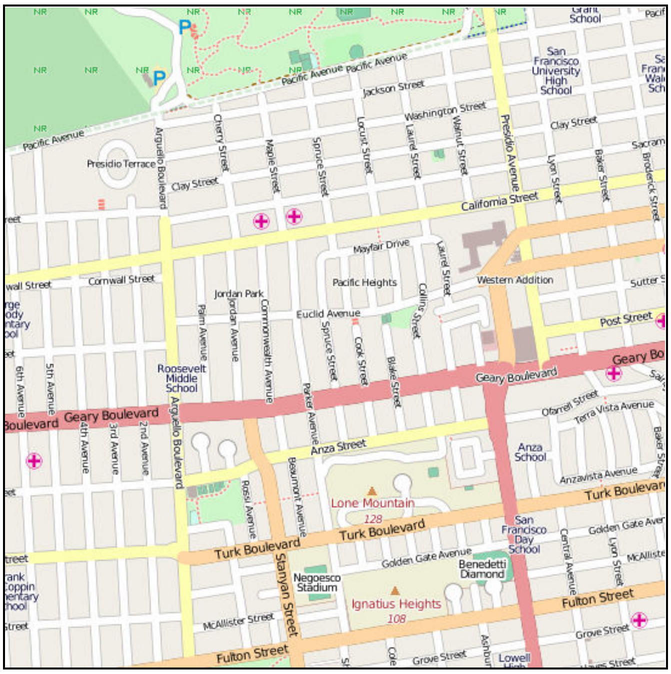


Figure 3.2: Simulated scenario of San Francisco, USA.

Table 3.3: Parameters used for performance simulation of different VANET mobility generators

VANET mobility generator	SUMO	VanetMobiSim	C4R
network simulator	ns-2.31		
number of vehicles	300		
map area size	$2000m \times 2000m$		
downtown size	-	-	$1000m \times 1000m$
downtown probability	-	-	0.6
number of warning mode vehicles	3		
warning packet size	$256B$		
normal packet size	$512B$		
packets sent by nodes	1 *per second*		
warning message priority	$AC3$		
normal message priority	$AC1$		
MAC/PHY	802.11p		
maximum transmission range	$400m$		
mobility models	Krauss	IDM with Lane Changes	Krauss and Downtown

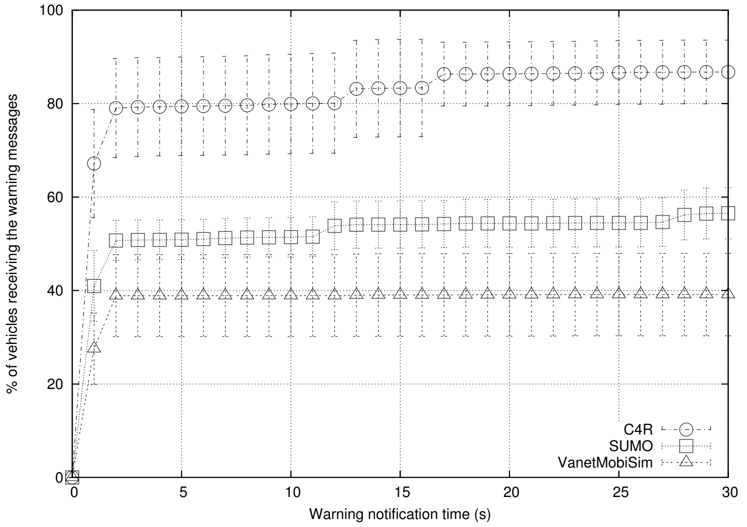


Figure 3.3: Cumulative histogram for the time evolution of disseminated warning messages using different mobility generators.

random nature of the mobility models used, we repeated the simulations to obtain reasonable confidence intervals. As shown in Figure 3.3 and Table 3.4, the shortest warning notification time[2] is achieved when using C4R traces, followed by SUMO and VanetMobiSim. In terms of percentage of vehicles informed, using C4R traces resulted in the largest percentage of vehicles receiving the warning messages. Finally, in terms of number of packets received, experiments using C4R show a higher packet delivery rate, being the lowest results achieved with SUMO. Results show that the effect of the Downtown concept included in our C4R mobility generator is crucial, since the higher density of vehicles, the easier becomes the warning message dissemination process. We consider that SUMO, and VanetMobiSim in particular, underestimate the performance of the WMD protocol in urban scenarios. Overall, our investigation shows that, when simulating the same WMD protocol with the same network simulator over different VANET mobility generators, different performance results may be obtained.

3.4 Limitations of the ns-2 simulator

We now address the problem of improving the radio propagation models provided by one of the most used network simulator, i.e. the ns-2. In particular, we developed some improved models dealing with the 802.11p standard as well as the effect of obstacles in the radio signal propagation.

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[2] The data presented for warning notification time, is the time needed to inform at least 40% of the vehicles.

Table 3.4: Performance of the WMD protocol under the different mobility generators

Performance	**SUMO**	**VMobiSim**	**C4R**
Warning notification time (s)	0.80	1.90	0.50
% of vehicles informed	56.51	39.12	86.75
Number of packets received	309.03	685.73	1153.50

Ns-2 is a discrete event simulator targeted at networking research which has become a widely used tool to simulate the behavior of wired and wireless networks. When simulating radio signal transmission, we use a mathematical formulation of the radio wave propagation as a function of parameters such as distance between vehicles and radio frequency. This formulation is called *Radio Propagation Model* (RPM). The ns-2 simulator offers some RPMs to account for wireless signal strength. These models assume a flat surface, where the simulation environment contains no objects that could block the signal (mostly buildings in urban environments), and thereby they do not accurately simulate the radio propagation process in vehicular environments. The RPMs included in ns-2 v2.35 are:

1. **Free Space model**: The received power is only dependent on the transmitted power, the antenna gains, and on the distance between sender and receiver. Obstacles are not modeled.
2. **Two-ray Ground (TRG) model**: Assumes that the received signal energy is the sum of the direct line-of-sight path and the reflected path from the ground. It does not account for obstacles, and sender and receiver have to be on the same plane.
3. **Rayleigh and the Ricean fading models**: Both models describe the time-correlation of the received signal power. The Rayleigh model considers indirect paths between the sender and the receiver, while the Ricean fading model applies when there is one dominant path and multiple indirect signals.
4. **Nakagami fading model**: Signal reception power is determined using a probability distribution dependent on distance. Configuration parameters are used to simulate different levels of fading. This model can be interpreted as a generalization of the Rayleigh distribution.
5. **Shadowing model**: usually defined as a log-normal shadowing model, it consists of two parts: the first one is known as the path loss model, which predicts the mean received power at a distance d in different environments, and the second one adopts a Gaussian random variable to reflect the variation of the received power at a certain distance.

Although the latest version of ns-2 (version 2.35) provides some changes to include the 802.11p standard [CSEJ$^+$07], existing RPMs found in ns-2 do not support obstacle modeling within the network. In fact, for the Free Space and the Two-ray Ground models, only the power level is taken into account. Hence, determining whether a packet reaches its destination or not is a deterministic process. The other three models included are based on probabilistic distributions that do not use information about the specific scenario. Therefore, situations where two vehicles are in line-of-sight are handled exactly in the same way as situations where there are obstacles between them, which cannot be considered realistic.

3.5 Enhancements to the ns-2 simulator

Our efforts to improve the realism of *Vehicular Network* (VN) simulations using ns-2 derived in two parts: (i) improving the models to represent the features of the 802.11p standard in terms of frequency, data rate, etc., and (ii) developing new Radio Propagation Models to model Packet Error Rate and fading due to obstacles in a realistic manner.

3.5.1 IEEE 802.11p MAC/PHY layers

We modified the simulator to follow the upcoming WAVE standard closely. Achieving this requires extending the ns-2 simulator to implement the IEEE 802.11p. In terms of the physical layer, the data rate used for packet broadcasting was fixed at 6 Mbit/s, i.e., the maximum rate for broadcasting in 802.11p when using 20 MHz channels. The MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA) *Quality of Service* (QoS) extensions [WH03]. Therefore, application messages are categorized into different *Access Categories* (ACs), where AC0 has the lowest and AC3 the highest priority. The contention parameters used for the *Control Channel* (CCH) are shown in [Eic07].

Authors in [Eic07] and [CSEJ$^+$07] use a theoretical maximum transmission range of 250 m for 802.11p in their experiments. However, our own real experimental results using 802.11a devices (which employs almost the same PHY layer as 802.11p, with extended sampling rate and clock rate) showed a maximum transmission range of 400 m in an obstacle-free environment, and also demonstrated the high impact of obstacles in radio signal propagation. Other published works regarding 802.11p-based real testbeds obtained very similar results [BLJL10, MBS$^+$10, SEGD11]. Hence, we modified the PHY layer configuration used in ns-2 to represent this behavior. Table 3.5 contains part of the ns-2 *Tcl* configuration file that provides the IEEE 802.11p configuration parameters.

3.5.2 Enhanced Radio Propagation Models proposed for the ns-2 simulator

We also modified the ns-2 simulator to include four additional RPMs that increase the level of realism in simulations, thereby allowing us to obtain more accurate and meaningful results. Three of these RPMs are designed to be used in synthetic Manhattan-style grid scenarios: (i) the Distance Attenuation Model (DAM), (ii) the Building Model (BM), and (iii) the Building and Distance Attenuation Model

Table 3.5: NS-2 Tcl file for the IEEE 802.11p

```
#Configuration for 802.11p PHY layer

Phy/WirelessPhy set CPThresh_   10.0
Phy/WirelessPhy set CSThresh_   1.559e-11
Phy/WirelessPhy set RXThresh_   3.652e-10
Phy/WirelessPhy set Rb_         2*e6
Phy/WirelessPhy set Pt_         3.57382      ;# Maximum tx range = 400 meters
Phy/WirelessPhy set freq_       5.9e9        ;# 5.9 GHz
Phy/WirelessPhy set L_          1.0
Phy/WirelessPhy set bandwidth_  54e6

#Configuration for 802.11p MAC layer (based on 802.11e MAC layer)

Mac/802_11p set CWMin_              15
Mac/802_11p set CWMax_              1023
Mac/802_11p set SlotTime_           0.000009        ;# 9 us
Mac/802_11p set SIFS_               0.000016        ;# 16 us
Mac/802_11p set PreambleLength_     96              ;# 96 bit
Mac/802_11p set PLCPHeaderLength_   40              ;# 40 bits
Mac/802_11p set PLCPDataRate_       6.0e6           ;# 6 Mbps
Mac/802_11p set RTSThreshold_       3000            ;# 3 Kbytes
Mac/802_11p set ShortRetryLimit_    7               ;# retransmissions
Mac/802_11p set LongRetryLimit_     4               ;# retransmissions
Mac/802_11p set basicRate_          6e6             ;# 6 Mbps
Mac/802_11p set dataRate_           6e6
```

(BDAM). The fourth one, the Real Attenuation and Visibility Model (RAV), is designed to be used in real map scenarios.

3.5.2.1 Distance Attenuation Model

The *Distance Attenuation Model* (DAM) considers the impact of signal attenuation due to the distance between the vehicles on packet loss. To estimate such impact we relate the BER (bit error rate) or PER (packet error rate) to distance under specific channel conditions. It allows us to simplify calculations and thus significantly reduce simulation run-time.

3.5.2.2 Building Model

The *Building Model* (BM) takes into consideration that, at a frequency of 5.9 GHz (i.e., the frequency band of the 802.11p standard), the signal is highly directional and will experience a very low depth of penetration. Hence, in most cases, buildings will absorb radio waves at this frequency, making communication only possible when the vehicles are in line-of-sight. Other previous works [BLJL10, MBS$^+$10, SEGD11] also consider these premises.

3.5.2.3 Building and Distance Attenuation Model

The *Building and Distance Attenuation Model* (BDAM) combines both DAM and BM models. Communication will only be possible, in most cases, when the received signal is strong enough and vehicles are within line-of-sight.

BDAM can be considered more realistic than both DAM and BM, but it still has lack of realism since it is designed for Manhattan-based scenarios alone. The Real Attenuation and Visibility model, presented in the next subsection, solves this problem.

3.5.2.4 Real Attenuation and Visibility model for real roadmap scenarios

A wireless signal propagation model can be characterized by: (a) attenuation schemes (signal power loss due to distance), and (b) visibility schemes (presence of obstacles interfering with signal propagation). The combination of these schemes makes up our Radio propagation model, called *Realistic Attenuation and Visibility* (RAV) model.

Our model implements signal attenuation due to the distance between vehicles as closely to reality as possible. In general, ns-2 offers deterministic RPMs, i.e., the selected function determines the maximum distance a packet could reach. If the receiver is within this range, the packet will be successfully received; on the contrary, if the distance is greater, it will be lost. In order to increase realism, we use a probabilistic approach to model packet losses due to channel noise and other situations. We use a probability density function to determine the probability of a packet being successfully received at any given distance.

With respect to other attenuation schemes, such as Two-Ray Ground and Nakagami, our scheme, instead of being theoretical, is obtained directly from experimental data.

Regarding visibility, the main objective that a realistic visibility scheme should accomplish is to determine if there are obstacles between the sender and the receiver which interfere with the radio signal. In most cases, when using the 5.9 GHz frequency band (used by the 802.11p standard), buildings absorb radio waves, and so communication is not possible. As previously mentioned, the *Building and Distance Attenuation Model* (BDAM) was designed to work in Manhattan-style grid layouts, where simple calculations were used to determine if two vehicles were in line-of-sight.

RAV goes one step forward by adapting the algorithm to support more complex and realistic layouts. Given a real reference map containing the street layout, our proposal determines whether two different vehicles can communicate using the following strategy:

- Two vehicles in the same street are always in line-of-sight. We consider that a vehicle is in a street (s) when the minimum distance (d_{min}) between its position ($P(x, y)$) and the line (r) formed as a extension of the street is less than a threshold (th_s).
- When a vehicle is at a junction (j), we consider that this vehicle may potentially communicate with all the vehicles present in the streets which start from the junction j, i.e., the vehicle is considered to be at all the neighbor streets simultaneously. A threshold distance (th_j) is used to determine if a vehicle is close enough to a junction for this rule to apply.
- Two vehicles in adjacent streets (labeled i and j) can communicate if the angular difference (α) between their streets is below a threshold th_a. This property can be extended if there is a series of linked streets between vehicles, and, for every street in the chain, the angular difference with the rest of streets is less than th_a. We consider this, since the electromagnetic waves forming the wireless signal can experience the effects of reflection, refraction and diffraction due to the presence of solid obstacles in urban scenarios. Hence, some situations where vehicles are not in line-of-sight can still result in effective communication between them.

3.5.3 Quantitative Comparison of the RPMs

In this section, we evaluate the impact of some of the presented RPMs on the performance of a Warning Message Dissemination application, typically used in VANETs. Specifically, we compared the performance of TRG, Nakagami, and our RAV proposal. Our intention is to evaluate the effect that the different radio propagation schemes have over the network performance, and measure the differences appearing when we increase the level of realism of the simulations.

Results in Figure 3.4 are obtained using a real map from San Francisco as the simulation topology (see Figure 3.2). As shown, when using TRG and Nakagami

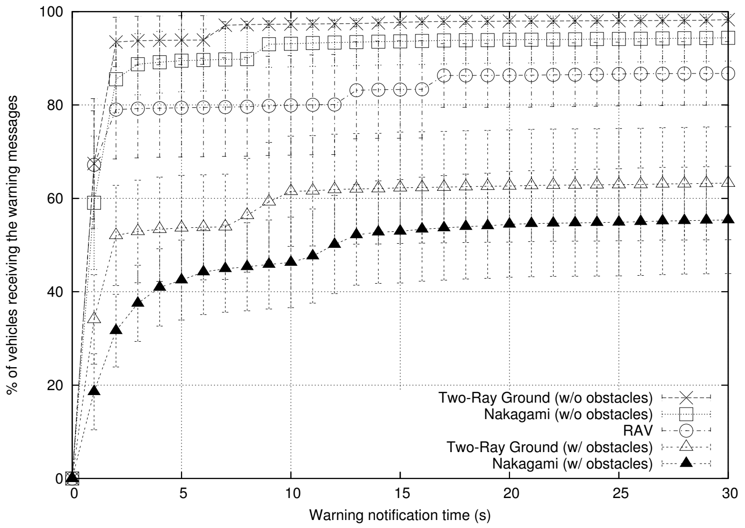

Figure 3.4: Warning notification time when varying the attenuation scheme.

RPMs, and when obstacles are not accounted for (as in the majority of VANET simulators), information reaches more vehicles (98.26% and 94.37%, respectively). However, the same models only achieved 63.24% and 55.37% of the vehicles being informed when the effect of obstacles in signal transmission is considered. Our RAV model, although accounting for the effect of obstacles, still considers that 86.75% of the vehicles are aware of the dangerous situation.

Table 3.6 presents a summary of the average performance results obtained when simulating the different attenuation schemes. As shown, the effect of obstacles can also be observed in the warning notification time, since the protocol requires more time to warn the same percentage of vehicles (e.g. TRG and Nakagami required much more time to inform 40% of the vehicles when accounting for the presence of obstacles). Regarding the number of packets received per vehicle, when ignoring obstacles, TRG considers that more messages are received compared to Nakagami. When obstacles are present, results show that RAV considers that vehicles receive more packets compared to the TRG and Nakagami RPMs since the maximum transmission range is higher and communication effectiveness improves.

3.6 Similar Simulation Tools

In this section, we present some other similar VANET simulation tools. VERGILIUS [GSPG10] is a VANET simulation tool which uses the Tiger digital maps to generate highly tunable city-based scenarios for both SUMO and Corsim microscopic-mobility simulators. In addition, the VERGILIUS propagation tool computes the attenuation-matrix using the city-block and road map information extracted from the Tiger digital map database by using the CORNER algorithm [GFPG10]. The

Table 3.6: Performance of the WMD protocol under the different radio propagation models

Performance	**Two-Ray w/o obs.**	**Nakagami w/o obs.**	**RAV**	**Two-Ray w/ obs.**	**Nakagami w/ obs.**
Warning notification time (s)	0.60	0.62	0.7	1.25	3.80
% of vehicles informed	98.26	94.37	86.75	63.24	55.37
Number of packets received	2224.70	1092.00	1153.50	461.17	234.70

simulation of the radio propagation is based on theoretical data and validated with empirical measures, and it does not need to know the exact location of the buildings since it approximates them by using the streets width. However, unlike our proposal, the CORNER algorithm implies very complex calculations and it is only valid for Manhattan-based topologies where the streets are arranged orthogonally. Therefore, real maps are not correctly simulated by VERGILIUS. In addition, it uses a Rayleigh fading propagation model, and it was only validated with 802.11b-based testeds.

Veins [SYGD08] is an Inter-Vehicular Communication (IVC) simulation framework composed of an event-based network simulator and a road traffic microsimulation model. Both domains' models are bi-directionally coupled and simulations are performed on-line. This way, not only the influence of road traffic on network traffic can be modeled, but also vice versa. In particular, the influences of IVC on road traffic can be modeled and complex interactions between both domains examined. The simulation of the radio propagation is based on empirical measures based on the 802.11p standard. However, unlike our proposal, Veins uses a deterministic radio propagation model (Free-space with some modifications), it requires to know the exact position of the buildings, and it considers that communications are possible even at very large distances, since it uses very high transmission power.

Finally, TraNS [PRL$^+$08] (Traffic and Network Simulation Environment) is a *Graphical User Interface* (GUI) tool that integrates traffic and network simulators (SUMO and ns-2) to generate realistic simulations of VANETs. As Veins, TraNS allows the information exchanged in a VANET to influence the vehicle behavior in the mobility model, although it does not account for the effect of obstacles (e.g. buildings) in radio signal propagation.

3.7 Summary

In this chapter we presented a complete simulation framework specially designed to simulate vehicular networks. Specifically, we have addressed two different issues: (i) we designed and implemented Citymob for Roadmaps (C4R), a mobility generator for vehicular networks, and (ii) we proposed and included several Radio Propagation Models into the ns-2 simulator, which are specially designed to support realistic vehicular communications.

All these enhancements allow researchers to simulate vehicular networks using real maps, thus obtaining far more accurate results than using other available simulation frameworks. In addition, C4R allows to significantly reduce the time required to prepare the simulation scenarios. In the future we will improve C4R's features by integrating mobility and network communications, since the information exchanged among vehicles should influence their mobility patterns.

Chapter 4

Identifying the key factors affecting Warning Message Dissemination in VANETs

In recent years, new architectures and technologies have been proposed for *Vehicular ad hoc networks* (VANETs). Due to the cost and complexity of deploying such networks, most of these proposals rely on simulation. However, we find that most of the experiments made to validate these proposals tend to overlook the most important and representative factors. Moreover, the scenarios simulated tend to be very simplistic (highways or Manhattan-based layouts), which could seriously affect the validity of the obtained results.

In this chapter, we present a statistical analysis based on the 2^k factorial methodology to determine the most representative factors affecting traffic safety applications under real roadmaps. Our purpose is to determine which are the key factors affecting Warning Message Dissemination in order to concentrate research tests on such parameters, thus avoiding unnecessary simulations and reducing the amount of simulation time required. Simulation results show that the key factors affecting warning messages delivery are the density of vehicles, and the roadmap used. Based on this statistical analysis, we consider that VANET researchers must evaluate the benefits of their proposals using different vehicle densities and city scenarios, to obtain a broad perspective on the effectiveness of their solution. Finally, since city maps can be quite heterogeneous, we propose a roadmap profile classification to further reduce the number of cities evaluated.

4.1 Introduction

When developing realistic VANET simulations, it is necessary to account for some specific characteristics found in vehicular environments. For instance, VANET simulations often involve large and heterogeneous scenarios. Traditional mobile systems also present a large number of parameters potentially affecting their performance, thus increasing considerably the simulation time required to correctly evaluate any proposal in a wide variety of scenarios. In recent years, new architectures and technologies have been proposed for VANETs, thanks to the use of simulation. However, the experiments to validate these proposals tend to overlook the most important and representative factors. Moreover, the scenarios simulated tend to be very simplistic (highways or Manhattan-based layouts), and most of them use the 802.11g standard, already implemented in most simulators, instead of using the 802.11p [IEE10] which is going to be used for inter-vehicular communication. Thus, we find that different proposals in the VANET field lack generality, being uncertain whether they will perform adequately in a real VANET environment.

In this chapter, we present a statistical analysis based on the 2^k factorial methodology [Jai91] to determine the most representative factors that govern the warning message dissemination performance in 802.11p-based VANETs. The aim of this methodology is to reduce the simulation time required to analyze the performance of a given VANET system, since it allows researchers to focus on the key factors affecting their proposals.

We start our analysis by selecting the following nine factors which have been widely used in the literature: (i) the number of warning mode vehicles, (ii) the density of vehicles, (iii) the channel bandwidth, (iv) the broadcast scheme, (v) the message priority, (vi) the periodicity of messages, as well as (vii) the mobility model used, (viii) the radio propagation model, and (ix) the simulated roadmap. In a factorial design strategy, all factors are varied together (as opposed to one-at-time). So, a key advantage of this methodology is that it allows researchers to find out not only the most representative factors, but also the possible interactions and interdependencies among them.

This chapter is organized as follows: Section 4.2 describes related work on the factors commonly studied in VANETs, and the use of 2^k factorial analyses in wireless networks. Section 4.3 presents the 2^k factorial analysis fundamentals. Section 4.4 describes the main factors of interest in VANET research. In Section 4.5 we determine the key factors in VANET simulation using the 2^k factorial analysis; based on the simulation results, we then provide some guidelines for future research. Finally, Section 4.6 concludes this chapter.

4.2 Related work

In this section we present some of the most representative works regarding: (i) the factors commonly studied in VANETs, and (ii) the use of 2^k factorial analyses in wireless networks.

4.2.1 Factors Commonly Studied in VANETs

Most currently available VANET research works rely on simulation. However, we find that most of the experiments made to validate these proposals tend to overlook the most important and representative factors.

Zuo et al. [ZWLZ10] proposed the vehicle-node density parameter to improve the performance of both AODV and OLSR routing protocols under two typical mobile models in VANET. Simulation results indicated the improvement of performance of routing protocols according to increase the node density around the receiver. In this work, they varied the density of vehicles and the mobility models, while maintaining unaltered other parameters such as the simulation area, the transmission range, the packet size, and the radio propagation model. Giordano et al. [GFG$^+$09] focused on the accuracy of urban propagation models and their impact on vehicular protocol results. They compared the Two Ray model and the Corner model in a city scenario. Moreover, they identified a number of factors that undermine the validity of the Two Ray model, for example, the presence of buildings causing propagation disruption and the heavy weight border effects that incorrectly compensate for the presence of hidden terminals in the networks. In this work, authors varied the transmission range, the map size and the radio propagation model, while maintaining unaltered other parameters such as the density of vehicles, the packet size, etc. Khorashadi et al. [KCG$^+$07] looked at the result of tuning transmission power and its effect on UDP throughput in VANETs. Results showed that the major mitigating factor in VANETs is the number of hops between the source and the destination. They assessed that increasing the transmission range results in decreasing the number of hops between source and destination effectively increasing throughput. Authors also found that the effect of vehicle densities is only important at lower transmission ranges to provide the required connectivity.

Regarding warning message dissemination, Cenerario et al. [CDI11] described in detail a vehicular dissemination protocol which allows sharing information such as available parking spaces, accidents or obstacles in the road, etc., by using vehicle-to-vehicle communications. The dissemination approach considers the relevance of the data to decide when a rediffusion is needed. In this work, authors varied some factors such as the density of vehicles and the vehicle's speed, while maintaining unaltered other parameters such as the transmission range, the map size, the radio propagation model, the simulated roadmap, etc. Farrokhi and Zokaei [FZ11] proposed a controlled repetition stochastic broadcast protocol. Authors studied the impact of employ controlled repetition and stochastic techniques on the performance of warning message dissemination in VANETs. The simulation results showed that the performance of VANET improved by setting proper parameters and the number of repetitions per priority class, although they only varied the density of the vehicles to assess their proposal. Sahoo et al. [SWSG11] proposed an IEEE-802.11-based multihop broadcast protocol to address the issue of warning message dissemination in VANETs. The protocol adopts a binary-partition-based approach to repetitively divide the area inside the transmission range to obtain the furthest possible segment. Aside from accomplishing directional broadcast for a highway scenario, the protocol also exhibits good adaptation to complex road structures. In this work, authors varied some factors such as the density of vehicles and the vehicles' speed, while maintaining unaltered other parameters such as the periodicity of messages, the radio propagation model, the transmission range, etc. Finally, Barberis and Malnati [BM09] investigated the impact that road-network and vehicle density have on the performance of epidemic dissemination and the correlation between these factors and other simulation parameters, such as percentage of equipped vehicles, message expiration time, scheduling algorithm for data retransmission, and number of circulating messages. In this work, authors varied some factors such as the density of vehicles, the roadmap topology, and the periodicity of messages, while maintaining unaltered other parameters such as the transmission range, the map size, the radio propagation models, etc.

The effect of obstacles in warning message dissemination has also been addressed by some works. Costa et al. [CFMM06] presented an approach where a message propagation function encodes information about target areas and preferred routes for the message dissemination. Selecting different functions produces different routing protocols accounting for connected and disconnected situations between vehicles. These protocols show a remarkable performance in simple grid-like scenarios with low and high density of vehicles, but real maps are not used in their simulations. Viriyasitavat et al. [VBT10] proposed the UV-CAST (Urban Vehicular broadCAST) protocol, which allows reducing the broadcast storm problem while solving disconnected network problems in urban VANETs. However, the density of vehicles studied is relatively low, and the authors did not study its performance when there are more than 50 vehicles per km^2. Liu and Chigan [LC12] proposed the RPB-MD protocol, a message dissemination approach with a relative position based (RPB) addressing model that allows defining the intended receivers in the zone of relevance. Simulation results show high delivery ratio and low data overhead; however, the scenario used is a single bidirectional highway, and the Radio Propagation Model selected is the deterministic Two-Ray Ground.

To the best of our knowledge, there is no research work that formally identifies the factors that significantly affect the performance of warning message dissemination systems for VANETs. Hence, we consider that the contributions made in this chapter offer significant guidance to the research community in this area.

4.2.2 2^k Factorial Analysis in Wireless Networks

In the networking literature we can find several works that adopted the 2^k factorial approach to discriminate among the many available parameters so as to determine the most relevant ones.

Gupta et al. [GACW07] studied *Distributed Network Control Systems* (D-NCS), a network structure and components that are capable of integrating sensors, actuators, communication, and control algorithms to suit real-time applications. They addressed the issue of D-NCS information security, as well as its time-sensitive performance with respect to network security schemes. Standard statistical approaches, such as 2^k factorial experiment design, analysis of variance, and hypothesis testing, were used to study and estimate the effect of each factor on the system performance, with an emphasis on its security features.

Liu et al. [LMH08] studied the use of multipath routes to improve throughput, end-to-end delay, and the reliability of data transport in *Wireless Sensor Networks* (WSNs). They reported the results of a series of simulations based on a factorial experimental design. Results showed that both the congestion window size and the retry limit are key factors. Vaz de Melo et al. [VdMdCA$^+$08] studied how different WSNs can cooperate in order to reduce the total energy consumption. Simulation results revealed that different densities and data collecting rates among WSNs, the routing algorithm, and the path loss exponent had a major impact in the establishment of cooperation. The initial assessment of the impact of these factors was made through a 2^k factorial experimental analysis.

Perkins et al. [PHO02] studied and quantified the effects of various factors and their two-way interactions on the overall performance of MANETs. Using 2^k factorial experimental design, they isolated and quantified the effects of five factors: (i) node speed, (ii) pause-time, (iii) network size, (iv) number of traffic sources, and (v) type of routing. They evaluated the impact that these factors have over the throughput, routing overhead, and power consumption. In [PH02], they investigated the impact of some characteristics on the performance of TCP in MANETs. Moreover, a factorial design experiment was conducted to quantify the effects and interactions that node speed and node pause time have over the TCP throughput. Buchegger and Le Boudec [BLB02] proposed a protocol, called CONFIDANT, based on selective detection and isolation of misbehaving nodes. They presented a performance analysis of DSR fortified by CONFIDANT, and compared it to a regular defenseless DSR scheme. A 2^k factorial design was performed to find out which factors affect performance. McClary et al. [MSL08] designed a transport protocol that uses *Artificial Neural Networks* (ANNs) to adapt the audio transmission rate to changing conditions in a MANET. The response variables of throughput, end-to-end delay, and jitter were examined.

Although the use of standard statistical approaches such as the 2^k factorial analysis is found in many other fields, it is not so frequently used in ad hoc network communications. Moreover, to the best of our knowledge, this sort of statistical analysis has not been used in VANET research.

4.3 The 2^k factorial analysis

VANET simulations often involve large and heterogeneous scenarios. The number of possible factors and their values, or levels, can be very large. In this section, we will explain how the 2^k factorial analysis [Jai91] can be used to determine the most relevant factors that govern a system's performance.

The use of 2^k factorial is important for several reasons: (i) to reduce the overall number of simulations needed, (ii) to evaluate the relationship between different factors, and (iii) to reduce the amount of simulation time required. The basic approach of this method is based on selecting a set of k parameters and determining 2 extreme levels (tagged with -1 and 1). An experiment is run for all the 2^k possible combinations of the parameters. From each experiment, we can also extract the $\binom{k}{2}$ two-factor interactions, the $\binom{k}{3}$ three-factor interactions, and so on.

For example, suppose that we have proposed a Warning Message Dissemination system, and that we want to study the impact of the density of vehicles (factor A) and the speed of these vehicles (factor B) in the warning notification time, i.e., the time required by normal vehicles to receive a warning message sent by a warning mode vehicle.

Table 4.1: Experiments defined by a 2^2 design

Experiment	**A**	**B**	**y**
1	-1	-1	y_1
2	1	-1	y_2
3	-1	1	y_3
4	1	1	y_4

Table 4.2: Example of results obtained in terms of warning notification time varying two factors

Density of vehicles	**Speed 10 km/h**	**Speed 80 km/h**
25 veh./km^2	1 *second*	0.8 *seconds*
150 veh./km^2	0.5 *seconds*	0.4 *seconds*

If we make a 2^2 factorial analysis, we can find out the impact of each factor (density of vehicles and speed), and their combination, in the studied metric (warning notification time). Table 4.1 shows the different experiments defined by the 2^2 design, and Table 4.2 shows the results obtained after the simulations.

Let us define two variables x_A and x_B as presented in Equations 4.1 and 4.2:

$$x_A = \begin{Bmatrix} -1 & \text{if} & density\,of\,vehicles = 25 \\ 1 & \text{if} & density\,of\,vehicles = 150 \end{Bmatrix} \tag{4.1}$$

$$x_B = \begin{Bmatrix} -1 & \text{if} & speed = 10\,km/h \\ 1 & \text{if} & speed = 80\,km/h \end{Bmatrix} \tag{4.2}$$

The warning notification time (y) can be regressed on x_A and x_B using a non linear regression model of the form:

$$\mathbf{y} = q_0 + q_A x_A + q_B x_B + q_{AB} x_A x_B \tag{4.3}$$

Substituting the four observations in the model, we get the following four equations:

$$1 = q_0 - q_A - q_B + q_{AB} \tag{4.4}$$

$$0.5 = q_0 + q_A - q_B - q_{AB} \tag{4.5}$$

$$0.8 = q_0 - q_A + q_B + q_{AB} \tag{4.6}$$

$$0.4 = q_0 + q_A + q_B + q_{AB} \tag{4.7}$$

Table 4.3: Sign table method of calculating the effects of the factors in a 2^2 design

I	**A**	**B**	**AB**	**y**
1	-1	-1	1	1 *second*
1	1	-1	-1	0.5 *seconds*
1	-1	1	-1	0.8 *seconds*
1	1	1	1	0.4 *seconds*
2.7	-0.9	-0.3	0.1	Total
0.675	-0.225	-0.075	0.025	Total/4

These equations can be solved uniquely for the four unknowns. The regression equation is:

$$\mathbf{y} = 0.675 - 0.225x_A - 0.075x_B + 0.025x_Ax_B \tag{4.8}$$

The result is interpreted as follows: the mean warning notification time is 0.675 seconds, the effect of the density of vehicles is -0.225 seconds, the effect of the speed of the vehicles is -0.075 seconds, and the interaction between speed and density of vehicles accounts for 0.025 seconds.

4.3.1 Calculating the Effects of the Factors

In a 2^k factorial analysis, by using the sign table method, we can get the results and detect variations which depend on the combination of factors. For a 2^2 design, the effects can be computed easily by preparing a 4×4 sign matrix as shown in Table 4.3. The first column of the matrix is labeled I, and it consists of all 1's. The next two columns, titled A and B, contain basically all possible combinations of -1 and 1. The fourth column, labeled AB, is the product of the entries in columns A and B. The four observations are listed in a column vector next to this matrix. The column vector is labeled y and consists of the results corresponding to the factor levels listed under columns A and B. The next step is to multiply the entries in column I by those in column y and put their sum under column I. The entries in column A are now multiplied by those in column y and the sum is entered under column A. This operation of column multiplication is repeated for the remaining two columns of the matrix. The sums under each column are divided by 4 to give the corresponding coefficients of the regression model.

The importance of a factor depends on the proportion of the metric *total variation* explained by the factor. The total variation of y is also known as *Sum of Squares Total* (SST), which can be calculated as follows:

$$Total\ variation\ of\ y = SST = \sum_{i=1}^{2^2}(y_i - \overline{y})^2 \tag{4.9}$$

where $\overline{y}$ denotes the mean of the responses from all four experiments. For a 2^2 design, the variation can be divided into three parts:

$$SST = 2^2q_A^2 + 2^2q_B^2 + 2^2q_{AB}^2 \tag{4.10}$$

These parts can be expressed as a fraction; for example:

$$Fraction\, of\, variation\, explained\, by\, A = \frac{SSA}{SST} = \frac{2^2 q_A^2}{SST} \tag{4.11}$$

Hence, we can indicate the percentage of variation of each studied metric explained by each factor. The more percentage of variation, the more impact this factor has in the measured metric. In our example, we found that the density of vehicles accounts for 89.01% (i.e. $\frac{2^2 \cdot -0.225^2}{0.2275}$) of the total variation of the warning notification time, the speed of the vehicles accounts for 9.89% (i.e. $\frac{2^2 \cdot -0.075^2}{0.2275}$), and their combination accounts for the remaining 1.10% (i.e. $\frac{2^2 \cdot 0.025^2}{0.2275}$). Therefore, in our selected example the density of vehicles is the most important factor which affects the warning notification time.

The outcome of the 2^k factorial analysis allows us in sorting out factors in the order of impact. At the beginning of any performance study, the number of factors and their levels could usually be large. A full factorial design with such a large number of factors and levels may not be the best use of available effort. The first step should be to reduce the number of factors and to choose those factors that have a significant impact on performance.

4.4 Factors to Study in VANETs

Some previous works have studied the most important factors in MANETs. Nevertheless, VANETs have special characteristics that make them different from MANETs. Hence, more research is required in order to identify the key factors that impact their performance. In this section we identify and describe the most important factors associated with VANET Warning Message Dissemination.

4.4.1 Number of Warning Vehicles

In traffic safety applications, vehicles may send safety messages to other vehicles in order to prevent collisions or to ask for emergency services. We consider that vehicles may operate in warning or normal mode. Warning mode vehicles inform other vehicles about their abnormal status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets and, periodically, they also send *beacons* with information about themselves, such as their position and speed.

This factor is important since the more vehicles in the warning mode are there in a scenario, the more network traffic there will be, thus increasing redundant rebroadcasts which provoke heavy contention and long-lasting collisions.

4.4.2 Density of Vehicles

In VANETs, the density of vehicles can be particularly high, which usually causes that VANET simulations require quite a long time to finish. Moreover, many network simulators do not scale well, and so simulating VANETs with high density of vehicles consumes a significant amount of time and resources.

As shown in previous works [MTC+09, MCC+09, MTC+11a], this factor seems to be important to measure Warning Message Dissemination performance in VANET scenarios. In fact, some authors have defined new compound factors derived from the density of vehicles (e.g. Jiang et al. [JCD07] defined the concept of communication density as the product of vehicle density, messaging rate and transmission range).

4.4.3 Channel Bandwidth

In radio communications, bandwidth is the width of the frequency band used to transmit the data. Channel spacing is a term used in radio frequency planning that describes the frequency difference between adjacent allocations in a frequency plan.

The 802.11p standard supports 10MHz and 20Mhz bandwidths. Using a 10Mhz bandwidth, the supported data rates are 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps, depending on the modulation and coding scheme considered.

In vehicular safety communications the efficiency of channel usage is important in managing the broadcast transmissions. The efficient channel usage helps to reduce the overall interference level and in turn impacts on the broadcast reception performance [JCD08].

Since vehicular information delivery systems support applications such as cooperative driving among cars on the road, traffic safety, or infotainment applications, we think that channel bandwidth requirements could change based on the selected application. For the specific case of Warning Message Dissemination mechanisms, the overall capacity of the channel can affect the effectiveness of warning dissemination schemes if the density of potential transmitters is high.

4.4.4 Broadcast Scheme

Another important factor in Warning Message Dissemination in VANETs is the selected broadcast scheme [LC12]. In VANETs, intermediate vehicles act as relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, flooding of broadcast messages commonly occurs. However, flooding results in many redundant rebroadcasts, heavy channel contention, and long-lasting message collisions (usually known as the broadcast storm problem).

Over the years, several schemes have been proposed to address the broadcast storm problem in wireless networks. In [TNCS02] we can find some of the most interesting approaches, which are the following: (i) the counter-based scheme, which uses a counter to keep track of the number of times the broadcast message is received in order to decide whether to inhibit the rebroadcast, (ii) the distance-based scheme, in which the relative distance between vehicles is used to decide whether to rebroadcast or not, (iii) the location-based scheme, which is very similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation of the additional coverage of a rebroadcast, and (iv) the cluster-based scheme, where vehicles are grouped in clusters, and only one member of each cluster (the cluster head) can rebroadcast the warning messages. The *weighted p-persistence*, the *slotted 1-persistence*, and the *slotted p-persistence* techniques presented in [WTP$^+$07] are some of the few rebroadcast schemes proposed for VANETs. These three probabilistic and timer-based broadcast suppression techniques can mitigate the severity of the broadcast storms by allowing nodes with higher priority to access the channel as quickly as possible, but their ability to avoid storms is limited, since they are specifically designed for being used in highway scenarios. *The Last One* (TLO) scheme [SP08] tries to reduce the broadcast storm problem by finding the most distant vehicle from the warning message sender, so that this vehicle will be the only one allowed to retransmit the message. This scheme does not take into account the effect of obstacles (e.g., buildings) in urban radio signal propagation. More recently, we proposed a scheme called *enhanced Street Broadcast Reduction* (eSBR) [MFC$^+$10a], which uses location and roadmap information to facilitate an efficient dissemination of warning messages in 802.11p-based VANETs.

It is easily noticeable that most existing solutions to the broadcast storm problem were only evaluated in obstacle-free environments, which are not comparable to real urban scenarios where plenty of obstacles can interfere with the signal, creating blind areas where vehicles will not receive the warning message unless intermediate forwarding nodes help to overpass the obstacle. In our experiments we use both the location-based scheme and our eSBR scheme to assess the relevance of the broadcast scheme adopted.

4.4.5 Message Priority

Wireless technologies such as 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.

The 802.11p MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA), and *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Classes* (ACs), where AC0 has the lowest and AC3 the highest priority.

In our experiments, *warning messages* (which contain information about abnormal situations such as accidents) have always the highest priority (AC3) at the MAC layer, while *beacons* (containing information such as vehicles' positions and speeds), which are not propagated by other vehicles, change their priority from the lowest (AC0) to the highest (AC3) priority in the 2^k factorial analysis.

4.4.6 Message Periodicity

As mentioned previously, warning mode vehicles inform other vehicles about their status by sending warning messages periodically. Normal mode vehicles participate in the diffusion of these warning packets and, moreover, they also send periodic *beacons* with information such as their positions, speed, etc.

Similarly to the number of warning vehicles, the more warning messages are sent at the same time, the more redundant rebroadcasts, channel contention, and message collisions there will be. Thus, message periodicity seems to be an important factor that offers a trade-off between performance and overhead.

4.4.7 Mobility Model

One of the challenges posed by the study of VANETs is the definition of a vehicular mobility model [AZ12] providing an accurate and realistic vehicular mobility description at both macroscopic and microscopic levels [HFB09]. To perform realistic simulations, it is especially important that the chosen mobility generator is able to obtain a detailed microscopic traffic simulation by importing network topologies from real maps. Our mobility simulations are performed with SUMO [KR07], an open source traffic simulation package which has interesting microscopic traffic capabilities such as: collision free vehicle movement, multi-lane streets with lane changing, junction-based right-of-way rules, traffic lights, etc. SUMO can also import roadmaps directly from map databases such as OpenStreetMap [osm09] and TIGER [tig09].

Our mobility simulations account for areas with different vehicle densities. In a real town, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [MCCM08] to add points of attraction in realistic roadmaps.

To generate the movements for the simulated vehicles, we used two different mobility models available in SUMO: (i) the Krauss mobility model [KWG97] with some modifications to allow multi-lane behavior [KHRW02], and (ii) the Wagner mobility model [Wag06]. The Krauss model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)\tau}{\tau + 1} + \eta(t), \tag{4.12}$$

where v represents the speed of the vehicle in m/s, t represents the period of time in seconds, v_1 is the speed of the leading vehicle in m/s, g is the gap to the leading vehicle in meters, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random numeric variable with a value between 0 and 1.

The Wagner model, unlike most driving models which assume an instantaneous or even delayed reaction of the driver to the surrounding situation, considers two important features of human driving and of human actions in general. Firstly, humans usually plan ahead, and secondly, the type of control that humans apply is not continuous, but discrete in time: they act only at certain moments in time. These specific moments are known as action-points.

4.4.8 Radio Propagation Model

We observe that the most widely used simulators, such as ns-2, Glomosim, QualNet and OPNET do not include a *Radio Propagation Model* (RPM) that offers enough accuracy for vehicular environments [MTC$^+$09]. In particular, the physical obstacles present in urban environments (mostly buildings) are not taken into account, which is overly optimistic. For example, the commonly used *Two Ray*

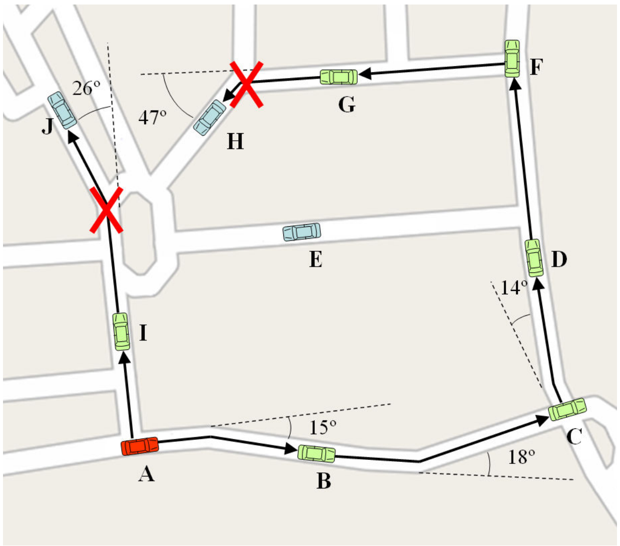

Figure 4.1: RAV visibility scheme: example scenario.

Ground (TRG) radio propagation model ignores effects such as *Radio Frequency* (RF) attenuation due to buildings and other obstacles, meaning that an alternative model must be introduced. However, for 802.11p-based VANETs, the received signal will largely depend on both the distance between the sender and the receiver, and the presence of obstacles.

In the 2^k factorial analysis, we use both the well-known deterministic TRG and the probabilistic *Real Attenuation and Visibility Model* (RAV) [MFC$^+$10b], a realistic RPM specifically designed for IEEE 802.11p-based VANETs that increases the level of realism of phenomena occurring at the physical layer, thereby allowing researchers to obtain more accurate and meaningful results [MTC$^+$09].

Figure 4.1 shows an example of the visibility scheme used in RAV, where vehicle (A) is trying to disseminate a message. In that case, and assuming that any vehicle receiving a message will rebroadcast it the first time, the result will be that some vehicles (B, C, D, F, G, and I) receive the message, while the others (E, H, and J) will never be reached by such message.

4.4.9 Roadmap

The roadmap (road topology) is an important factor accounting for mobility in simulations, since the topology constrains cars' movements. Roughly described, an urban topology is a graph where vertices and edges represent, respectively, junction and road elements. Simulated road topologies can be generated ad hoc by users, randomly by applications, or obtained from real roadmap databases. Using complex layouts implies more computational time, but the results obtained are closer to the real ones [MFC$^+$10a]. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). These approaches are simple and easy to implement in a simulator. However, layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the results obtained are likely to be similar in realistic environments.

Our simulation scenarios used in the 2^k factorial analysis are based on two different real roadmaps, which were obtained from real cities using OpenStreetMap. The two locations represent environments with different street densities and average street lengths. The chosen scenarios were the South part of the Manhattan Island from the city of New York (USA), and the area located at the North of the Colosseum in the city of Rome (Italy). The fragments selected have an extension of 4 km^2 (2 km × 2 km). Figure 4.2 depicts the street layouts used. As shown, the fragment from New York presents the longest streets, arranged in a Manhattan-grid style. The city of Rome represents the opposite situation, with short streets in a highly irregular layout. The third fragment was extracted from the city of San Francisco, and the results of its simulation are presented in Section 4.5.4.

4.5 Simulation Results

Simulation results presented in this chapter were obtained using the ns-2 simulator [FV00]. We modified the simulator to follow the upcoming WAVE standard closely[1], extending it to implement IEEE 802.11p [IEE10]. Mobility is performed with CityMob for Roadmaps (C4R) [FGM$^+$12b], a mobility generator which can import maps directly from OpenStreetMap.

In our study, each simulation lasted for 120 seconds. In order to achieve a stable state before gathering data traffic, we only started to collect data after the first 60 seconds. All results represent an average over thirty executions with different random scenarios, presenting all of them a maximum error of 10% with a degree of confidence of 90%. We evaluated the following performance metrics: (i) the warning notification time, (ii) the percentage of blind vehicles, and (iii) the number of packets received per vehicle. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle. The percentage of blind vehicles is the percentage of vehicles that does not receive the warning messages sent by the warning mode vehicles. These vehicles can remain blind because of their positions, due to collisions, or due to signal propagation limitations. Table 4.4 shows the parameters used for the simulations. The downtown probability and the downtown attraction are the probability that a vehicle is within the downtown, and the probability that a vehicle travels into the downtown area, respectively.

4.5.1 Results of the 2^k Factorial Analysis

In this section, we use the 2^k factorial analysis [Jai91] to determine the most relevant factors that govern Warning Message Dissemination performance. We

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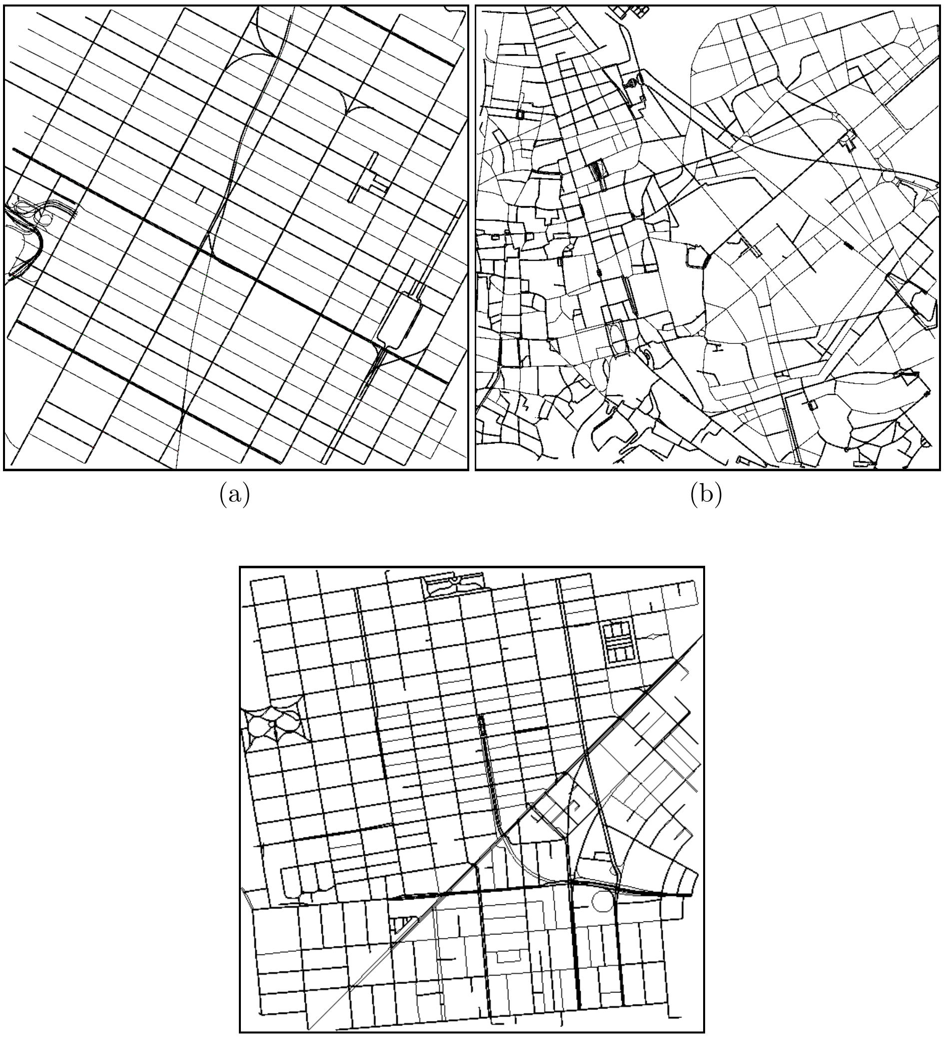
[1] All these improvements and modifications of the simulator are publicly available at http://www.grc.upv.es/software/



(a) (b)

(c)

Figure 4.2: Scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of Rome (Italy), and (c) fragment of the city of San Francisco.

Table 4.4: Parameters used for the simulations

Parameter	**Value**
roadmap size	$2000m \times 2000m$
downtown size	$1000m \times 1000m$
downtown probability	0.5
downtown attraction	0.5
warning packet size	$256B$
normal packet size	$512B$
warning messages priority	$AC3$
MAC/PHY	802.11p
maximum transmission range	$400m$

Table 4.5: Factors considered and their values

Factor	**Level -1**	**Level 1**
warning vehicles (A)	3	10
density of vehicles (B)	25 $vehicles/km^2$	100 $vehicles/km^2$
channel bandwidth (C)	$3Mbps$	$6Mbps$
broadcast scheme (D)	location-based [TNCS02]	eSBR [MFC$^+$10a]
normal messages priority (E)	AC0	AC3
periodicity of messages (F)	1 $packet/s$	20 $packets/s$
mobility model (G)	Krauss modified [KHRW02]	Wagner [Wag06]
radio propagation model (H)	Two Ray Ground	RAV [MFC$^+$10b]
roadmap (I)	New York	Rome

Table 4.6: The percentage of variation explained using the sign table method up to the combination of 2 factors. Highlighted values indicate representative variations

Factors	**Variation explained (%)**		
	warning notification time	*% of blind vehicles*	*number of packets received*
A	5.67	1.88	1.13
B	0.89	**8.61**	**28.55**
C	0.02	0.00	3.63
D	3.22	0.14	3.28
E	0.00	0.00	0.00
F	0.00	0.00	0.00
G	0.47	2.70	0.23
H	**20.72**	**49.87**	**36.26**
I	**9.35**	**14.07**	**7.92**
AB	0.37	1.30	0.05
AC	0.06	0.00	0.19
AD	0.77	0.03	0.59
AE	0.00	0.00	0.00
AF	0.00	0.00	0.00
AG	0.01	0.35	0.61
AH	0.09	1.87	0.29
AI	0.90	0.15	0.01
BC	0.05	0.00	2.39
BD	1.03	0.06	0.22
BE	0.00	0.00	0.00
BF	0.00	0.00	0.00
BG	**33.35**	0.42	0.56
BH	**14.40**	**9.09**	5.62
BI	1.06	5.37	4.21
CD	0.07	0.00	0.06
CE	0.00	0.00	0.00
CF	0.00	0.00	0.00
CG	0.00	0.00	0.05
CH	0.01	0.00	1.59
CI	0.03	0.00	0.51
DE	0.00	0.00	0.00
DF	0.00	0.00	0.00
DG	5.26	0.06	0.25
DH	0.07	0.13	1.16
DI	0.94	0.13	0.03
EF	0.00	0.00	0.00
EG	0.00	0.00	0.00
EH	0.00	0.00	0.00
EI	0.00	0.00	0.00
FG	0.00	0.00	0.00
FH	0.00	0.00	0.00
FI	0.00	0.00	0.00
GH	0.25	2.60	0.00
GI	0.94	1.17	0.60

consider 9 factors, previously presented in Section 4.4. They are listed in Table 4.5. We tag each of the factors with A, B, C, ...I accordingly, as stated in the table. Thereafter, we specify two representative and basically opposite scenarios, which are described by two different levels, i.e. Level -1 and Level 1. Each level provides different parameter values to define the scenario.

After having executed the 2^k factorial analysis, Table 4.6 indicates the percentage of variation of each studied metric explained by each factor. The more the percentage of variation, the more impact this factor has in the measured metric.

Results of our 2^k factorial analysis show that:

- The average time required to complete the propagation process is largely affected by the RPM used (H), the simulated roadmap (I), the combination of the density and the mobility model (BG), and the combination of the density and the RPM used (BH).
- The average number of blind vehicles is largely affected by the density of vehicles (B), the RPM used (H), the simulated roadmap (I), and the combination of the density and the RPM used (BH).
- The average number of packets received per vehicle is largely affected by the density of vehicles (B), the RPM used (H), and the simulated roadmap (I).

Based on the above outcome, we can state that the key factors to be accounted for when studying warning dissemination systems are the density of vehicles, the radio propagation model, and the simulated roadmap. We now perform a detailed study to evaluate the impact of the most representative factors one by one.

4.5.2 Evaluating the Impact of the Radio Propagation Model

Figure 4.3 shows the simulation results when varying the number of vehicles. We selected the TwoRay Ground, the Nakagami fading, and the RAV models. Table 4.4 shows some of the parameters used for the simulations; the rest of parameters are the following: the roadmap used is Rome, vehicles follow the Krauss mobility model, there are 3 warning mode vehicles, the periodicity of messages is 1 message per second, normal message priority is AC0, the broadcast scheme applied is eSBR, and the channel bandwidth is 6 Mbps.

According to the 2^k factorial analysis, the results show that the warning notification time is highly affected by the RPM used. When using the TRG model, information reaches 30% of the vehicles in less than 1 second, and propagation is completed in less than 8 seconds. When using the RAV model, the system needs 2 seconds to reach 30% of the vehicles, although the propagation process was completed in only 2.5 seconds.

Table 4.7 shows the percentage of blind vehicles and the number of packets received per vehicle when varying the RPM. As shown, the behavior in terms of percentage of blind vehicles and the number of packets received also highly depends on this factor. In fact, when using TRG and Nakagami fading models, there are practically no blind vehicles, while we find 60.92% of blind vehicles when using RAV. So, when the model is more realistic, more time is needed to reach the

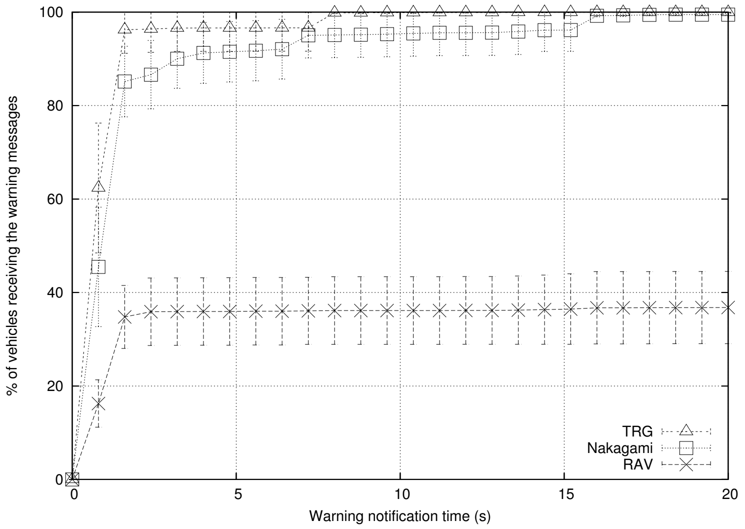


Figure 4.3: Cumulative histogram for the time evolution of disseminated warning messages when varying the RPM used.

Table 4.7: Blind vehicles and packets received per vehicle when varying the Radio Propagation Model

RPM	**% of blind vehicles**	**packets received**
TRG	0%	3417.10
Nakagami	0.1%	1291.10
RAV	60.92%	229.07

same percentage of vehicles, and thus the percentage of blind vehicles increases. This occurs because both TRG and Nakagami models are really optimistic, and they do not account for the presence of obstacles in signal propagation. Moreover, the average number of packets received per vehicle highly differs depending on the model (see Table 4.7). The number of packets received decreases considerably for RAV since signal propagation encounters more restrictions.

In order to better understand the warning dissemination process, Figure 4.4 offers a heat map of the number of messages received in one of our simulations at different time instants. Each heat map was obtained by splitting the Rome scenario in a 100 × 100 grid, meaning that each cell depicted represents 400 m^2 (20 m × 20 m).

Figure 4.4 shows the number of warning messages received in each area when using TRG and RAV radio propagation models, respectively. White areas indicate that no messages were received during the simulation (blind zones and buildings), whereas yellow areas represent locations where 5 or more messages were received. Yellow areas indicate more messages received and blue areas represent fewer mes-

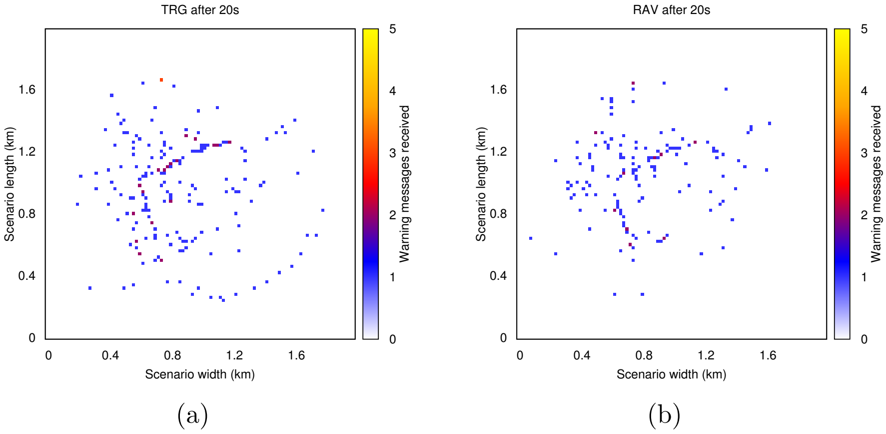


Figure 4.4: Evolution of the warning message dissemination process in the Rome scenario after 20 seconds, when using (a) the TwoRay Ground and (b) the RAV model.

sages.

When using the TRG model the dissemination process is able to reach a wider area of the scenario since the signal encounters no restrictions except the maximum transmission range. The results show that using a more realistic model tends to reduce protocol performance, allowing us to better understand the impact of buildings and obstacles along the road on car-to-car communications. Although the RAV model yields poorer performance results than TRG, it is in fact a more realistic radio propagation model, which should be considered in VANET simulations.

4.5.3 Evaluating the Impact of the Density of Vehicles

Figure 4.5 shows the simulation results when varying the number of vehicles. We selected 100, 200, 300, and 400 vehicles (i.e. 25, 50, 75, and 100 vehicles/km^2). Table 4.4 shows some of the parameters used for the simulations; the rest of parameters are the following: the roadmap used is Rome, the radio propagation model used is RAV, vehicles follow the Krauss mobility model, there are 3 warning mode vehicles, the periodicity of messages is 1 message per second, normal message priority is AC0, the broadcast scheme applied is eSBR, and the channel bandwidth is 6 Mbps.

As expected, the warning notification time is lower when the vehicle density increases. When simulating with 400 vehicles, information reaches about 60% of the vehicles in only 1.3 seconds, and the propagation process is completed in 2.4 seconds.

Table 4.8 shows the percentage of blind vehicles and the number of packets received per vehicle when varying the density of vehicles. The behavior in terms of percentage of blind vehicles highly depends on this factor. This characteristic is explained because the flooding propagation of warning messages works better

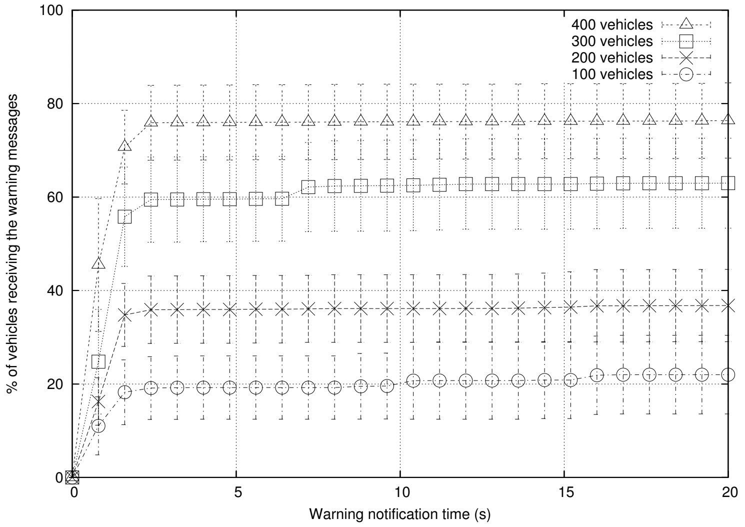


Figure 4.5: Warning notification time when varying the density of vehicles.

Table 4.8: Blind vehicles and packets received per vehicle when varying the density of vehicles

Vehicles	**% of blind vehicles**	**packets received**
100	76.63%	197.37
200	60.92%	229.07
300	36.40%	432.60
400	21.01%	949.40

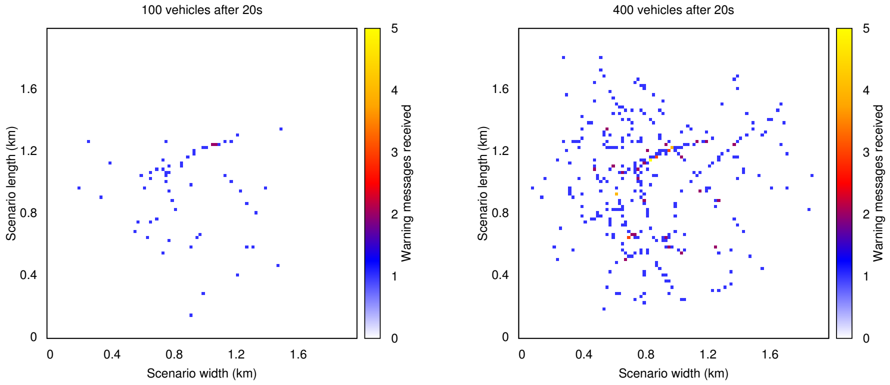
with higher vehicle densities. As for the number of packets received per vehicle, this number highly increases when increasing vehicle density.

Figure 4.6 shows the number of warning messages received in each area when simulating 100 and 400 vehicles, respectively. When only 100 vehicles are simulated the dissemination process presents a very slow progression. If the simulations include 400 vehicles, the dissemination process is able to reach a wider area of the scenario since finding appropriate rebroadcasting nodes becomes easier.

4.5.4 Evaluating the Impact of the Roadmap

This subsection presents the results obtained when varying the roadmap used. We selected scenarios from New York, San Francisco, and Rome. In Table 4.9 we present the main features of the chosen fragments of the cities.

Table 4.4 shows some of the parameters used for the simulations; the rest of parameters are the following: 200 vehicles are simulated, the radio propagation model used is RAV, vehicles follow the Krauss mobility model, there are 3 warning mode vehicles, the periodicity of messages is 1 message per second, normal message



(a)

(b)

Figure 4.6: Evolution of the warning message dissemination process in the Rome scenario after 20 seconds, when simulating (a) 100 and (b) 400 vehicles.

Table 4.9: Main features of the selected maps

Selected city map	New York (USA)	San Francisco (USA)	Rome (Italy)
Streets/km^2	175	428	695
Junctions/km^2	125	205	298
Avg. street length	122.55m	72.71m	45.89m
Avg. lanes/street	1.57	1.17	1.06

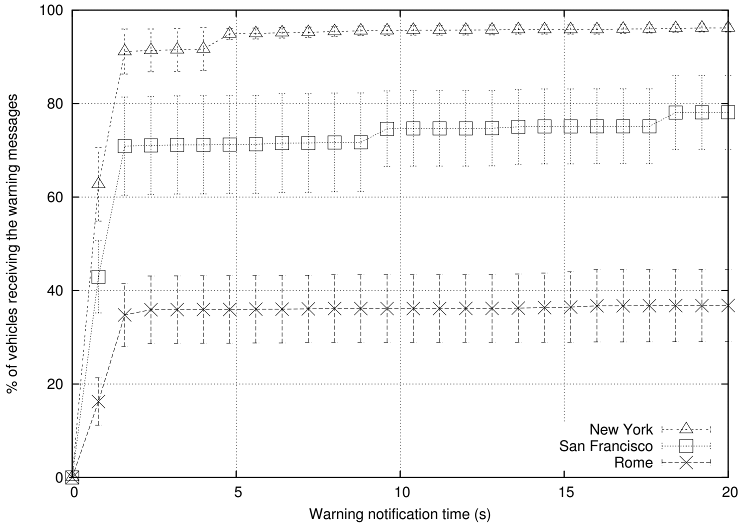


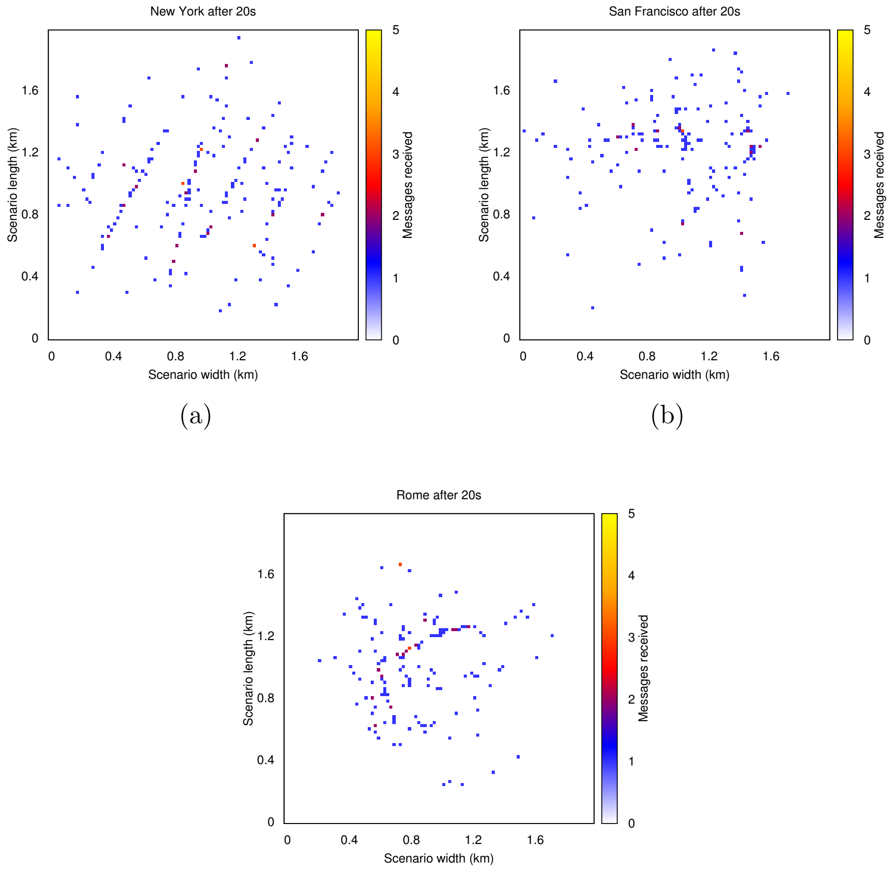
Figure 4.7: Warning notification time when varying the roadmap.

priority is AC0, the broadcast scheme applied is eSBR, and the channel bandwidth is 6 Mbps.

As shown, the warning notification time is lower when simulating the New York map (see Figure 4.7). Information reaches about 60% of the vehicles in less than 0.8 seconds, and propagation is completed in 5 seconds. When simulating the map of San Francisco, information needs more time (1.4 seconds) to reach the same percentage of vehicles. As for Rome, the propagation process was completed in only 2.4 seconds, but less than 40% of the vehicles are informed.

The behavior in terms of percentage of blind vehicles and the number of packets received also highly depends on this factor (see Table 4.10). In fact, when simulating New York, the percentage of blind vehicles is almost negligible, while we find 60.92% of blind vehicles when simulating Rome. So, when the simulated layout is more complex, the percentage of blind vehicles increases, and more time is needed to reach the same percentage of vehicles. This occurs mainly because the signal propagation is blocked by buildings. Moreover, the average number of packets received per vehicle highly differs depending on the map. Compared to New York, the number of packets received decreases considerably for San Francisco and even more for Rome since signal propagation encounters more restrictions.

Figure 4.8 shows the number of warning messages received in each area when simulating New York, San Francisco, and Rome, respectively. As mentioned before, when simulating the New York scenario the dissemination process is able to reach a wider area since streets are longer and wider, and there are fewer junctions, so messages can be disseminated more easily.



(a) (b) (c)

Figure 4.8: Evolution of the warning message dissemination process after 20 seconds, when simulating (a) New York, (b) San Francisco, and (c) Rome scenarios.

Table 4.10: Blind vehicles and packets received per vehicle when varying the roadmap

Roadmap	% of blind vehicles	packets received
New York	2.92%	1542.07
San Francisco	20.55%	885.13
Rome	60.92%	229.07

4.5.5 Lessons Learnt and Guidelines for Future Research

The 2^k factorial analysis has shown that the key factors to take into account when simulating VANETs are: (i) the radio propagation model, (ii) the density of vehicles, and (iii) the roadmap used. By evaluating the impact of each factor one by one, we confirmed the outcome of the 2^k factorial analysis. We observed that the results obtained are highly affected by the selected radio propagation model, the roadmap and the density of vehicles. The propagation of warning messages works better with simpler layouts and higher vehicle densities.

Results also showed that other important factors, such as the broadcast scheme used, the channel bandwidth, and the priority and the periodicity of messages, have little impact in the warning message delivery process. Nevertheless, we believe that these parameters could be important factors in other VANET scenarios and applications, such as live video streaming services to vehicles.

4.6 Summary

In this chapter, we identified and described the different factors to be taken into account when simulating VANETs. Since the number of possible factors can be very large, we identified the representative factors by using the 2^k factorial analysis. The purpose is to reduce the required simulation time in future research works.

The key factors affecting the delivery of warning messages were found to be the radio propagation model, the density of vehicles, and the roadmap used. Some other factors, such as the broadcast scheme used, the channel bandwidth, and the priority and the periodicity of messages, did not have a significant impact on the metrics considered in our study. We believe that the results of our analysis can save researchers' time by discarding unnecessary factors when performing simulations for VANET-related research.

Results obtained from our simulations confirmed that the selected roadmap is a crucial factor. In fact, performance parameters such as warning notification time, the percentage of blind vehicles, and the number of packets received per vehicle highly depend on it. To further reduce the scope of warning message dissemination tests made in real cities, we consider that researchers must carefully determine the scenarios to assess their proposals, ideally picking several scenarios with different street layout to validate their proposals.

Chapter 5

Improving message dissemination in Vehicular Networks

In traffic safety applications for *Vehicular Networks* (VNs), some warning messages have to be urgently disseminated in order to increase the number of vehicles receiving the traffic warning information. In those cases, redundancy, contention, and packet collisions due to simultaneous forwarding (usually known as the broadcast storm problem) are prone to occur.

In the past, several approaches have been proposed to solve the broadcast storm problem in multi-hop wireless networks such as *Mobile ad hoc Networks* (MANETs). Among them we can find counter-based, distance-based, location-based, cluster-based, and probabilistic schemes, which have been mainly tested in non-realistic simulation environments.

In this chapter, we present the *enhanced Message Dissemination based on Roadmaps* (eMDR), a novel scheme specially designed to increase the percentage of informed vehicles and reduce the notification time; at the same time, it mitigates the broadcast storm problem in real urban scenarios. We evaluate the impact that our scheme has on performance when applied to VANET scenarios based on real city maps, and the results show that it outperforms previous schemes in all situations.

5.1 Introduction

Many possible applications, ranging from inter-vehicle communication and file sharing, to obtaining real-time traffic information (such as jams and blocked streets), can benefit of the use of VANETs. In this chapter, we focus on traffic safety and efficient warning message dissemination applications, where the objective is to reduce the latency and to increase the accuracy of the information received by nearby vehicles when a dangerous situation occurs, e.g., an accident, a traffic jam, etc.

In dense wireless vehicular environments (e.g., urban scenarios), an accident may cause many vehicles to send warning messages, and using a simple blind broadcast protocol will cause all vehicles within the transmission range, receiving the broadcast transmissions, to rebroadcast those messages. Hence, a broadcast storm [TNCS02] may occur and any useful algorithm for information dissemination should incorporate mechanisms to avoid redundancy, contention and massive packet collisions due to simultaneous forwarding. In the past, several schemes have been proposed to avoid or alleviate the broadcast storm problem. However, they have been specifically proposed for MANETs and have only been validated using simple scenarios such as a highway (several lanes, without junctions) [SP08, SPC09], or a Manhattan-style grid scenario [KEOO04].

In this work, we propose a novel scheme called *enhanced Message Dissemination based on Roadmaps* (eMDR), which uses location and street map information to facilitate an efficient dissemination of warning messages in 802.11p [Tas06] based VANETs. We evaluate the performance of our eMDR proposal in a realistic urban scenario, that is, obtained from real maps of existing cities, and demonstrate how our approach could benefit drivers on the road.

This chapter is organized as follows: Section 5.2 reviews the related work on the broadcast storm problem in wireless ad hoc networks and delay-tolerant strategies proposed to improve message dissemination in intermittently connected networks. Section 5.3 describes our eMDR scheme and details its functionality using a real map scenario; for the sake of clarity, we also provide a formal definition of our proposal using set theory. Section 5.4 presents the simulation environment. Simulation results are then discussed in Section 5.5. Finally, Section 5.6 concludes this chapter.

5.2 Related Work

5.2.1 On the broadcast storm problem in wireless networks

In VANETs, intermediate vehicles act as message relays to support end-to-end vehicular communications. For applications such as route planning, traffic congestion control, and traffic safety, the flooding of broadcast messages might be considered a straightforward approach to achieve a wide-spread dissemination. However, if flooding is done blindly, broadcast storms may arise, with several disadvantages to the dissemination process [TNCS02]:

- Many redundant rebroadcasts: a physical location may be covered by the transmission ranges of several hosts, making subsequent rebroadcasts unnecessary.

- Heavy channel contention: in dense networks, after a vehicle broadcasts a message and many of its neighbors decide to rebroadcast it, these transmissions will contend with each other since all neighbors are located near the sender.

- Long-lasting message collisions: in a CSMA/CA network (like the one studied), not using specific collision detection mechanisms causes collisions to be more likely to occur and cause more damage.

Over the years, several schemes have been proposed to address the broadcast storm problem in wireless networks. In [TNCS02] we can find some of the most interesting approaches, which are the following:

1. The *Counter-based scheme.* To mitigate broadcast storms, this scheme uses a threshold C and a counter c to keep track of the number of times the broadcast message is received. Whenever $c \geq C$, rebroadcast is inhibited.

2. The *Distance-based scheme.* In this scheme, authors use the relative distance d between vehicles to decide whether to rebroadcast a message or not. It is demonstrated that, when the distance d between two vehicles is short, the *additional coverage* (AC) of the new rebroadcast is lower, and so rebroadcasting the warning message is not recommended. If d is larger, the additional coverage will also be larger.

3. The *Location-based scheme* is similar to the distance-based scheme, though requiring more precise locations for the broadcasting vehicles to achieve an accurate geometrical estimation (with convex polygons) of the AC of a warning message. Since vehicles usually have GPS systems on-board, it is possible to estimate the additional coverage more precisely. The main drawback of this scheme is the high computational cost of calculating the AC, which is related to calculating many intersection areas among several circles.

Note that all these previous schemes alleviate the broadcast storm problem by inhibiting certain vehicles from rebroadcasting, reducing message redundancy, channel contention, and message collisions. In particular, they inhibit vehicles from rebroadcasting when the *additional coverage* (AC) area is very low. Overall, [TNCS02] demonstrated that a rebroadcast can only provide up to 61% additional coverage over that area already covered by the previous transmission in the best case (on average, the additional area is of 41%).

Additional efforts to find efficient solutions to the broadcast storm problem can be found in the following works:

1. The *weighted p-persistence*, the *slotted 1-persistence*, and the *slotted p-persistence* techniques presented in [WTP$^+$07] are some of the few rebroadcast schemes proposed for VANETs. These three probabilistic and timer-based broadcast suppression techniques can mitigate the severity of the broadcast storms by allowing nodes with higher priority to access the channel as quickly as possible, but their ability to avoid storms is limited. These schemes are specifically designed for use in highway scenarios.

2. *The Last One* (TLO) scheme [SP08] tries to reduce the broadcast storm problem by finding the most distant vehicle from the warning message sender, so that this vehicle will be the only one allowed to retransmit the message. This method uses GPS information from the sender vehicle and the possible receivers to calculate the distance. Although it brings a better performance than simple broadcast, this scheme is only effective in a highway scenario because it does not take into account the effect of obstacles (e.g., buildings)

in urban radio signal propagation. Moreover, the scheme does not clearly state how a node knows the position of nearby vehicles at any given time.

3. The TLO scheme was extended using a protocol named *Adaptive Probability Alert Protocol* (APAL), which uses adaptive wait-windows and adaptive probability to transmit [SPC09]. This scheme shows even better performance than the TLO scheme, but it is also only validated in highway scenarios.
4. A stochastic broadcast scheme is proposed by [SM10] to achieve an anonymous and scalable protocol where relay nodes rebroadcast messages according to a retransmission probability. The performance of the system depends on the vehicle density, and the probabilities must be tuned to adapt to different scenarios. However, the authors only test this scheme in an obstacle-free environment, thus not considering urban scenarios where the presence of buildings could interfere with the radio signal.
5. The *Cross Layer Broadcast Protocol* (CLBP) [BCSZ10] uses a metric based on channel condition, geographical locations and velocities of vehicles to select an appropriate relaying vehicle. This scheme also supports reliable transmissions exchanging *Broadcast Request To Send* (BRTS) and *Broadcast Clear To Send* (BCTS) frames. CLBP reduces the transmission delay but it is only conceived for single-direction environments (like highway scenarios), and its performance in urban environments has not been tested.

It is easily noticeable that most existing solutions to the broadcast storm problem were only evaluated in obstacle-free environments, which are not comparable to real urban scenarios where plenty of obstacles can interfere with the signal, creating blind areas where vehicles will not receive the warning message unless intermediate forwarding nodes help to overpass the obstacle. This effect is shown in Figure 5.1, which includes an example of wireless signal propagation in a real city scenario obtained from Google Maps. If vehicle A is trying to broadcast a warning message, a basic radio propagation model will consider that all vehicles within its transmission range (vehicles B and C) would receive it. However, if we account for buildings as obstacles, there will be a blind area (dark area in the figure) that will impede vehicle C from receiving the message if vehicle B decides not to rebroadcast it.

The effect of obstacles in warning message dissemination has been addressed by other proposed schemes, specifically designed for information propagation in urban areas. Some of the most interesting pieces of work in this area are the following:

1. Costa et al. [CFMM06] presented an approach where a message propagation function encodes information about target areas and preferred routes for the message dissemination. Selecting different functions produces different routing protocols accounting for connected and disconnected situations between vehicles. These protocols show a remarkable performance in simple grid-like scenarios with low and high density of vehicles, but real maps are not used

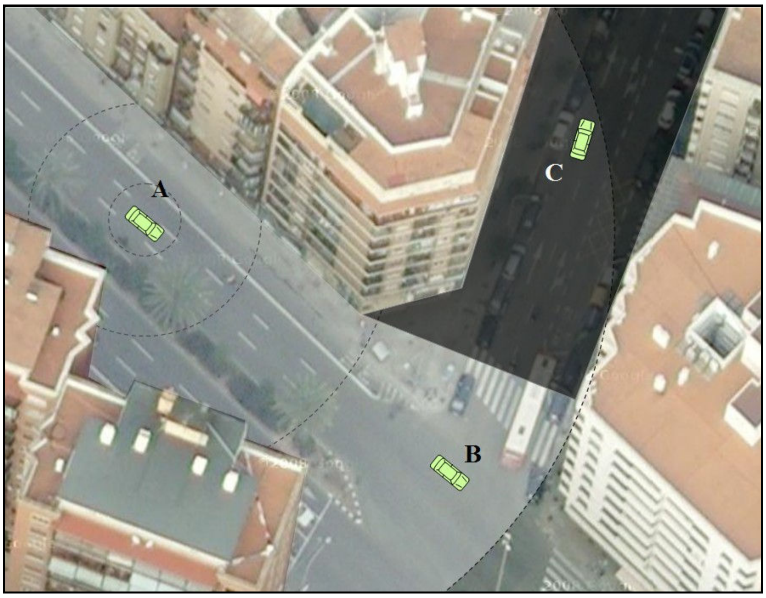


Figure 5.1: Example of wireless signal propagation in an urban scenario extracted from Google Maps. The lightest area represents the transmission range in a obstacle free environment, and the darkest area indicates the zone where the signal would not be propagated due to blocking by the nearby building.

in their simulations. Moreover, this scheme requires to define target zones for the messages to obtain optimal results, which is not always possible.

2. The UV-CAST (Urban Vehicular broadCAST) protocol [VBT10] allows reducing the broadcast storm problem while solving disconnected network problems in urban VANETs. It defines a region of interest for each VANET application, and the propagation is adapted to maximize the number of informed vehicles in this region. Despite showing good results in a scenario obtained from the city of Pittsburgh, this scheme is not compared with other protocols that could produce similar results. In addition, the density of vehicles studied is relatively low and the authors do not study its performance when there are more than 50 vehicles/km^2.

3. The RPB-MD protocol [LC12] is a message dissemination (MD) approach with a relative position based (RPB) addressing model that allows defining the intended receivers in the zone of relevance. Simulation results show high delivery ratio and low data overhead; however, the scenario used is a single bidirectional highway, and the Radio Propagation Model selected is the deterministic Two-Ray Ground. Hence, we consider that this proposal should be revised to ensure that results are comparable to real ones obtained from existing urban scenarios.

Overall we find that, even if the utility of these schemes is proven, none of them is designed to improve the dissemination and reduce the warning notification time by making use of the topology of the area where the propagation takes place, since they only use basic metrics such as the distance or the relative angles between vehicles. Our work includes additional knowledge about the roadmap to determine the optimal set of relaying vehicles.

5.2.2 VANETs as Delay-Tolerant Networks (DTN)

The vehicles in a VANET are, typically, sparsely spread across the roadmap, forming time-varying clusters of nodes due to the distance between vehicles and the effect of building blocking the wireless signal. This environment is subject to disruption, disconnection and long delay. Hence, there is not always a complete path of forwarding nodes from the source to every possible destination. Hence, VANETs can be considered a *Delay-Tolerant Network* (DTN) where routes must be found over intermittently-connected hops. Routing strategies for DTNs can be divided into two main groups: flooding strategies and forwarding strategies.

In the flooding family, each node delivers multiple copies of each message to other nodes, which act as relays, without using prior information about the network structure. [JW06] present some examples of these protocols, such as *Direct Contact* (data transmitted in one hop), *Two-Hop Relay*, and *Tree-Based Flooding* (more than two hops). In epidemic routing [VB00], all nodes will eventually receive all messages, obtaining a maximum delivery ratio at the cost of consuming network resources (channel, buffer, etc.) heavily.

Algorithms in the forwarding family require to add some knowledge about the network that is used to select the best path from the source to the destination. The simplest approach is using a distance metric to estimate the cost of delivering messages between nodes (*Location-Based Routing*). Other more sophisticated schemes such as the *Per-Hop Routing*, where the forwarding decision is made by the intermediary node which determines the next hop, and the *Per-Contact Routing*, where the routing table is recomputed each time a contact is available, are presented in [JLW05].

Again, all the existing DTN schemes have been only tested in simple scenarios, where all the nodes are in line-of-sight, and the decision whether to transmit a message or not is taken only based solely on the presence of other nodes, not on the specific layout. Including information about the scenario could help at improving the warning dissemination process, especially when integrated maps are available in the vehicles. In addition, the amount of resources needed to implement these strategies are not necessary in our proposal, since it does not store any message in queues or buffers for future relays.

Finally, our work is mainly focused on improving traffic safety by rapidly informing as many vehicles as possible. A high delay between the time when a dangerous situation takes place and its notification time makes the system become useless; thus, typical delay-tolerant schemes do not fulfill our requirements.

5.3 The enhanced Message Dissemination based on Roadmaps

In this section, we present the *enhanced Message Dissemination based on Roadmaps scheme* (eMDR) - our novel proposal which takes into account the effect that buildings have over the signal propagation to improve message dissemination in real urban scenarios. At the frequency of 5.9 GHz (i.e., the frequency band adopted by the 802.11p standard), radio signals are highly directional and will experience a low depth of penetration in urban scenarios. Hence, in most cases, buildings will absorb radio waves at this frequency, making communication only possible when vehicles are in line-of-sight.

In our model, vehicles operate in either *warning* or *normal* mode. Normal mode represents a default behavior; however, when a vehicle detects a dangerous condition, it will start operating in warning mode. Warning mode vehicles inform other vehicles about abnormal situations by sending warning messages periodically (every T_w seconds) using the highest priority at the MAC layer. We consider abnormal situations as any condition that could affect the traffic security and probably cause an accident, e.g., slippery road, a previous accident where the involved vehicles are an obstacle for the normal traffic flow, works on the road, etc. Only messages representing this situations will be produced using the highest priority, while messages for comfort and entertainment applications will be sent using lower priorities. Normal mode vehicles enable the diffusion of these warning packets and, periodically (every T_b seconds), they also send *beacons* with non-critical information such as their positions and speed. Normal messages have lower priority than warning messages, and they are not propagated by other vehicles. With respect to warning messages, each vehicle only propagates them once for each sequence number, i.e., older messages are dropped.

Algorithms 1 and 2 describe our eMDR scheme, where $vehicle_i$ identifies each vehicle in the scenario; m indicates each message sent or received by each vehicle; *warning* represents a warning message generated by a warning mode vehicle; *beacon* represents a normal message generated by a normal vehicle; T_w is the interval between two consecutive warning messages; T_b is the interval between two consecutive normal messages; P_w indicates the priority of the warning messages and P_b indicates the priority of the normal messages.

When $vehicle_i$ starts the broadcast of a message, it sends m to all its neighbors. When any nearby vehicle receives m for the first time, it rebroadcasts it by further relaying m to its neighbors. Depending on their characteristics, every vehicle repeats the $send(warning)$ or the $send(beacon)$ operations periodically with different periods (T_w and T_b, respectively). When a new message m is received, the vehicle tests whether m has already been received. To evaluate this condition, each vehicle maintains a list of message IDs. An incoming warning message ID is inserted in the list if m is received for the first time (i.e., its ID has not been previously stored in the list), and it is rebroadcasted to the surrounding vehicles only when the distance d between sender and receiver is higher than a distance threshold D, or the receiver is in a different street than the sender. We consider that two vehicles are in a different street when: (i) both are indeed in different roads (this

Algorithm 1 eMDR_Send()

```
$P_w$ = AC3;    // set the highest priority
$P_b$ = AC1;    // set default priority
$ID$ = 0;       // initialize sequence number of messages
while (1) do
    if (vehicle$_i$ is in warning mode) then
        create message $m$;
        set $m$.priority = $P_w$;
        set $m$.seq_num = $ID$++;
        broadcast warning message ($m$);
        sleep ($T_w$)
    else
        create message $m$;
        set $m$.priority = $P_b$;
        broadcast beacon ($m$);
        sleep ($T_b$)
```

Algorithm 2 eMDR_OnRecv()

```
for (every received message) do
    if ($m$ is a warning and $m$.seq_num received for the first time) then
        if (distance between sender and receiver > $D$ or both vehicles are in different streets) then
            rebroadcast($m$)
        else
            discard($m$);
            /* warnings are only rebroadcasted when additional coverage area is high or they can be propagated to different streets */
    else
        discard($m$);
        // duplicated warnings and beacons are not rebroadcasted
```

information is obtained by on-board GPS systems with integrated street maps), or (ii) the receiver, in spite of being in the same street, is near to an intersection. Hence, warnings can be rebroadcasted to vehicles which are traveling on other streets, overcoming the radio signal interference due to the presence of buildings. If the message is a *beacon*, it is simply discarded since we are not interested in the dissemination of beacons.

Figure 5.2 shows an example in a real map scenario. When vehicle A broadcasts a warning message, it is only received by neighboring vehicles B, C, and D because buildings interfere with the radio signal propagation. In this situation, if we use distance or location-based schemes, vehicles B, C, and D will rebroadcast the message only if distances $d1$, $d2$ and $d3$, respectively, are large enough (i.e., the distance is larger than the distance threshold D), or its additional coverage areas are wide enough (i.e., the AC is larger than the coverage threshold A). Supposing that only vehicle B meets this condition in our scenario, the warning message could still not be propagated to the rest of vehicles (i.e., E, F, and G).

Our eMDR scheme improves this situation as follows. In eMDR, vehicle D

Figure 5.2: The enhanced Message Dissemination based on Roadmaps scheme: example scenario taken from the city of Valencia in Spain.

will rebroadcast the warning message since vehicle D is in a different street than vehicle A. The warning message will then arrive to all the nearby vehicles (in our scenario) in only three hops. In modern *Intelligent Transportation Systems* (ITS), vehicles are equipped with on-board GPS systems containing integrated street maps. Hence, location and street information can readily be used by eMDR to ease the dissemination of warning messages. When the additional coverage area is wide enough, vehicles will rebroadcast the received warning message. However, when the additional coverage area is low, vehicles will rebroadcast warning messages only if they are in a different street. Note that distance and location-based schemes can be excessively restrictive, especially when buildings interfere with radio signal propagation. Without eMDR, warning messages will not arrive to vehicles E, F and G due to the presence of buildings.

One of the strengths of our algorithm, compared to existing protocols based on Delay-Tolerant Networks, is its low resource requirements. The eMDR scheme does not need specific buffers to store messages in the relaying nodes until a specific condition is satisfied, since all the transmissions in eMDR are performed using direct rebroadcasts when a new message arrives. New vehicles arriving to the affected area will be informed with subsequent warning messages, which are generated periodically (see Algorithm 1).

As shown, the proposed scheme relies on GPS locations to decide the next forwarding nodes. [MKH06] discovered that average urban scenarios (like those used to validate our system) produce a mean error on GPS location of about 15 meters when the street presents high buildings at both sides, but the error is

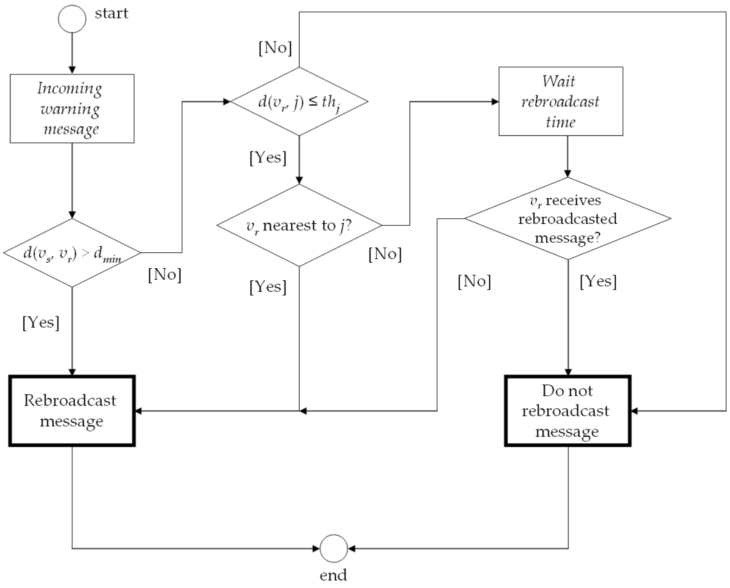


Figure 5.3: eMDR algorithm flow chart.

reduced to just 2 meters on average when there is a clearer view of the sky (since more satellites could be used to estimate the position). Additionally, using the information contained in the in-built street maps to correct the current location of the receptor (e.g., avoiding impossible positions inside of buildings) helps to reduce the mean error to just 5 meters. Moreover, [CFPFR07] focused on statistical computation to improve the positioning accuracy, generating maximum likelihood estimators under multipath conditions which are able to reduce the maximum error to 10 meters. Hence, even if the current location of the vehicle may present some degree of error, it is possible to achieve a good performance of the system.

To cope with GPS location errors, our simulations also use some defined thresholds to consider when a vehicle is near a junction, which allows reducing the influence of positioning errors. In addition, in order to ensure that at least one vehicle forwards a received warning message when it is near a junction of the roadmap and to reduce the influence of GPS errors, all vehicles within the range of a junction start a time counter with 1 second of duration after a warning message is received. If no rebroadcasted message is detected at the end of this interval, the vehicle will rebroadcast it on its own. Figure 5.3 summarizes the eMDR function, where v_s is the sender vehicle, v_r is the receiver vehicle, j is a junction of the roadmap, d represents a geographical distance function, d_{min} is the minimum rebroadcast distance and th_j is the threshold representing a junction's influence range.

5.3.1 eMDR Formal Definition

In order to obtain a clearer definition of the eMDR scheme, we now formally define it using set theory. This analysis provides a mathematical basis for the proposed scheme, which could be used for validation and analytical prediction of its behavior on a particular scenario, prior to actual simulation. Most existing schemes are not formally defined and it could lead to ambiguities, making it difficult to properly implement them, and achieve adequate comparisons with other proposed schemes.

Using the street layout to improve the warning message dissemination has not received too much attention from the academia up to now. However, due to the significant impact of buildings and other obstacles on the wireless signals present in urban scenarios, it could help overpass obstacles and reach new areas of the topology that would remain hidden otherwise. This condition is represented in the following analysis, where we focus on the streets instead of single vehicles. The objective is to determine which streets are potentially able to disseminate the message, as this will be later applied to the vehicles located on them. The results will determine the influence of the roadmap on the message diffusion.

Let us define three different sets (V, S, and J) where V represents the set of vehicles, S represents the set of streets, and J represents the set of junctions between streets. Each street is defined as a straight line linking two junctions: j_{start} and j_{end}, and thus we define two functions, *start* and *end*, that return the start and end junction's position of a street. Other defined functions are *dist*, which computes the Euclidean distance between two points of the map; *have_common_junction* to determine if two streets have a junction in common; and *ang_diff* that computes the angular difference between two streets (angle formed between the vectors representing the streets).

We call $\Omega_{j,t}$ the set of streets which are visible from the position of vehicle j (v_j) on time t. This set can be calculated as follows:

$$\Omega_{j,t} = \underbrace{\Phi_{j,t} \cup \Psi_{j,t}}_{streets\_located} \cup \underbrace{\Theta_{j,t} \cup \Xi_{j,t}}_{reachable\_streets} \tag{5.1}$$

We can decompose this set in a series of subsets:

- $\Phi_{j,t}$: set of streets in which v_j is located due to its position in the map.
- $\Psi_{j,t}$: set of streets in which v_j is located due to its proximity to a junction. A vehicle is near a junction when the distance between the junction and the vehicle is below a given threshold (th_c).

$$\begin{aligned}\Psi_{j,t} = \{\psi_i : \psi_i \in S \,\wedge\, (dist(pos(v_{j,t}), start(\psi_i)) < th_c \,\vee \\ dist(pos(v_{j,t}), end(\psi_i)) < th_c)\}\end{aligned} \tag{5.2}$$

- $\Theta_{j,t}$: set of streets reachable by v_j (i.e., it has visibility) because they are adjacent (have one junction in common) to the streets where the vehicle is located (s_k in Equation 5.3) and the angular difference between these streets and the previous ones is below a threshold (th_a).

$$\begin{aligned}\Theta_{j,t} \;=\;& \{\theta_i : \theta_i \in S \;\wedge\; (\exists s_k | s_k \in (\Phi_{j,t} \cup \Psi_{j,t}) \;\wedge \\ & have\_common\_junction(\theta_i, s_k) \wedge ang\_diff(\theta_i, s_k) < th_a)\}\end{aligned} \tag{5.3}$$

- $\Xi_{j,t}$: set of streets reachable by v_j because there is a chain of streets linked by common junctions (subset of streets S' in Equation 5.4) where the first street is visible by the vehicle (street s'_{vis}), and the angular difference between any pair of streets (s'_i and s'_j) in the chain is below a threshold (th_a).

$$\begin{aligned}\Xi_{j,t} \;=\;& \{\xi_i : \xi_i \in S \;\wedge\; \exists S' \mid S' \subseteq S \wedge \xi_i \in S' \;\wedge \\ & (\forall s'_i \mid s'_i \in S' \Rightarrow (\exists s'_j | s'_j \in S' \wedge s'_j \neq s'_i \;\wedge \\ & have\_common\_junction(s'_i, s'_j))) \;\wedge \\ & (\exists s'_{vis} \mid s'_{vis} \in S' \wedge s'_{vis} \in (\Phi_{j,t} \cup \Psi_{j,t} \cup \Theta_{j,t})) \;\wedge \\ & (\forall s'_i, s'_j \mid s'_i \in S' \wedge s'_j \in S' \Rightarrow ang\_diff(s'_i, s'_j) < th_a))\}\end{aligned} \tag{5.4}$$

Given two vehicles, v_s and v_r, where v_s is the sender and v_r is the receiver, and supposing that the radio signal is strong enough to reach v_r, the eMDR scheme will rebroadcast an incoming warning message only if the following condition is satisfied concerning the streets where the sender and the receiver are located (i.e., ω_s and ω_r respectively):

$$\begin{aligned}\exists \omega_s, \omega_r \mid \omega_s \in (\Phi_{s,t} \cup\; \Psi_{s,t}) \wedge \omega_r \in (\Phi_{r,t} \cup\; \Psi_{r,t}) \wedge \omega_r \notin \Omega_{s,t} \;\vee \\ (\exists j \mid j \in J \wedge (start(\omega_r) = j \vee end(\omega_r) = j) \;\wedge \\ (\forall v_i | v_i \in V \wedge v_i \neq v_r \Leftrightarrow dist(pos(v_i, t), j) \geq dist(pos(v_r, t), j)))\end{aligned} \tag{5.5}$$

which means that the eMDR scheme is activated (i.e., it allows that receiver to rebroadcast) when (a) the receiver is able to reach new streets unreachable for the sender ($\omega_r \notin \Omega_{s,t}$), or (b) the receiving vehicle is near to a junction (j) and it is the nearest vehicle to the center of the junction. This situation represents, in practice, the highest likability to reach new areas of the roadmap, thus informing new vehicles about dangerous situations.

5.4 Simulation Environment

Simulation results presented in this chapter were obtained using the ns-2 simulator. We modified the simulator to follow the upcoming *Wireless Access in Vehicular Environments* (WAVE) standard closely. VANET simulations must account for some extra characteristics that are specific to vehicular environments [MTC$^+$11b], and so we have extended the ns-2 simulator to implement IEEE 802.11p, which is a draft amendment to the IEEE 802.11 standard that defines enhancements to support *Intelligent Transportation Systems* (ITS) applications.

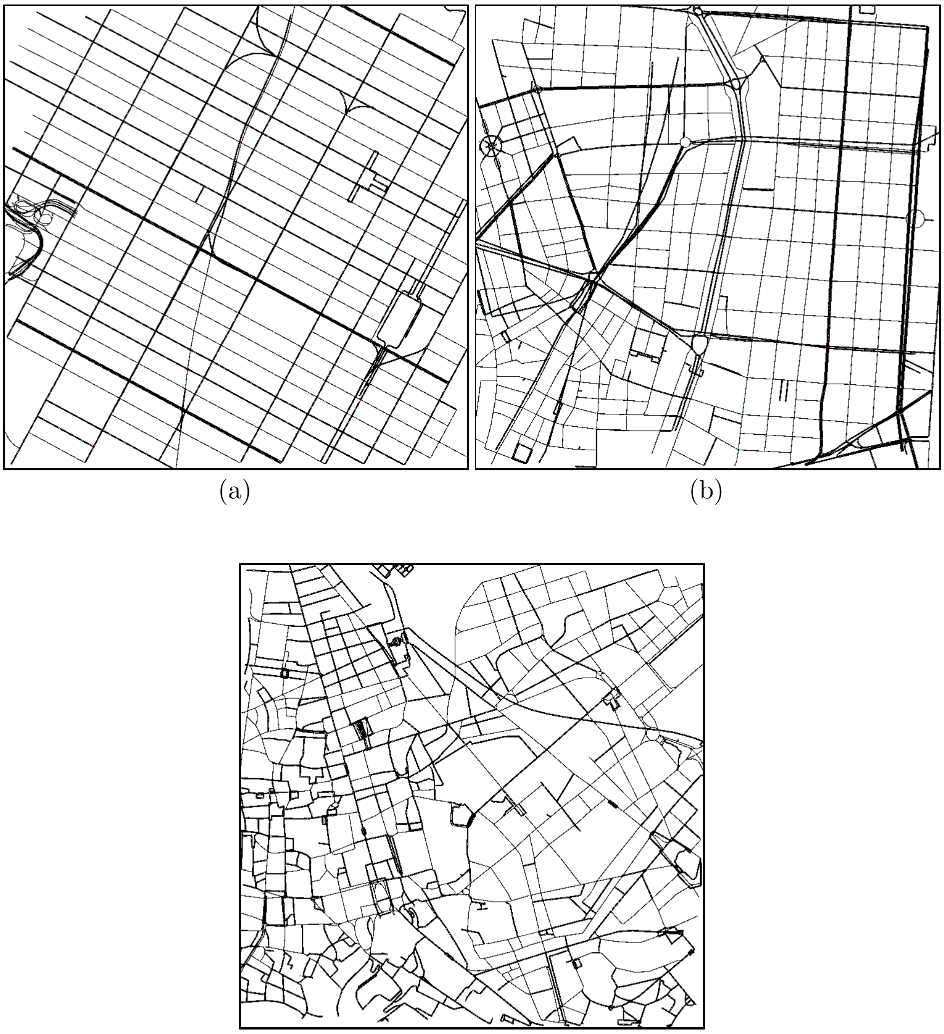
In terms of the physical layer, the data rate used for packet broadcasting was fixed at 6 Mbit/s, i.e., the maximum rate for broadcasting in 802.11p when assuming a 20 MHz channel. The MAC layer is based on the IEEE 802.11e *Enhanced Distributed Channel Access* (EDCA) *Quality of Service* (QoS) extensions. Therefore, application messages are categorized into different *Access Categories* (ACs), where AC0 has the lowest, and AC3 the highest priority. The contention parameters used for the *Control Channel* (CCH) are shown in [Eic07]. In our proposed eMDR scheme, warning messages have the highest priority (AC3) at the MAC layer, while *beacons* have lower priority (AC1).

Moreover, since we are simulating real city maps with buildings, we have modified the ns-2 simulator to model the impact of distance and obstacles in signal propagation. The Radio Propagation Model selected was the *Real Attenuation and Visibility Model* (RAV) [MFC$^+$10b], a model which proved to increase the level of realism in VANET simulations using real urban roadmaps as scenarios where buildings act as obstacles. RAV implements the signal attenuation due to the distance between vehicles based on real data obtained from experiments in different streets of the cities of Valencia and Teruel (Spain). The test were performed using D-Link DWL-AG132 [D-L11] wireless adapters, configured to use the IEEE 802.11a standard in the 5.9 GHz frequency band (the same band as 802.11p), obtaining a maximum transmission range of 400 meters. This model also accounts for the presence of buildings to determine if two vehicles are in line-of-sight, and otherwise the angular difference between the streets and the proximity to a junction are computed to approximate the effects of diffraction and reflection of the signal from the buildings.

The RAV model is an improvement over models based on path loss with stochastic fading. RAV approximates the effects of diffraction and reflection on urban junctions by using thresholds associated to each junction, considering only the vehicles close to a junction as potential receivers. The vehicles in the scenarios are also potential obstacles for wireless signals if they are large enough to block the line of sight. Nevertheless, the RAV model does not include the impact that other vehicles in the road have on the signal propagation, since simulations become too computationally expensive. Moreover, the random traffic makes it harder to find representative scenarios when so many factors are taken into account.

To perform realistic simulations, it is specially important that the chosen mobility generator could obtain a detailed microscopic traffic simulation importing network topologies from real maps. Our mobility simulations are performed with SUMO [KR07], an open source traffic simulation package which has microscopic traffic capabilities such as: collision free vehicle movement, multi-lane streets with lane changing, junction-based right-of-way rules and traffic lights. SUMO can also import maps directly from map databases such as [osm09] and [tig09].

Our simulation scenarios are based on three different roadmaps, which were obtained from real cities using OpenStreetMap. The three selected locations represent real scenarios having different streets densities and average street lengths. The chosen scenarios were the South part of the Manhattan Island from the city



(a) (b)

(c)

Figure 5.4: Scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of Madrid (Spain), and (c) fragment of the city of Rome (Italy).

Table 5.1: Main features of the selected maps

Selected city map	New York (USA)	Madrid (Spain)	Rome (Italy)
Total streets	700	1387	2780
Total junctions	500	715	1193
Avg. street length	$122.54m$	$83.08m$	$45.88m$
Avg. lanes/street	1.57	1.27	1.06

of New York (USA), the area around Paseo de la Castellana in the city of Madrid (Spain), and the area located at the North of the Colosseum in the city of Rome (Italy). All the selected maps have an extension of 4 km^2 (2 km × 2 km). Figure 5.4 depicts the street layouts used in SUMO to represent the selected scenarios, and Table 5.1 includes the main features of the chosen areas of the cities. As we can see, the New York map presents the longest streets, arranged in a Manhattan-grid style. The city of Rome represents the opposite situation, with short streets in a highly irregular layout, and the city of Madrid shows an intermediate layout, with a medium density of streets in a less irregular arrangement compared to Rome.

To generate the movements for the simulated vehicles, we used the Krauss mobility model [KWG97] available in SUMO with some modifications to allow multi-lane behavior [KHRW02]. This model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)\tau}{\tau + 1} + \eta(t), \tag{5.6}$$

where v represents the speed of the vehicle in m/s, t represents the period of time in seconds, v_1 is the speed of the leading vehicle in m/s, g is the gap to the leading vehicle in meters, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random numeric variable with a value between 0 and 1.

Our mobility simulations also account for areas with different vehicle densities. In a real town, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [MCCM08] to add points of attraction in realistic roadmaps. The simulated scenarios include a square area of 1 km^2 in the center of the map where the probability to attract vehicles is 50%. This means that about 50% of the vehicles will be moving around this area on average, while the other 50% will be spread over the remaining 3 km^2 area.

5.5 Simulation Results

In this section, we perform a detailed analysis to evaluate the impact of the proposed eMDR scheme on the overall system performance. Since performance results highly depend on the selected scenarios, and due to the random nature of the mobility model, we performed thirty simulations to obtain reasonable confidence intervals. All the results shown here have a 90% confidence interval. Each

Table 5.2: Parameter values for the simulations

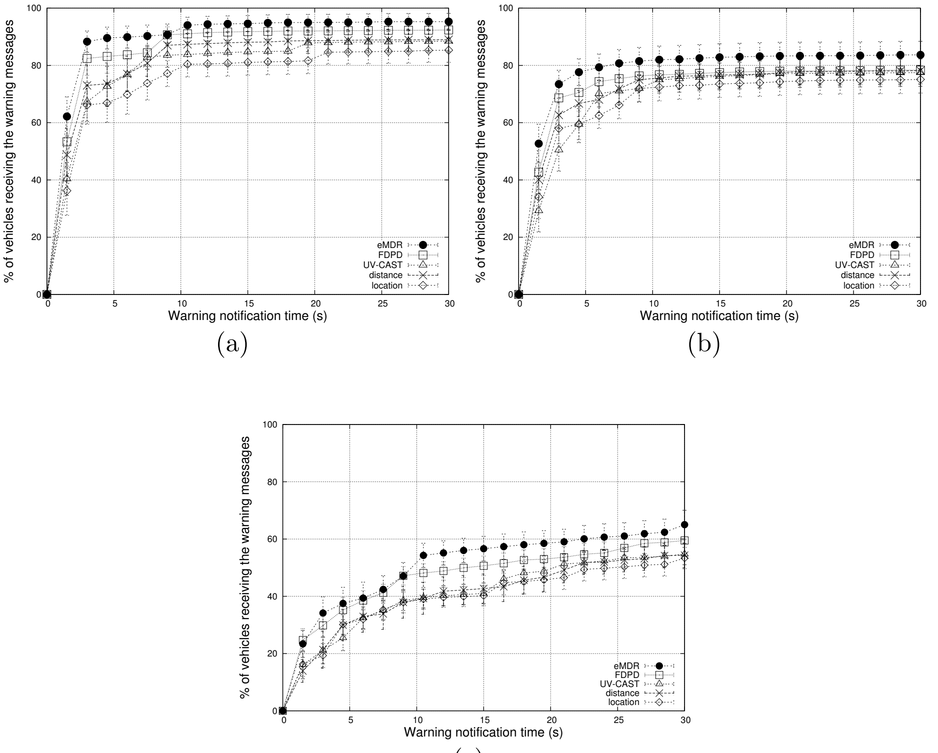
Parameter	**Value**
number of vehicles	$100, 200, 300, 400$
map area size	$2000m \times 2000m$
number of warning mode vehicles	3
warning packet size	$256bytes$
normal packet size	$512bytes$
interval between consecutive messages	2 *seconds*
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
Radio Propagation Model	RAV
maximum transmission range	$400m$
eMDR distance threshold (D)	$200m$

simulation lasted for 450 seconds, and in order to achieve a stable state, we only started to collect data after the first 60 seconds.

We evaluated the following performance metrics: (a) percentage of vehicles informed, (b) warning notification time, (c) number of packets received per vehicle, and (d) reception overhead. The percentage of vehicles informed is the percentage of vehicles receiving the warning messages sent by warning mode vehicles. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle (a vehicle that broadcasts warning messages). The reception overhead measures the average number of duplicate warning messages received at any vehicle. Table 5.2 shows the simulation parameters used.

For comparison purposes, we evaluated the performance of our eMDR proposed scheme with respect to several existing proposals. We chose a location-based scheme and a distance-based scheme from [TNCS02], which are proven to provide reasonable performance in obstacle-free environments, but their results on urban environments were not tested by the authors. From [CFMM06], we selected the *Function Driven Probabilistic Diffusion* (FDPD) algorithm, a probabilistic scheme that uses the distance between sender and receiver to determine the forwarding vehicles and reduce the broadcast storm problem. Finally, we also compared our approach with respect to the more recent UV-CAST algorithm [VBT10], especially designed for disconnected networks but with the additional cost of using more memory structures to implement a *Store-Carry-Forward* (SCF) approach. Despite some of these schemes were designed for urban environments, none of them use the information of the topology map to improve message dissemination, like our proposed eMDR algorithm.

In our study, we also vary the density of vehicles ranging from 100 vehicles (25 vehicles/km^2) to 400 vehicles (100 vehicles/km^2). The impact of other parameters affecting warning message dissemination, such as the density of vehicles and the priority and periodicity of messages, was previously studied in [MCCM09].



(a) (b)

(c)

Figure 5.5: Average notification time and percentage of vehicles informed obtained when simulating 200 vehicles and varying the simulation scenario: (a) New York, (b) Madrid, and (c) Rome.

5.5.1 Warning notification time and percentage of vehicles informed

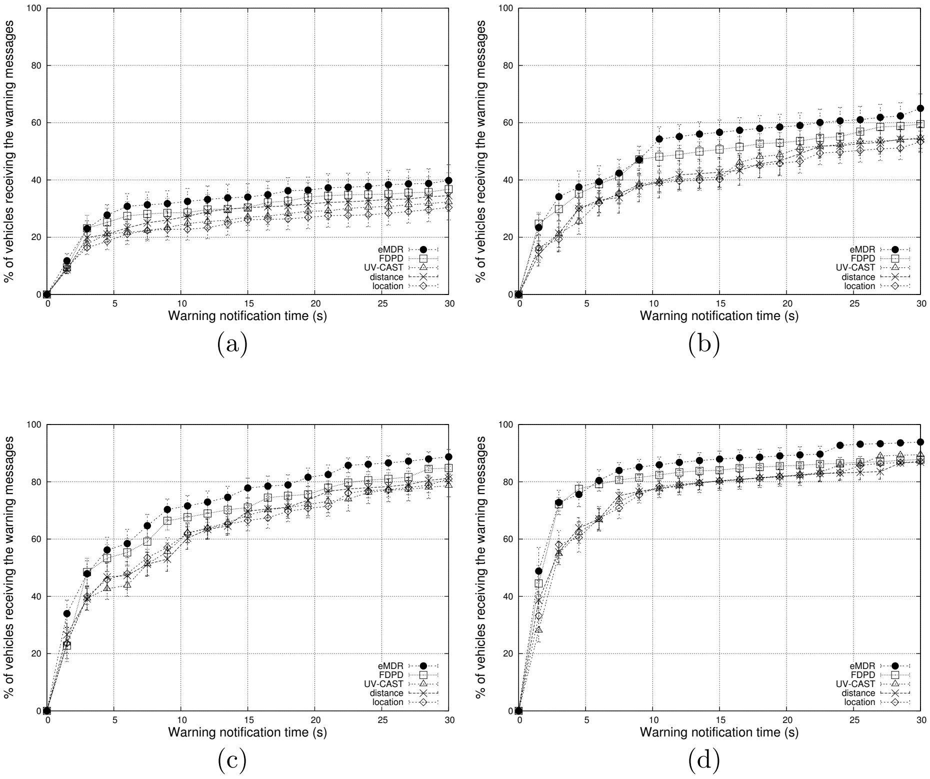
Figure 5.5 shows the impact that the selected scenario has over the warning notification time (vehicle density is 50 vehicles/km^2). The first noticeable conclusion about the results is that our proposed eMDR scheme outperforms the other four dissemination schemes in terms of both percentage of vehicles informed and warning notification time. In addition, when the eMDR scheme is used we obtain more stable results. Tseng et al. [TNCS02] demonstrated that the location-based scheme was more efficient than the distance-based scheme, since it reduces redundancy without compromising the number of vehicles receiving the warning message. The main drawback of using the location-based scheme is the high computational cost involved in evaluating the additional coverage. However, although its effectiveness is proved in obstacle-free environments, our simulations show that the location-based scheme is too restrictive in urban scenarios. Many of the vehicles which could rebroadcast the message to reach new streets of the roadmap will in fact refrain from doing so in most cases. The UV-CAST algorithm obtains similar results to the location-based dissemination, increasing at the same time the computational complexity and the amount of memory required. The FDPD scheme is the closest one to our eMDR in terms of warning notification time, although it is not able to outperform our proposal in any of the tested scenarios.

Another important effect that may be observed is that the percentage of vehicles informed is highly dependent on the specific selected scenario. In scenarios with long streets arranged orthogonally, like New York, our proposal is able to inform more than 95% of the vehicles, while in scenarios with high density of short streets only about 70% of vehicles can be informed. Using the eMDR scheme notably increases the percentage of vehicles informed, presenting a similar behavior in all scenarios where eMDR allows informing at any moment of time about 10-15% more vehicles compared to the distance-based scheme, and about 15-20% compared to the location-based and UV-CAST algorithms. The message propagation speed is also higher for eMDR, mainly during the first seconds of the dissemination process.

Figure 5.6 evaluates the impact that the network density has on the performance metrics. We vary the vehicle density from 100 to 400 vehicles, and the selected scenario is Rome. The trend is similar independently of the vehicle density, i.e., by using eMDR there is a higher number of informed vehicles, while the location-based and the UV-CAST schemes are not able to find suitable rebroadcast nodes in the selected environment. As the number of vehicles in the scenario grows, the advantage of our eMDR scheme remains evident, and so the warning notification time is reduced while the percentage of informed vehicles increases. When we select 300 vehicles, the location-based, distance-based, and UV-CAST algorithms need about 10 seconds on average to reach 60% of the simulated vehicles, the FDPD scheme requires more than 7 seconds, and the eMDR scheme only needs 6 seconds. If the number of vehicles raises to 400, it takes 4 seconds for the location-based, distance-based, and UV-CAST schemes to inform 60% of vehicles, whereas eMDR and FDPD are able to reach the same percentage in only 2.5 seconds.

5.5.2 Messages received per vehicle

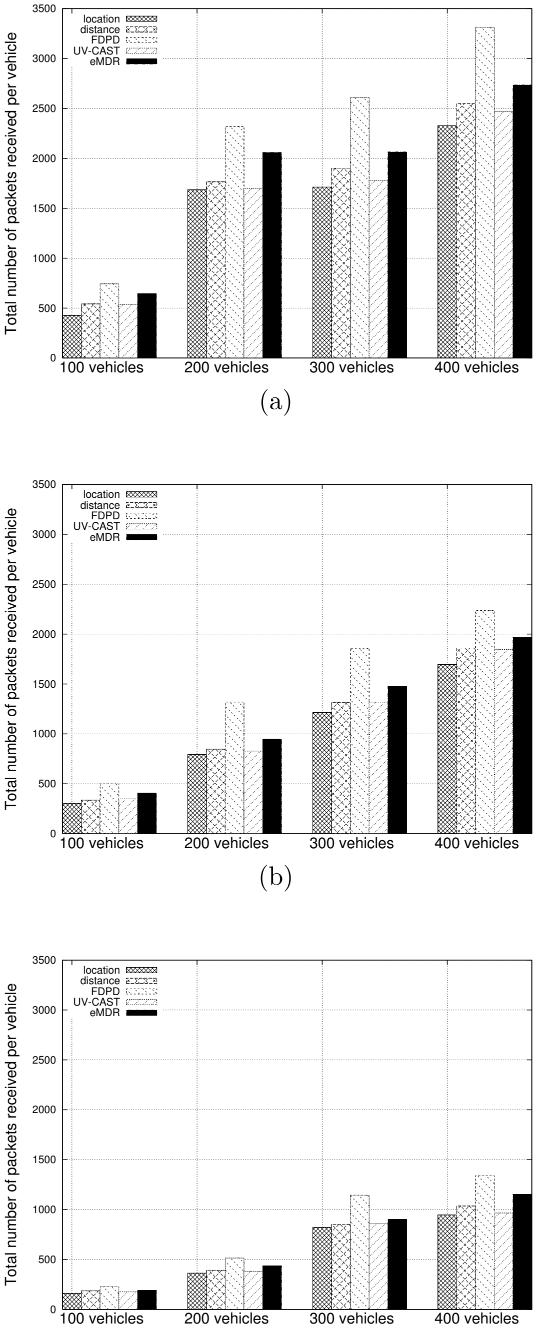
The results achieved in terms of number of messages (including beacons) received per vehicle appear in Figure 5.7. As shown, scenarios like New York, with long streets arranged in a regular way, are prone to increase the number of messages received, mainly when the vehicle density is high since many of the vehicles in the roadmap are in line-of-sight. The differences between the five schemes are not very remarkable in this scenario when the vehicle density is not very high, with 5-10% more messages received using eMDR compared to the distance-based and UV-CAST schemes, and about 10-15% compared to the location-based scheme. The number of messages received using the eMDR scheme slightly increases due to the higher probability for a vehicle to rebroadcast a message when they are close to a junction. However, these vehicles are forwarding nodes since they are the most suitable ones to increase the percentage of informed vehicles, reducing the warning notification time without notably increasing the number of messages.



(a) (b)

(c) (d)

Figure 5.6: Average notification time and percentage of vehicles informed obtained in the Rome scenario and simulating: (a) 100 vehicles, (b) 200 vehicles, (c) 300 vehicles, and (d) 400 vehicles.



(a)

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Figure 5.7: Average number of messages received per vehicle in the different scenarios: (a) New York, (b) Madrid, and (c) Rome.

The FDPD algorithm introduces the highest amount of messages in the system, (up to 25% more messages than eMDR) increasing the risk of broadcast storms.

When Simulating scenarios like Madrid, the number of messages is reduced by 20-40% in all cases, and the decrement is even more noticeable in the Rome scenario where the dissemination process only produces less than half of the messages obtained in the New York scenario. The reduction of the number of messages also decreases the differences between the five schemes, and thus the eMDR scheme is specially suitable in environments with medium and high density of streets, where the amount of messages received is low and a slight increase of the number of messages is not likely to produce broadcast storms.

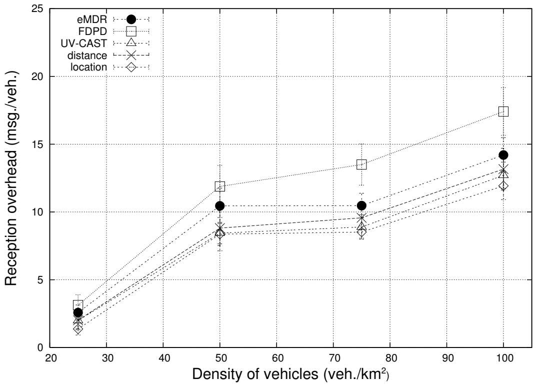
These results also lead to a significant conclusion: our proposed eMDR scheme is specially suitable for situations where the density of vehicles is not too high, mostly due to its ability to inform as many vehicles as possible without notably increasing the number of messages. This situation is likely to occur during the first steps of the mass implantation of wireless devices in vehicles, when the market penetration rate will be low, and only a reduced number of vehicles will be able to communicate with each other.

5.5.3 Reception overhead

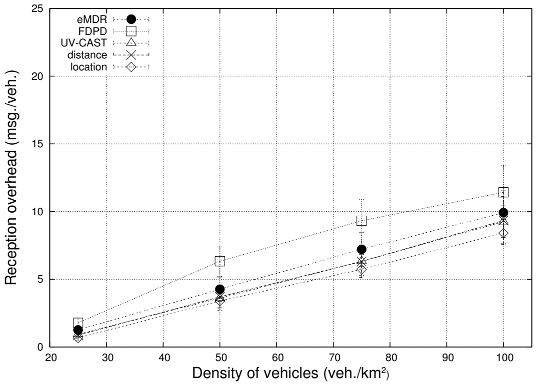
The reception overhead is a measure of the average number of duplicate messages received by any vehicle involved in our simulations. This metric is useful to determine if a protocol can effectively solve or mitigate the broadcast storm problem. Duplicate messages also represent an ineffective use of the channel bandwidth, so they must be avoided whenever possible. We include both warning messages and control beacons in our results.

Figure 5.8 shows the reception overhead measured for the different tested dissemination algorithms in a scenario with 200 vehicles (50 vehicles/km^2). As can be seen, the obtained results are again highly dependent on selected roadmap: maps with long and regular streets (e.g., New York) are prone to produce broadcast storm problems even in situations with low density of vehicles, thus producing a higher level of reception overhead. Irregular scenarios like Rome reduce the number of duplicate messages received by the vehicles since the wireless signal finds more obstacles during its propagation.

Concerning the dissemination algorithms, the FDPD scheme obtains the worst results in all simulated scenarios, and the differences increase in maps like New York. As previously shown, this algorithm presented the closest results to eMDR in terms of warning notification time. However, Figure 5.8 demonstrates that the FDPD scheme provokes a noticeable increase in the number of duplicate messages present in the network. The schemes that reduce the reception overhead in a higher degree are the location-based and the UV-CAST algorithms. Our proposed eMDR algorithm produces more reception overhead than these schemes, but this is only noticeable in the New York roadmap (where the increase is about 15%), whereas the differences are almost negligible in the other scenarios. Therefore, the eMDR scheme introduces little overhead compared to other more restrictive schemes, which is compensated by the improvement in terms of warning notification time and vehicles informed.



(a)



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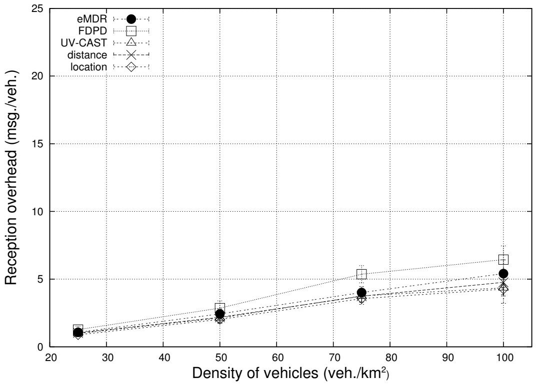


(c)

Figure 5.8: Average reception overhead in the different scenarios: (a) New York, (b) Madrid, and (c) Rome.

5.5.4 Performance under GPS inaccuracy

Our proposal is based on positioning data to determine the vehicles closest to the junctions of the roadmap to maximize the message propagation process in any urban area; thus, inaccuracy on GPS data could result in performance degradation. Modern GPS devices usually produce an average positioning error ranging from 10 to 15 meters, which could be reduce to less than 5 meters using correction techniques (as shown in Section 5.3). Despite current systems typically adopt these error correction techniques, we incorporated these errors to our simulations in order to represent extreme situations where the positioning device produces significant mistakes; our purpose is to study the impact of the GPS error on the results obtained when the eMDR scheme is active.

In particular, the average error introduced in our experiments ranges from 0 meters (perfect location) to 50 meters, representing scenarios where the positioning is difficult due to surrounding buildings or other urban structures. By applying these error margins in our simulations, we obtained the results presented in Figure 5.9.

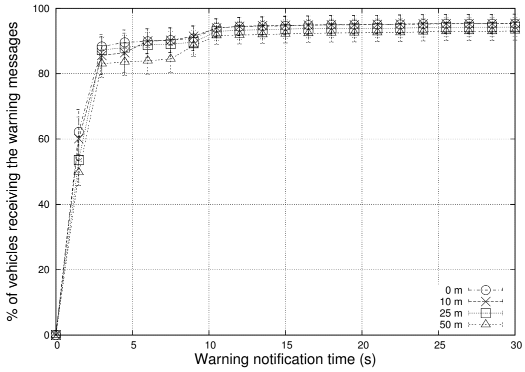
As shown, errors on GPS location cause a variation on the performance of the algorithm, which becomes more noticeable as the error increases. However, the results are similar in all the scenarios for average errors below 25 meters, and the performance is only reduced when the error exceeds this threshold. The map where the differences are more noticeable is Rome, where a 50 meters error causes 10% less informed vehicles after the first 10 seconds. In Madrid, the performance is reduced by approximately 5% when comparing the perfect location scenario and the maximum error situation. Finally, in maps like the Manhattan area in New York, the differences are hardly noticeable even for the highest level of error.

To sum up, the eMDR scheme is robust enough to support positioning errors up to 25 meters without showing performance degradation. The impact on warning notification time is more evident on irregular maps (like Rome), since the GPS error impedes an optimal selection of vehicles for rebroadcasting, making it more difficult to reach certain areas of the topology occluded by buildings. In Manhattan-like scenarios, positioning error has little effect on the eMDR performance, and thus our algorithm can cope with errors produced by tall buildings and other urban structures, typical in city downtown areas.

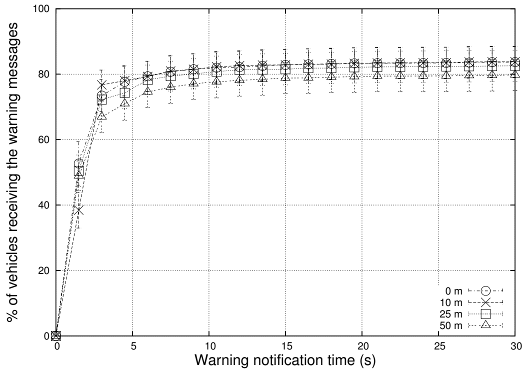
5.5.5 Performance under background traffic

In a real deployment scenario, the warning message dissemination application may coexist with different applications that generate additional traffic on the wireless channel. These applications are expected to receive less priority than the warning message dissemination process, but it is interesting to study how this additional traffic influences the propagation of warning information when sharing the same channel.

Some authors have already studied how a vehicular environment is affected by large amounts of traffic. [TMJH04] quantified via simulation the probability of reception for the two-ray ground propagation model, as well as for the Nakagami distribution in saturated environments; [CFF+12] optimized content delivery per-



(a)



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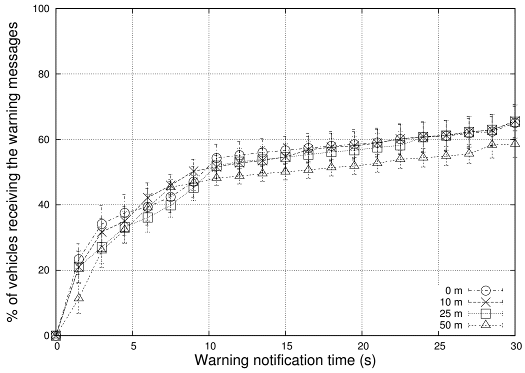


(c)

Figure 5.9: Average notification time and percentage of vehicles informed obtained when simulating 200 vehicles under different levels of GPS inaccuracy and varying the simulation scenario: (a) New York, (b) Madrid, and (c) Rome.

formance by seeking the optimal packet size in urban scenarios with added infrastructure. In our case, we study how the eMDR scheme behaves in high traffic load scenarios that would increase the contention level in the wireless channel.

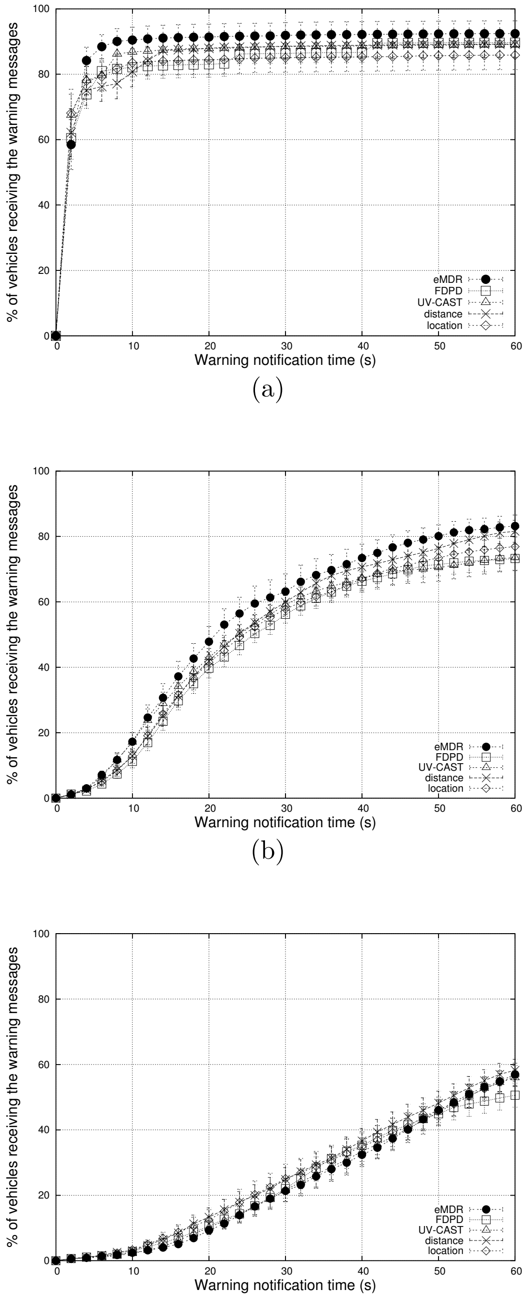
We designed an experiment with different levels of background traffic. In addition to messages related to warning message dissemination (beacons and warnings), vehicles also broadcast messages produced by other applications (road conditions, local traffic congestion, video captured by a car, etc.). We studied three different scenarios: (i) no background traffic (only the warning message dissemination is working), (ii) vehicles sending 5 messages per second with 200 KB size each, producing 1 MB/s per vehicle, and (iii) vehicles sending 5 messages per second with 400 KB size each, producing 2 MB/s per vehicle. These additional messages have the same priority as the beacons sent by normal mode vehicles (AC0), while warning messages are broadcasted with priority AC3 (the highest). Also notice that the maximum broadcasting data rate is of 6 Mbit/s.

Figure 5.10 shows the simulation results for the three studied scenarios in the Madrid roadmap when simulating 400 vehicles (100 vehicles/km^2). As shown, the dissemination speed is reduced as we increase the amount of background traffic. However, when each vehicle sends 1 MB/s of additional traffic, the eMDR scheme is still able to outperform all other algorithms. It is interesting to note that simpler schemes, such as the distance-based one, are the closest ones to the eMDR, which means that more restrictive dissemination algorithms are better at avoiding channel saturation under high background traffic load. This is confirmed when we increase the additional traffic to 2 MB/s per vehicle, where the distance-based and location-based schemes obtain the best performance. As the simulation progresses, our proposed eMDR gets closer to them, and the differences become negligible after 50 seconds, whereas the FDPD performance is reduced after the first 40 seconds. The UV-CAST algorithm achieves more stable results, but it is unable to outperform the distance-based scheme in all cases.

Therefore, we can conclude that the existence of background traffic could have a noticeable impact on warning message dissemination performance. For additional traffic load of about 1 MB/s produced by each vehicle, the eMDR is still able to obtain better results than the rest of schemes. However, higher levels of background traffic benefit simpler and more restrictive schemes, which are able to achieve good results in high contention scenarios. This effect must be taken into account when designing a critical application to be used in vehicular environments. As shown in Figure 5.10, it is not guaranteed that all vehicles receive the warning messages during the first minute after the dangerous situation under heavy background traffic. Hence, safety-critical applications should include mechanisms to adapt the dissemination schemes depending on the channel conditions to optimize their efficiency.

5.5.6 Evolution of the warning message dissemination process

In order to better understand the warning dissemination process, Figures 5.11 to 5.14 offer a visual representation of the number of messages received in one of our simulations at different time instants. Each image was obtained by splitting the

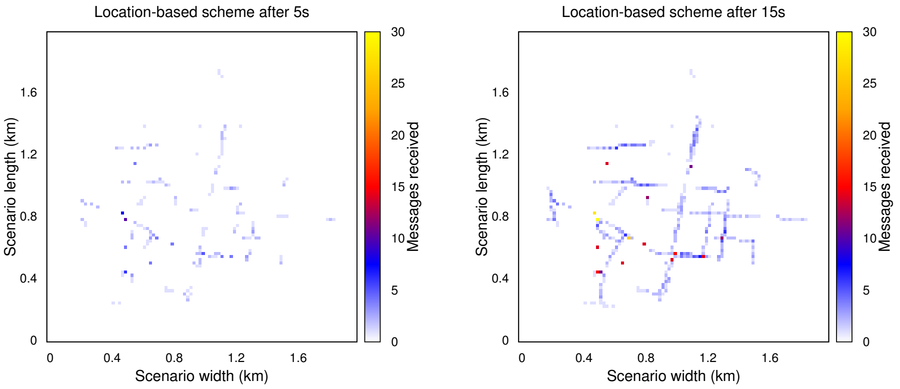


(a)

(b)

(c)

Figure 5.10: Average notification time and percentage of vehicles informed obtained when simulating 400 vehicles in the Madrid scenario under different levels of background traffic: (a) only warning message dissemination, (b) additional 1 MB/s broadcast by each vehicle, and (c) additional 2 MB/s broadcast by each vehicle.



(a) (b)

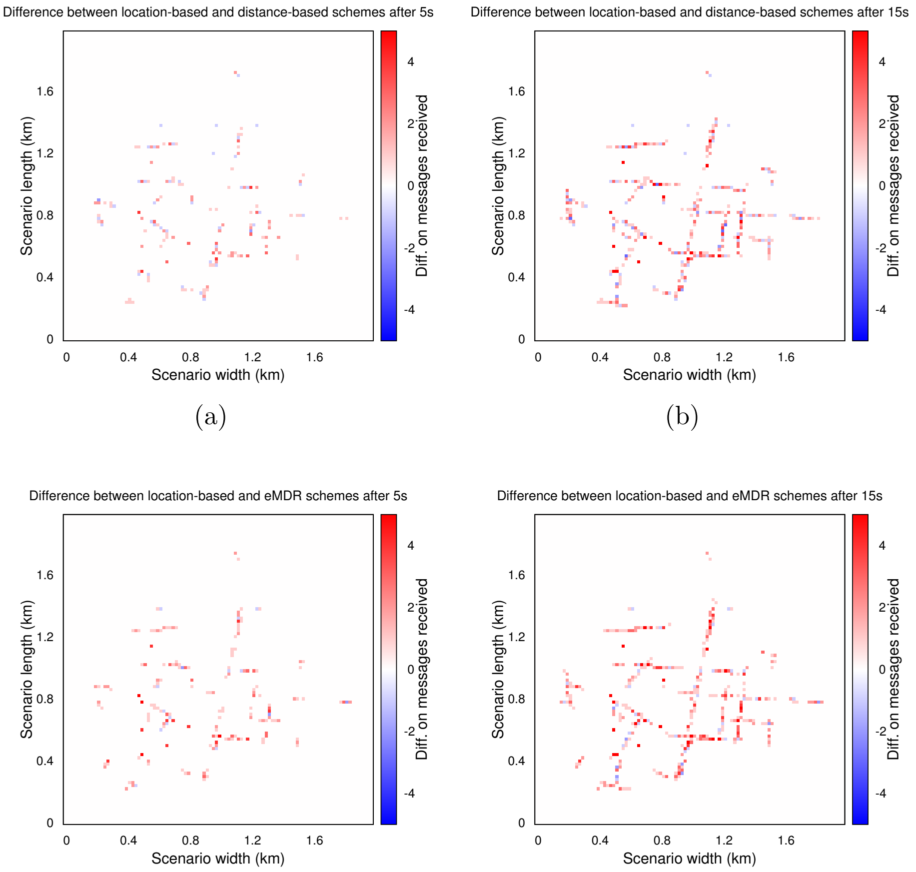
Figure 5.11: Evolution of the warning message dissemination process in the Madrid scenario simulating 100 vehicles and using a location-based scheme after (a) 5 seconds and (b) 15 seconds.

Madrid simulated scenario in a 100 × 100 grid, meaning that each cell depicted represents 400 m^2 (20 m × 20 m).

Figures 5.11 and 5.13 show the number of messages received in each area when simulating 100 and 400 vehicles, respectively, and a location-based dissemination scheme is selected. White areas indicate that no messages were received during the simulation (blind zones and buildings), whereas yellow areas represent locations where 30 or more messages were received. These results are used as a basis to illustrate the variations between the three dissemination schemes, and so the heatmaps found on Figures 5.12 and 5.14 show the differences in terms of number of messages per area for the distance-based and eMDR schemes with respect to the location-based scheme. Red areas indicate a higher number of messages received and blue areas represent fewer messages.

When only 100 vehicles are simulated (Figures 5.11 and 5.12), the location-based scheme presents a slow progression. Our proposed eMDR is able to spread messages to a larger area compared to the other two schemes. In fact, the eMDR scheme is the only one that reaches a small area in the South-West part of the map. After 15 seconds, eMDR presents the highest percentage of areas of the city informed about the dangerous situation, reaching about 7% additional area compared to the distance-based scheme and 17% more area than the location-based scheme.

If the simulations include 400 vehicles (Figures 5.13 and 5.14), the three schemes are able to reach a wider area of the scenario since it is easy to find appropriate rebroadcasting nodes. The eMDR scheme presents the highest coverage area after 5 and 15 seconds (up to 12% and 8% additional area, respectively), especially when compared to the location-based scheme which inhibits too many nodes from forwarding in an urban scenario. Our results show that the differences between



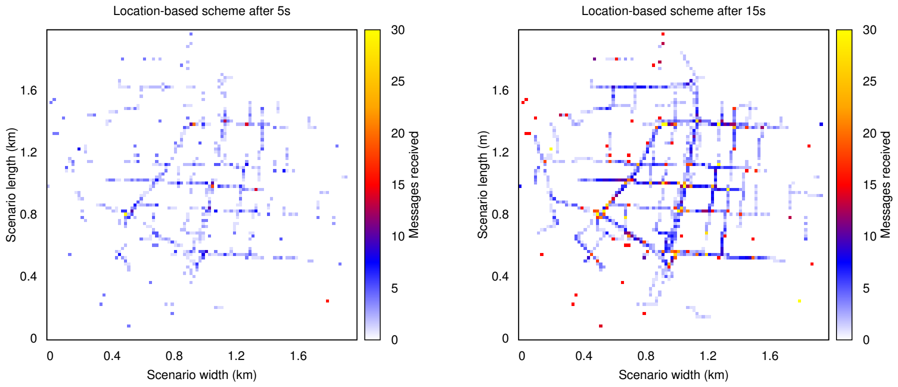
(a)

(b)

(c)

(d)

Figure 5.12: Differences in number of messages with respect to the location-based scheme simulating 100 vehicles in the Madrid scenario; using a distance-based scheme after (a) 5 seconds and (b) 15 seconds, and our proposed eMDR after (c) 5 seconds and (d) 15 seconds.



(a)

(b)

Figure 5.13: Evolution of the warning message dissemination process in the Madrid scenario simulating 400 vehicles and using a location-based scheme after (a) 5 seconds and (b) 15 seconds.

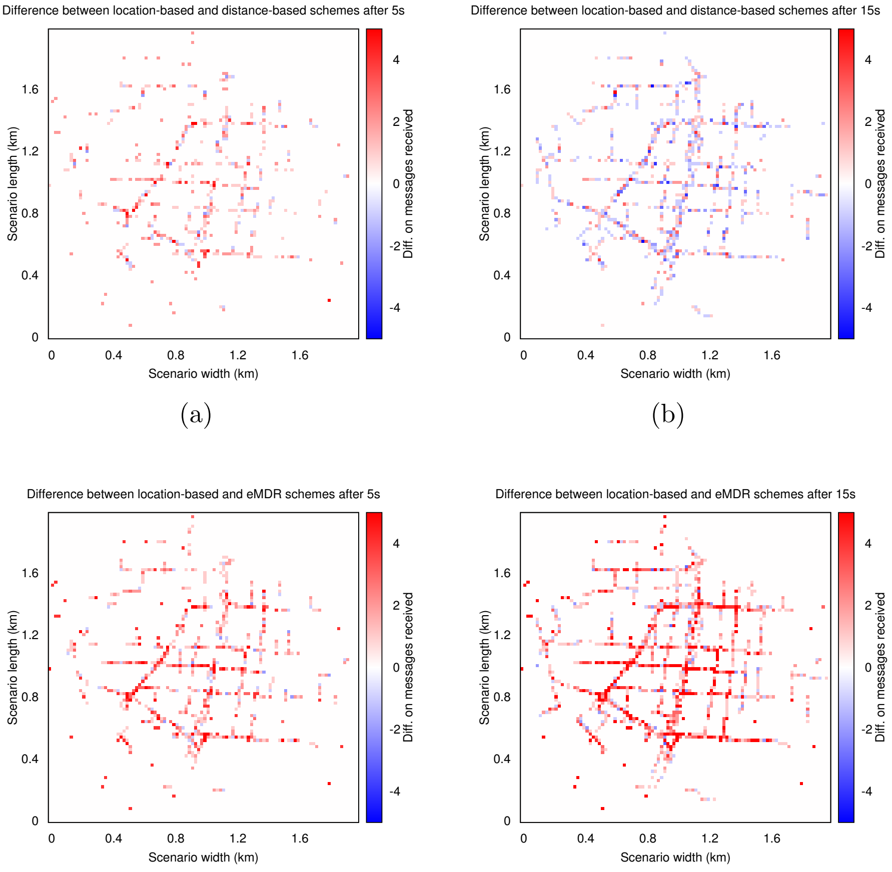
location-based and distance-based schemes when the density of nodes is high become less significant after the initial period of the simulation. However, the eMDR scheme works more efficiently from the beginning of the dissemination process, and thus this effect could be interesting to spread critical messages to neighbor vehicles as soon as possible without the risk of generating broadcast storms.

5.5.7 Overall result analysis

Our obtained results show how our proposed eMDR is able to outperform other existing dissemination schemes in different scenarios and under different vehicle densities. The closest approach to eMDR, in terms of warning notification time, is FDPD; however, the amount of messages generated using this algorithm is far greater than those generated with eMDR, increasing the probability of channel contention. The rest of studied algorithms are more restrictive than eMDR, reducing the dissemination efficiency especially in low vehicle density scenarios, since eMDR selects more appropriate forwarding nodes.

The eMDR scheme uses GPS information in the selection of forwarding nodes, but we showed how it supports positioning errors of up to 25 meters without relevant performance degradation.

Background traffic also affects the performance of the dissemination process, since additional traffic generated by other simultaneous applications will slow down the propagation of warning messages and it will increase the percentage of blind nodes. The eMDR outperforms the other selected schemes for traffic up to 1 MB/s produced per vehicle, although higher amounts of traffic benefit more restrictive schemes.



(a)

(b)

(c)

(d)

Figure 5.14: Differences in number of messages with respect to the location-based scheme simulating 400 vehicles in the Madrid scenario; using a distance-based scheme after (a) 5 seconds and (b) 15 seconds, and our proposed eMDR after (c) 5 seconds and (d) 15 seconds.

5.6 Summary

Achieving efficient message dissemination is of utmost importance in vehicular networks to warn drivers about critical road conditions. However, the broadcasting of warning messages in VANETs can result in increased channel contention and packet collisions due to simultaneous message transmissions. In this chapter, we introduce the *enhanced Message Dissemination based on Roadmaps* (eMDR) scheme to improve the performance of the warning message dissemination process in real map urban scenarios. Simulation results show that eMDR outperforms other schemes in all scenarios, yielding a higher percentage of vehicles informed, and a reduced warning notification time while not introducing broadcast storm problems; thus, we consider it suitable for real scenarios.

We find that using scenarios with different values for the density of streets and junctions, or average street length, may affect notably the results in terms of informed vehicles and messages received per vehicle. Roadmaps with irregular, short streets need a higher vehicle density for the dissemination to be effective, while using nearly orthogonal topology scenarios provides good results with very low vehicle densities. Hence, the dissemination system could be tuned to use a more or less restrictive broadcast scheme, depending on the features of the current scenario, to maximize performance.

The proposed eMDR scheme is specially suitable in situations where there are few vehicles able to forward messages, which can be due to either the low vehicle density or the low market penetration rate of wireless devices. Thus, the eMDR scheme may be successfully used during the first steps of the mass implantation of 802.11p compliant devices on vehicles. Moreover, by studying the time evolution of the message propagation process, we find that our proposal can be useful to transmit critical messages that should be spread out as soon as possible; in particular, we show that eMDR clearly outperforms all the studied proposals, i.e., the distance-based and location-based schemes, the Function Driven Probabilistic Diffusion algorithm, and the UV-CAST protocol in terms of warning notification time and percentage of informed vehicles, while exhibiting a reduced overhead.

Chapter 6

Enhancing Warning Message Dissemination in VANETs through roadmap profiling

In recent years, new applications, architectures and technologies have been proposed for Vehicular Ad hoc Networks (VANETs). Regarding traffic safety applications for VANETs, warning messages have to be quickly and smartly disseminated in order to reduce the required dissemination time and to increase the number of vehicles receiving the traffic warning information.

In the past, several approaches have been proposed to improve the alert dissemination process in multi-hop wireless networks, but none of them was tested in real urban scenarios, adapting its behavior to the propagation features of the scenario.

In this chapter, we present the Profile-driven Adaptive Warning Dissemination Scheme (PAWDS) designed to improve the warning message dissemination process. With respect to previous proposals, our proposed scheme uses a mapping technique based on adapting the dissemination strategy according to both the characteristics of the street area where the vehicles are moving, and the density of vehicles in the target scenario. Our algorithm reported a noticeable improvement in the performance of alert dissemination processes in scenarios based on real city maps.

6.1 Introduction

In the last chapter, we proved how the roadmap can be used to improve warning message dissemination by an adequate selection of forwarding nodes, which allows a faster notification of the warning messages while maintaining a low amount of traffic generated, thus minimizing broadcast storms. However, the proposed eMDR scheme is only designed to select nodes independently of the features of the street map. A step forward efficient dissemination would also use the shape and configuration of the roadmap to adapt the dissemination scheme.

Results in Chapter 4 showed how the roadmap was one of the most influential factors affecting the performance of a warning message dissemination scheme in an urban scenario. Therefore, adapting to the specific environment where the vehicles are located can be beneficial in order to reduce broadcast storm related problems, and also to increase the efficiency of the warning message dissemination process. Existing adaptive techniques for VANETs only make use of the vehicle density to adapt the process; however, this information in not enough in many situations to determine the most effective configuration. In this chapter we propose PAWDS, a *Profile-driven Adaptive Warning Dissemination System* that dynamically modifies some of the key parameters of the propagation process, such as the interval between notifications and the selected broadcast scheme, to achieve an optimal performance depending on the features of the roadmap in which the propagation takes place. Our proposal is combined with the *enhanced Street Broadcast Reduction* (eSBR) [MFC$^+$10a], to improve performance when the dissemination process takes places in real urban scenarios where the signal can be seriously affected by nearby buildings.

The rest of the chapter is organized as follows: Section 6.2 reviews the related work on the broadcast storm problem and adaptive schemes in VANETs. Section 6.3 justifies the importance of the specific roadmap in VANET simulations and shows a classification of real urban environments depending on their density of streets and junctions. Section 6.4 presents our proposed adaptive scheme. Section 6.5 shows the simulation environment used to validate our proposal. Section 6.6 presents and discusses the obtained results. Finally, Section 6.7 concludes this chapter.

6.2 Related Work

Not much research can be found in the literature about adaptive schemes for message dissemination in VANETs. In Chapter 5, we cited some of the most representative techniques for message dissemination and broadcast storm reduction. All these approaches are mainly static, and they do not use the information about the environment to increase the efficiency of the process. However, there are some remarkable attempts to adapt the dissemination strategy depending on the conditions of the environment.

Mariyasagayam et al. [MML09] proposed an adaptive forwarding mechanism to improve message dissemination in VANETs. Vehicles compute the density of neighbor nodes to calculate a forwarding sector in which vehicles are not allowed to rebroadcast the message.

The *Adaptive-ADHOC* (A-ADHOC) protocol [MRLL09] uses a variable frame length to increase channel utilization and to reduce response time. Another adaptive algorithm is the *Junction-based Adaptive Reactive Routing* (JARR) [TL09], a reactive position-based routing protocol that estimates the vehicle density of the available paths to be taken to send a message, also accounting for the direction and speed of traveling nodes in order to choose the optimal path.

Existing VANET adaptive systems only consider features related to the vehicles in the scenario such as density, speed and position to adapt the performance of the dissemination process. Moreover, most authors only evaluate their schemes using very simple scenarios and topologies that are not constrained by any obstacles, and where all the vehicles are in line-of-sight with each other. Unlike our proposal, these scenarios are not realistic enough to conclude that the proposed protocols and schemes could work efficiently in real VANET scenarios.

6.3 City profile classification

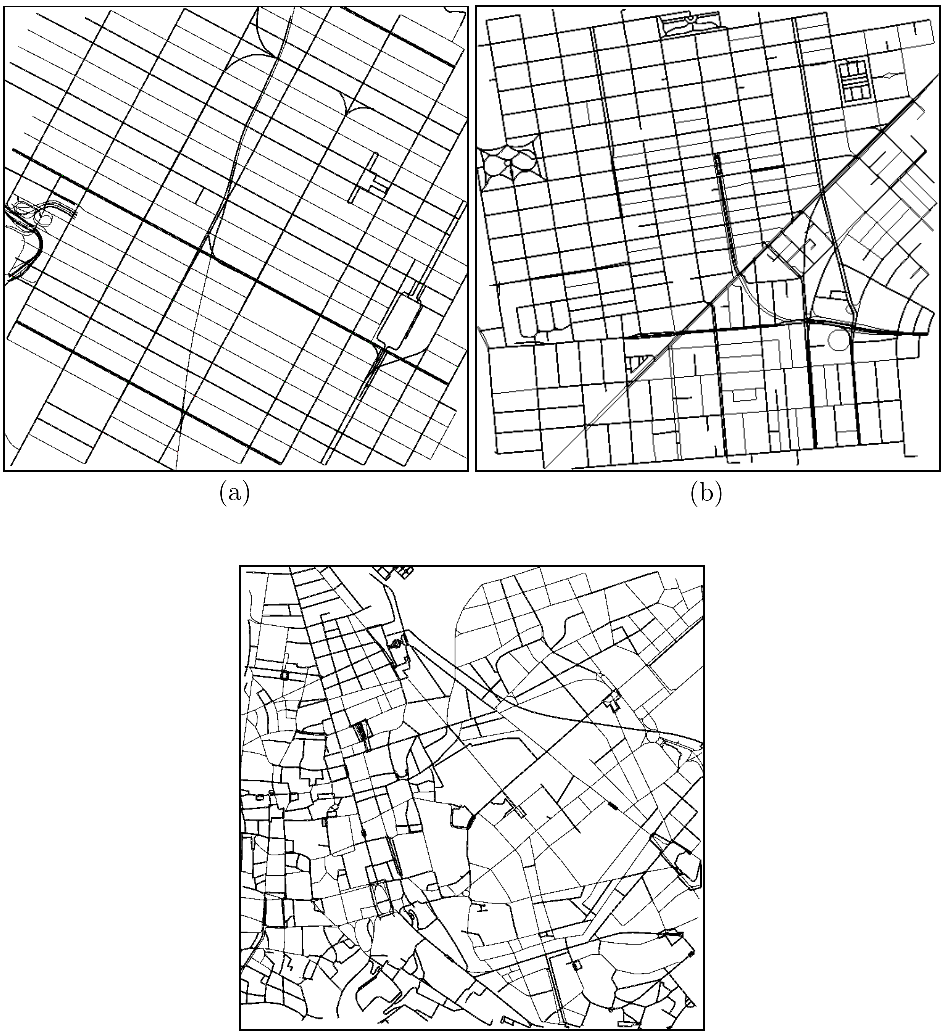
In previous works, we identified the most representative factors to be taken into account in VANET simulation using the 2^k factorial analysis [FGM+11b]. We showed that the roadmap, which serves as scenario for the warning dissemination, has an important influence in the effectiveness of the process. So, next we demonstrate the impact that the roadmap will have over the performance of dissemination processes in VANETs.

6.3.1 Importance of the roadmap in VANET simulation

The roadmap (road topology) is an important factor accounting for mobility in simulations, since the topology constrains cars' movements. Roughly described, an urban topology is a graph where vertices and edges represent, respectively, junction and road elements. Simulated road topologies can be generated ad hoc by users, randomly by applications, or obtained from real roadmap databases. Using complex layouts implies more computational time, but the results obtained are closer to the real ones. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). These approaches are simple and easy to implement in a simulator. However, layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the results obtained are likely to be similar in realistic environments.

To prove how the results in VANET simulations depends on the chosen scenarios, we selected three different roadmaps from real cities using OpenStreetMap [osm09], representing environments with different street densities and average street lengths. The chosen scenarios were the South part of the Manhattan Island from the city of New York (USA), the streets around Market Street in the city of San Francisco (USA), and the area located at the North of the Colosseum in the city of Rome (Italy). The fragments selected have an extension of 4 km^2 (2 km × 2 km). Figure 6.1 depicts the street layouts used, and Table 6.1 includes the main features of the chosen fragments of the cities. As shown, the fragment from New York presents the longest streets, arranged in a Manhattan-grid style. The city of Rome represents the opposite situation, with short streets in a highly irregular layout. The city of San Francisco shows an intermediate layout between these two in terms of regularity and average street length. We also consider the presence of open areas, such as gardens, squares, etc., to ensure that simulations produce realistic results for each individual roadmap even if not all the space between streets is filled with buildings.

We simulate the three selected scenarios using the same configuration: 200 vehicles are simulated, there are 3 warning mode vehicles, the radio propagation model used is RAV [MFC+10b], the channel bandwidth is 6 Mbps, warning mode vehicles send 1 message per second, the broadcast scheme applied is eSBR [MFC+10a], and vehicles follow the Krauss mobility model [KWG97] (further information about



(a)

(b)

(c)

Figure 6.1: Scenarios used in prior simulations as street graphs in SUMO: (a) fragment of the city of New York (USA), (b) fragment of the city of San Francisco (USA), and (c) fragment of the city of Rome (Italy).

Table 6.1: Main features of the selected maps

Selected city map	New York (USA)	San Francisco (USA)	Rome (Italy)
Streets/km^2	175	428	695
Junctions/km^2	125	205	298
Avg. street length	122.55m	72.71m	45.89m
Avg. lanes/street	1.57	1.17	1.06

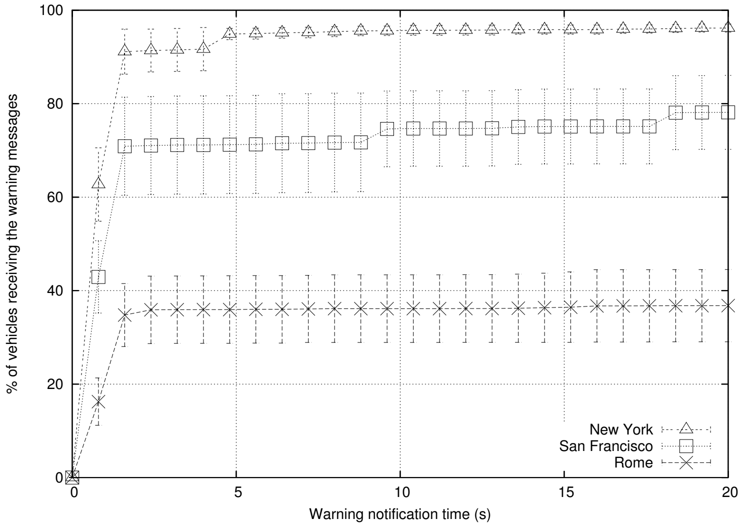


Figure 6.2: Warning notification time when varying the roadmap under the same simulation configuration.

our simulation parameters can be found in Section 6.5). Figure 6.2 shows that the warning notification time is lower when simulating the New York map. Information reaches about 60% of the vehicles in less than 0.8 seconds, and propagation is completed in 5 seconds. When simulating the map of San Francisco, information needs more time (1.4 seconds) to reach the same percentage of vehicles. As for Rome, the propagation process was completed in only 2.4 seconds, but less than 40% of the vehicles are informed.

The behavior in terms of percentage of blind vehicles, i.e., not receiving warning messages, and the number of packets received also highly depends on this factor (see Table 6.2). In fact, when simulating New York, the percentage of blind vehicles is almost negligible, while we find 60.92% of blind vehicles when simulating Rome. So, when the simulated layout is more complex, the percentage of blind vehicles increases, and more time is needed to reach the same percentage of vehicles. This occurs mainly because the signal propagation is blocked by buildings. Moreover, the average number of packets received per vehicle highly differs depending on the city map. Compared to New York, the number of packets received decreases

Table 6.2: Blind vehicles and packets received per vehicle when varying the roadmap

Roadmap	% of blind vehicles	packets received
New York	2.92%	1542.07
San Francisco	20.55%	885.13
Rome	60.92%	229.07

considerably for San Francisco and even more for Rome since signal propagation encounters more restrictions.

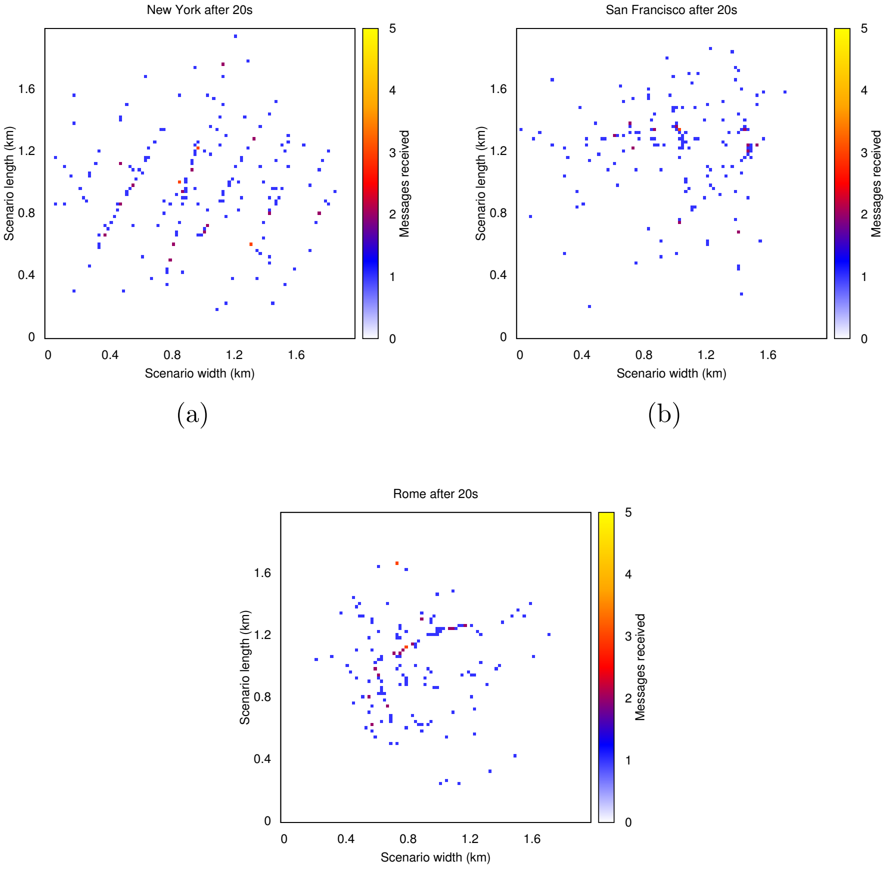
Figure 6.3 shows the number of warning messages received in each area when simulating New York, San Francisco, and Rome, respectively. As mentioned before, when simulating the New York scenario the dissemination process is able to reach a wider area since streets are longer and wider, and there are fewer junctions, so messages can be disseminated more easily.

6.3.2 Roadmap layout clustering

We can easily deduce from the previously presented results that the selected topology has a great influence on the obtained results in a VANET simulation. Hence, aiming at using the specific features of the scenarios to improve performance, a wide set of maps from several existing cities have been tested to obtain a classification that allows warning dissemination to dynamically adapt its parameters based on the scenario type. The chosen area tries to represent the overall layout of the streets in each city, and is usually taken from the downtown area. We selected cities from Europe (Berlin, Lisbon, London, Milan, Moscow, Munich, Paris, Rome, Seville, Teruel, Valencia), Asia (Beijing, Hong Kong, Istanbul, Kuala Lumpur, New Delhi, Seoul, Shanghai, Taipei, Tokyo), North America (Boston, Chicago, Los Angeles, Manhattan, Mexico City, New York, San Francisco, Washington DC), South America (Bogotá, Buenos Aires, Montevideo, Rio de Janeiro), and Africa (Cape Town, Casablanca, Cairo, Kinshasa, Rabat).

Figure 6.4 shows the number of streets and junctions present in a 4 km^2 square area in these cities. As shown, the relationship between the number of streets and the number of junctions is almost linear, in an approximate ratio of 2 streets per junction. Since three different groups of cities can be distinguished in the figure, the well-known *k-means* clustering algorithm [Mac67] was used with a number of clusters $k = 3$ to obtain a precise classification of the cities. By using the results of the clustering process in Figure 6.4, we can classify a new city according to the cluster whose centroid is the nearest (using the Euclidean distance as a measure). We can classify existing cities by their street profiles into:

- *Simple layouts*: maps with low density of streets and junctions that are usually arranged orthogonally like a Manhattan style grid. Examples of these cities are New York (USA), Rio de Janeiro (Brazil) and Seoul (South Korea).



(a) (b) (c)

Figure 6.3: Evolution of the warning message dissemination process after 20 seconds, when simulating (a) New York, (b) San Francisco, and (c) Rome scenarios.

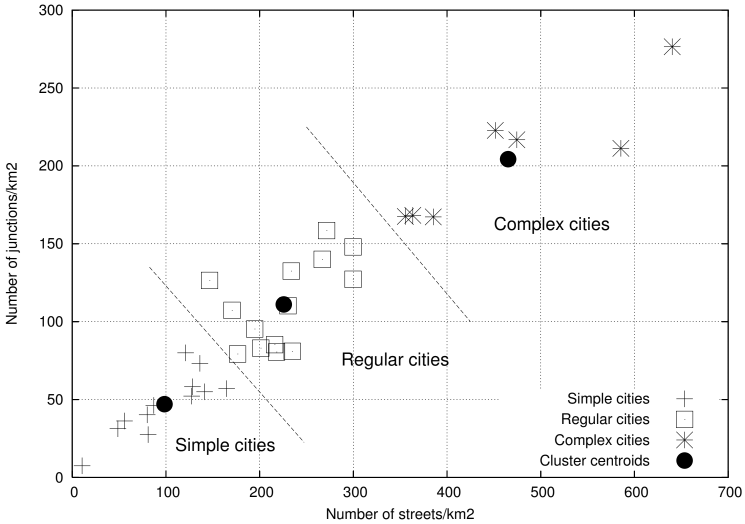


Figure 6.4: Classification of different cities based on the density of streets and junctions.

Table 6.3: Map Profiles Classification

Roadmap profile	**Street and junction density**	**Cluster centroid**		**Max. acceptable vehicle density**
		Streets/ km^2	**Junctions/ km^2**	
Simple	Low	216.79	99.57	25 veh./km^2
Regular	Medium	480.96	223.70	50 veh./km^2
Complex	High	818.23	388.80	75 veh./km^2

- *Regular layouts*: maps with medium density of streets and junctions. Some cities in this group are San Francisco (USA), Madrid (Spain) and Hong Kong (China).
- *Complex layouts*: maps with high density of streets and junctions. Cities which belong to this group are Rome (Italy), London (UK), and Tokyo (Japan).

As shown, each one of the previously studied roadmaps (Figure 6.1) belongs to different street profiles clusters, causing noticeable differences in the performance of warning message dissemination. Table 6.3 summarizes the classification process of the studied cities, and shows the location of the centroid of the cluster assigned to each profile. It also shows the maximum vehicular density accepted in our simulations before the number of received messages grows excessively, thereby provoking broadcast storm problems with the base configuration used in the previous section. Results show that the roadmap which serves as scenario for the warning dissemination has a considerable influence in the effectiveness of the process. Moreover, we can differentiate three groups of city profiles in which the propagation process is likely to behave in a similar way. This is the basis for our proposal, the *Profile-driven Adaptive Warning Dissemination Scheme* (PAWDS), which is based on the fact that the effectiveness of the alert dissemination can be increased if vehicles determine the city profile of their current area.

6.4 The Profile-driven Adaptive Warning Dissemination System (PAWDS)

In [FGM$^+$11c] we demonstrated that the propagation process is likely to behave in a similar way when vehicles are moving in different cities as long as they belong to a same roadmap profile group (i.e., dissemination processes behave similarly in New York and Seoul, but differently than in San Francisco, Rome, or Tokyo). This is the basis for our proposal: the effectiveness of the alert dissemination can be increased if vehicles determine the city profile of their current area, and adapt their dissemination schemes accordingly.

To enhance the performance of the alert dissemination, we propose to tune the warning dissemination system using the information provided by the on-board GPS system (with integrated street maps from the city that is being evaluated) to determine the profile of the city and select the most effective parameters to achieve a proper warning message dissemination. Previously proposed schemes use a fixed set of parameter values, or they only consider the vehicle density to adapt the system. Instead, our algorithm can obtain a preliminary estimation of the parameters to use just by checking the map of the area where the vehicle is located in.

It is also beneficial to use a more restrictive dissemination scheme when the vehicle density is high to avoid broadcast storm problems. Hence, it is helpful to estimate the vehicle density in the surrounding area to maximize the effectiveness of the dissemination scheme. This estimation is done in our system using the beacons periodically sent among the vehicles with information about their position and speed. Moving vehicles use this information to compute the predicted position of nearby vehicles in order to determine how many vehicles are there in their proximities.

We observed that three parameters have a notable influence in both warning notification time and the induced overhead in terms of number of messages received in the dissemination process. These three parameters are: (a) the interval between consecutive messages, (b) the broadcast scheme used, and (c) the minimum rebroadcast distance. If we vary their values, we observed how the target performance indexes of our scheme are mutually exclusive, i.e. we cannot increase the percentage of notified vehicles and decrease the notification time at the same time if we do not increase the number of messages involved, and vice versa. Hence, our scheme must be able to find a balance among all these metrics. To facilitate the selection of the parameters, we have defined three adaptive working modes specially adapted to different situations. The dissemination scheme will select the most suitable one depending on the profile of the roadmap and the estimated

Algorithm 3 PAWDS() pseudo-code

```
use standard dissemination mode
while (1) do
    obtain street-profile from the current map
    estimate vehicle-density from messages sent by neighbor vehicles
    if (street-profile is Simple) then
        if (vehicle-density > 25 vehicles/km$^2$) then
            use reduced dissemination mode
        else
            use standard dissemination mode
    else if (street-profile is Regular) then
        if (vehicle-density > 50 vehicles/km$^2$) then
            use standard dissemination mode
        else
            use full dissemination mode
    else if (street-profile is Complex) then
        if (vehicle-density > 75 vehicles/km$^2$) then
            use standard dissemination mode
        else
            use full dissemination mode
    sleep($T_r$);
```

Table 6.4: Working Modes in the Adaptive Algorithm

Working mode	**Interval between consec. messages**	**Broadcast scheme**	**Min. rebroadcast distance**
Full dissemination	2 seconds	counter-based	—
Standard dissemination	4 seconds	eSBR	200 m.
Reduced dissemination	5 seconds	distance-based	250 m.

vehicle density. The defined operation modes are:

- *Full dissemination*: vehicles move in low density areas, and hence they can send a high number of messages with little danger in term of inducing broadcast storm problems.
- *Standard dissemination*: vehicles try to achieve a balance between the number of informed vehicles and the number of messages received.
- *Reduced dissemination*: vehicles send as few messages as possible due to the high density of vehicles detected in the area that could easily lead to broadcast storm problems.

Table 6.4 contains the parameter values used in each working mode. Several preliminary simulations representing different environments were performed in order to select the sets of values with an optimal behavior in different situations.

Table 6.5: Main features of the additional maps

Selected city map	Los Angeles (USA)	Madrid (Spain)	London (UK)
Streets/km^2	263	479	878
Junctions/km^2	77	284	408
Avg. street length	$111.58m$	$67.23m$	$45.38m$
Avg. lanes/street	1.45	1.26	1.15
Profile cluster	Simple	Regular	Complex

Algorithm 3 summarizes the PAWDS algorithm, where the values of vehicle density are obtained from Table 6.3, and T_r is the interval between reconfigurations of the system (30 seconds).

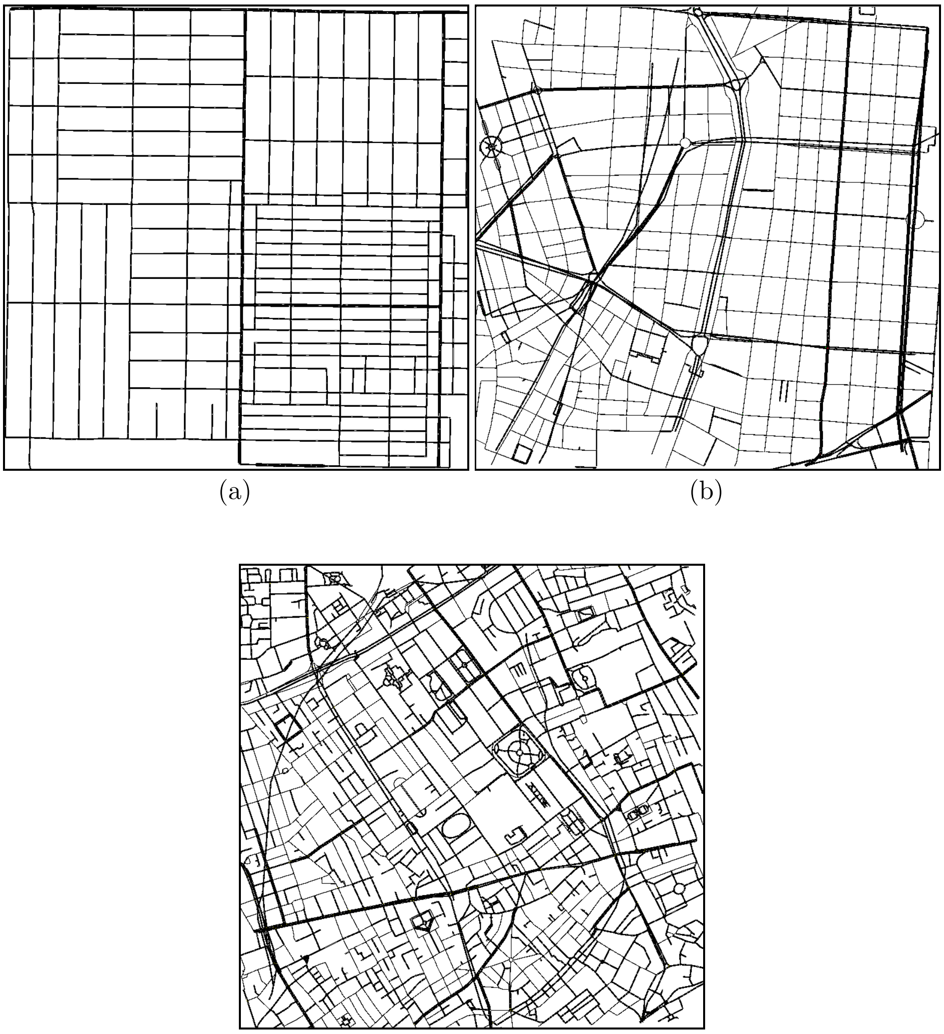
According to our algorithm, PAWDS is configured to use the *Full dissemination* mode in low vehicle density scenarios to inform as many vehicles as possible, except when the density of streets and junctions is low (Simple profile cities), which causes the number of messages to grow excessively. In this situation, the *Standard dissemination* is more suitable.

When the vehicle density is high, the *Full dissemination* mode should not be used, as it produces a huge amount of messages and it could easily yield broadcast storms. The *Standard dissemination* mode can be appropriate in most of cases, but the number of messages received when the street density is too low (Simple profile cities) may be excessive. In these cases, the *Reduced dissemination* mode is the most suitable one.

6.5 Simulation Environment

Since deploying and testing VANETs involves high cost and intensive labor, simulation is a useful alternative prior to actual implementation [MTC$^+$11b]. Simulation experiments have shown that different dissemination strategies are associated with a different behavior in an urban environment, but they also showed that the features of each specific scenario determine the efficiency of the process. To prove how maps from the same cluster produce similar results using them as simulation scenarios, we selected three street maps in addition to those presented in Figure 6.1. These additional roadmaps are taken from different cities and they belong to different clusters, as shown in Table 6.5. The scenarios were obtained from OpenStreetMap, each one representing 4 km^2 of square area.

Figure 6.5a shows the area between Martin Luther King Boulevard and West Slauson Avenue in the city of Los Angeles (CA, USA), which belongs to the Simple layout cluster. It has a very regular street layout where the simulations should have a similar behavior compared to simulations performed using synthetic Manhattan-grid layouts. The street map around Paseo de la Castellana in the city of Madrid (Spain), shown in Figure 6.5b, is classified as a Regular profile. It is an example of town with medium density of streets and junctions, arranged in a complex layout different from typical Manhattan-grid layouts. Finally, Figure 6.5c presents the area around Russell Square in the city of London (UK), which contains an



(a) (b)

(c)

Figure 6.5: Additional scenarios used in our simulations as street graphs in SUMO: (a) fragment of the city of Los Angeles (USA), (b) fragment of the city of Madrid (Spain), and (c) fragment of the city of London (UK).

extremely high density of streets and junctions, and therefore it belongs to the Complex topologies cluster. We will study warning message dissemination efficiency in these scenarios and we will compare the results with those obtained with the formerly presented roadmaps.

Simulations to test our experiments were done using the ns-2 simulator [FV00], modified to include the IEEE 802.11p [IEE10] standard so as to follow the upcoming WAVE standard closely. In terms of the physical layer, the data rate used for packet broadcasting is of 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.

The simulator was also modified to make use of our *Real Attenuation and Visibility* (RAV) scheme [MFC^{+}10b], which proved to increase the level of realism in VANET simulations using real urban roadmaps in presence of obstacles. In order to mitigate the broadcast storm problem, our simulations use: (a) the counter-based scheme [TNCS02], (b) the distance-based scheme [TNCS02], and (c) the *enhanced Street Broadcast Reduction* (eSBR) scheme [MFC^{+}10a], which employs a minimum distance under which vehicles are refrained from forwarding, except if they are close enough to a junction.

With regard to data traffic, vehicles operate in two modes: (a) warning mode, and (b) normal mode. Warning mode vehicles inform other vehicles about their status by sending warning messages periodically with the highest priority at the MAC layer; each vehicle is only allowed to propagate them once for each sequence number. Normal mode vehicles enable the diffusion of these warning packets and, periodically, they also send *beacons* with information such as their positions, speed, etc. These periodic messages have lower priority than warning messages and are not propagated by other vehicles.

Mobility is performed with CityMob for Roadmaps (C4R)[1], a mobility generator which can import maps directly from OpenStreetMap. C4R is based on SUMO [KR07], an open source traffic simulation package. Our mobility simulations account for areas with different vehicle densities. In a realistic town setting, traffic is not uniformly distributed; there are downtowns or points of interest that may attract vehicles. Hence, we include the ideas presented in the *Downtown Model* [MCCM09] to add points of attraction in roadmaps. Hence, we include points of attraction in the roadmaps used in our simulations. To generate the movements for the simulated vehicles, we used the Krauss mobility model [KWG97] (with some modifications to allow multi-lane behavior [KHRW02]) found in SUMO. The Krauss model is based on collision avoidance among vehicles by adjusting the speed of a vehicle to the speed of its predecessor using the following formula:

$$v(t+1) = v_1(t) + \frac{g(t) - v_1(t)\tau}{\tau + 1} + \eta(t), \tag{6.1}$$

where v represents the speed of the vehicle in m/s, t represents the period of time in seconds, v_1 is the speed of the leading vehicle in m/s, g is the gap to the

---

[1] `C4R` is available at http://www.grc.upv.es/software/

Table 6.6: Parameter Values Used for the Simulations

Parameter	**Value**
number of vehicles	$100, 400$
simulated area	$2000m \times 2000m$
number of warning mode vehicles	3
warning message size	$256B$
normal message size	$512B$
warning message priority	$AC3$
normal message priority	$AC1$
MAC/PHY	802.11p
maximum transmission range	$400m$
mobility generator	C4R
mobility models	Krauss [KHRW02] and Downtown model [MCCM09]
maximum speed of vehicles	$23\ m/s \approx 83\ km/h$
maximum acceleration of vehicles	$1.4\ m/s^2$
maximum deceleration of vehicles	$2.0\ m/s^2$
driver reaction time (τ)	$1\ s$

leading vehicle in meters, τ is the driver's reaction time (set to 1 second in our simulations) and η is a random numeric variable with a value between 0 and 1.

All results represent an average over several executions with different random scenarios, presenting all of them a degree of confidence of 90%. Each simulation run lasted for 450 seconds, and we only collect data after the first 60 seconds in order to achieve a stable state. We are interested in the following performance metrics: (a) warning notification time, (b) percentage of blind vehicles, and (c) number of packets received per vehicle. The warning notification time is the time required by normal vehicles to receive a warning message sent by a warning mode vehicle. The percentage of blind vehicles is the percentage of vehicles that do not receive the warning messages sent by warning mode vehicles. The number of packets received per vehicle (including beacons and warning messages) gives an estimation of channel contention. Table 6.6 summarizes the parameter values used in our simulations.

6.6 Simulation Results

In this section, we first present the impact of the roadmap and vehicle density in warning message dissemination performance and, afterwards, we evaluate and demonstrate the benefits of using our proposed adaptive scheme.

6.6.1 Evaluating the Impact of the Roadmap and Vehicle Density

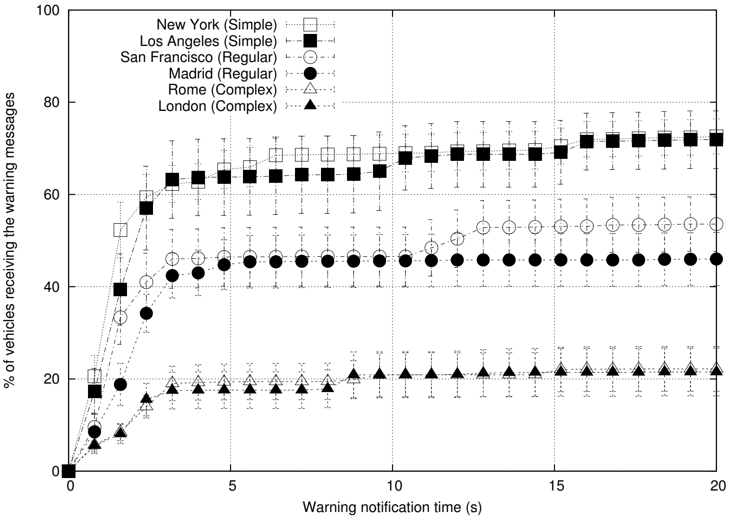
Results in this section are obtained using the maps of New York, San Francisco and Rome from Figure 6.1, and also the roadmaps from Los Angeles, Madrid and London from Figure 6.5. There is a city from each defined cluster in these two sets of roadmaps, and we will compare warning message dissemination using these different topologies. Figures 6.6 and 6.7 show the differences in terms of both warning notification time and messages received per vehicle when varying the density of vehicles in the aforementioned city scenarios. In all these simulations we used the same base configuration: 2 seconds between messages, 200 meters for minimum rebroadcast distance, and the broadcast scheme used was eSBR.

Results in Figure 6.6 show that the selected scenario notably affects the efficiency of the dissemination process, especially in scenarios with low vehicle density. As the density of vehicles grows, the differences become smaller but they are still noticeable. In addition, roadmaps from the same cluster present a very similar behavior in both low and high vehicle density scenarios. Topologies from the Simple layout cluster obtains the best performance in warning notification time and percentage of blind vehicles in all scenarios, since the wireless signal propagates more easily in environments with few long streets. As the layout becomes more irregular and the density of streets and junctions grows, the dissemination process develops more slowly and the number of uninformed vehicles increases.

In the six scenarios, increasing the density of vehicles yields better performance in terms of both warning notification time and percentage of blind vehicles (i.e. not receiving warning messages), especially in roadmaps like Rome and London where the streets are the shortest and the most irregular, producing very poor results when there are few vehicles in the simulated scenario. Complex layout scenarios need higher vehicle densities to obtain satisfactory results in terms of warning notification time and blind vehicles.

As shown in Figure 6.7, topologies from the same cluster also produce a similar number of messages. For Simple roadmaps there is a sudden increment in the amout of received messages when the vehicle density grows more than 25 vehicles/km^2, whereas Regular ones support up to 50 vehicles/km^2 and Complex roadmaps obtain sustainable results up to 75 vehicles/km^2, with complete coherence with respect to Algorithm 3. Urban scenarios with low density of streets and junctions greatly increase the number of messages received per vehicle because of the higher number of vehicles reached by the wireless signal, thanks to the long streets forming the layout that make easier to find vehicles in line-of-sight. This substantial increment of the amount of produced messages could produce broadcast storms even in scenarios with relatively low presence of vehicles relaying warning messages. We conclude that, in these environments, the dissemination process should be tuned to use operation modes with low message generation rates. On the contrary, topologies with higher density of streets and junctions allow using less restrictive dissemination schemes since the number of messages received per node remains low even for high density scenarios, reducing the probability of broadcast storms. This is especially important in Complex roadmaps, where more vehicles are needed to increase dissemination efficacy and the *Full dissemination* mode could reduce this problem.

To sum up, it is very important to reduce the amount of messages generated when the density of vehicles is high, but with low densities it is a good idea to produce enough messages to reach as many vehicles as possible, as the probability of broadcast storms becomes small.



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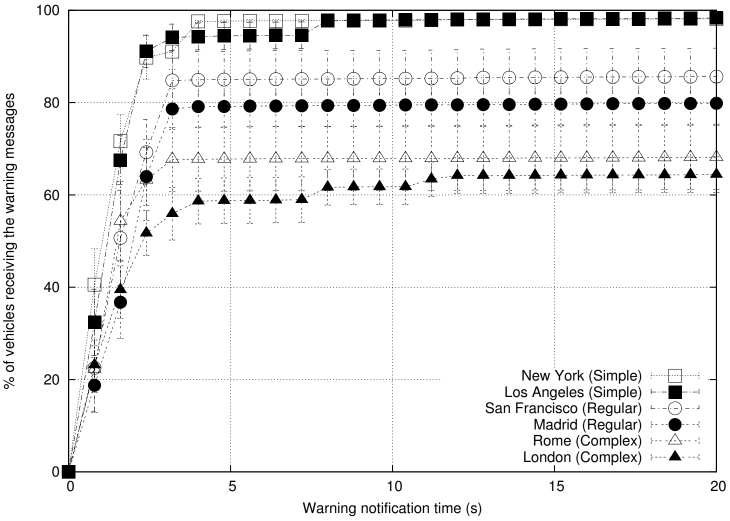
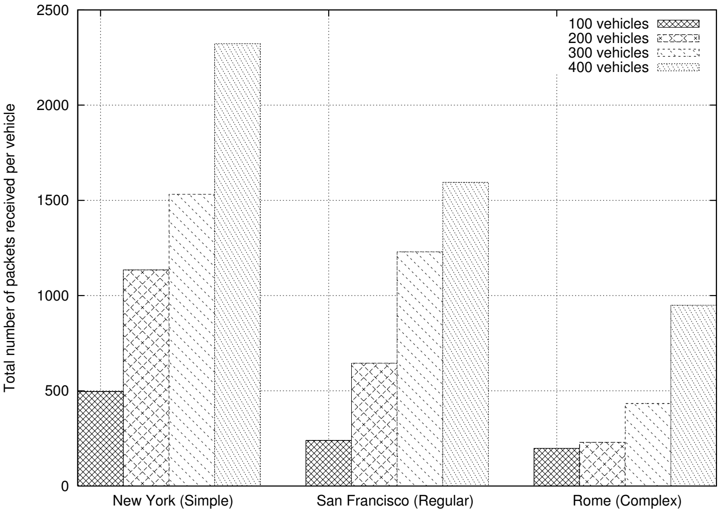


(b)

Figure 6.6: Warning notification time in different scenarios simulating (a) 100 vehicles (25 vehicles/km^2) and (b) 400 vehicles (100 vehicles/km^2).



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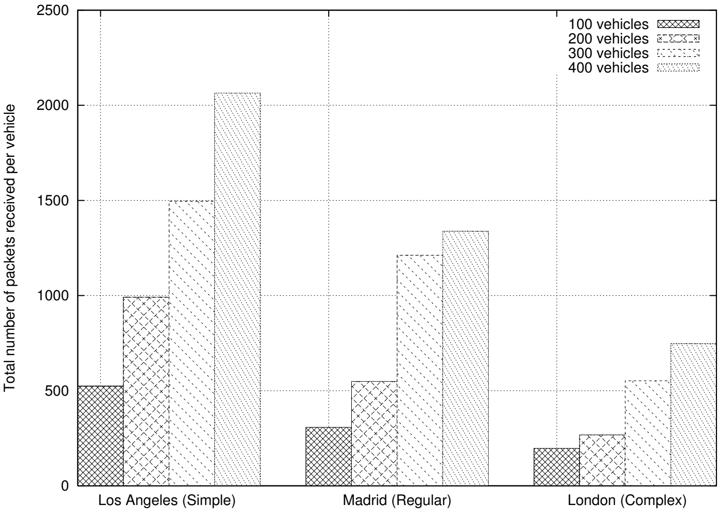


(b)

Figure 6.7: Number of messages received per vehicle simulating (a) the formerly presented scenarios, and (b) the additional street maps, under different vehicle densities.

Table 6.7: Average simulation results after 30 runs. The working modes selected by PAWDS are in boldface.

		Working Mode		
Map	**Veh. density**	Full diss.	Standard diss.	Reduced diss.
Los Angeles (Simple profile)	Low (25 veh./km^2)	WNT(50%): 1.93 s BV: 24.57% MR: 721.53	***WNT(50%): 3.14 s*** ***BV: 25.50%*** ***MR: 283.30***	WNT(50%): 4.81 s BV: 34.47% MR: 176.83
	High (100 veh./km^2)	WNT(50%): 1.15 s BV: 1.60% MR: 2463.07	WNT(50%): 2.86 s BV: 1.87% MR: 1083.07	***WNT(50%): 2.62 s*** ***BV: 1.97%*** ***MR: 715.43***
Madrid (Regular profile)	Low (25 veh./km^2)	***WNT(30%): 1.37 s*** ***BV: 50.93%*** ***MR: 266.43***	WNT(30%): 3.49 s BV: 56.17% MR: 166.70	WNT(30%): 6.36 s BV: 65.93% MR: 105.47
	High (100 veh./km^2)	WNT(50%): 1.48 s BV: 22.62% MR: 1559.33	***WNT(50%): 3.29 s*** ***BV: 23.24%*** ***MR: 678.77***	WNT(50%): 3.54 s BV: 33.00% MR: 516.53
London (Complex profile)	Low (25 veh./km^2)	***WNT(15%): 1.36 s*** ***BV: 75.57%*** ***MR: 168.33***	WNT(15%): 3.05 s BV: 80.57% MR: 98.17	WNT(15%): 5.93 s BV: 80.93% MR: 72.87
	High (100 veh./km^2)	WNT(50%): 2.18 s BV: 32.77% MR: 873.17	***WNT(50%): 4.47 s*** ***BV: 33.13%*** ***MR: 387.60***	WNT(50%): 6.34 s BV: 44.23% MR: 229.03

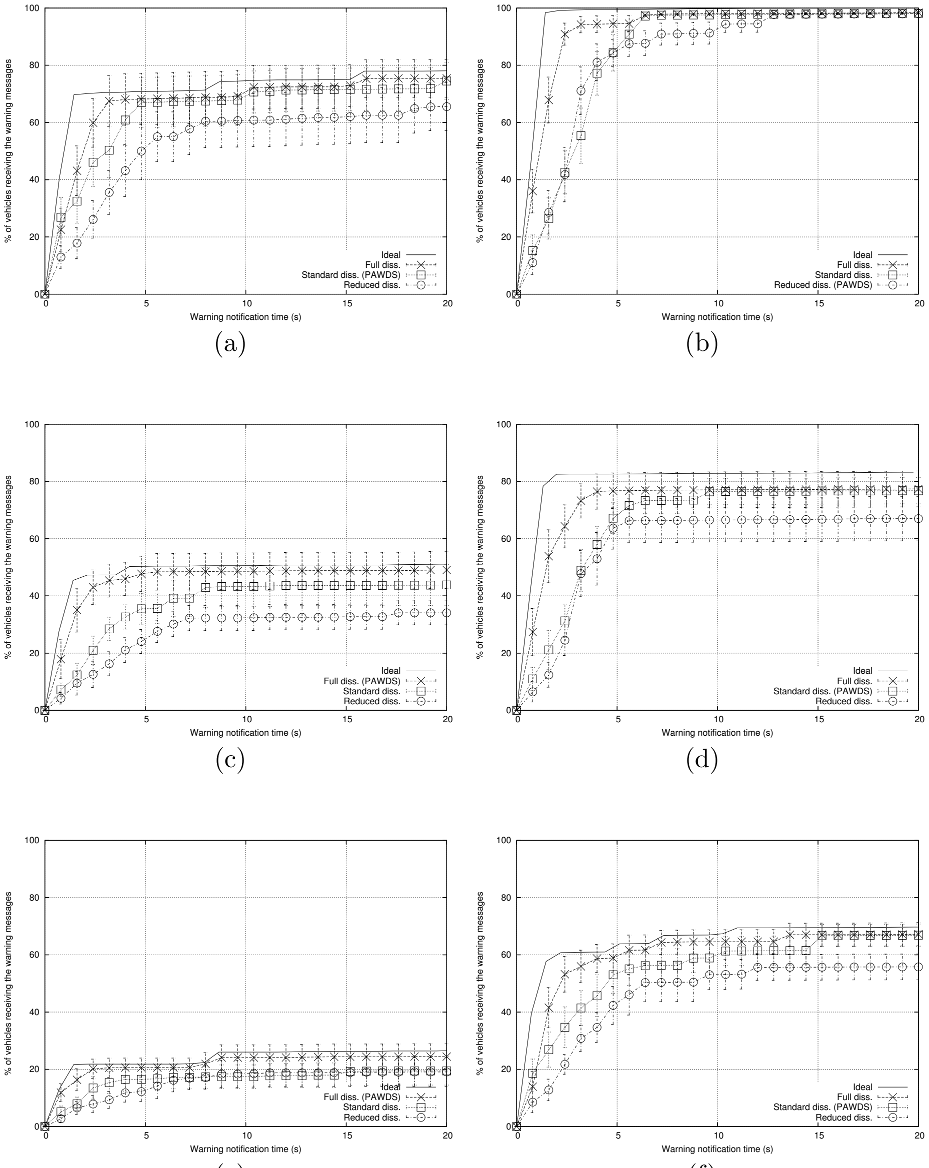
6.6.2 Performance Testing

In this subsection we show the result of a wide set of experiments whose goal is to prove the effectiveness of our proposed adaptive algorithm when disseminating warning messages. The proposed technique consists of determining the adequate selection of working modes in every possible situation. The maps used in this case are taken from the cities of Los Angeles, Madrid and London (Figure 6.5), representing Simple, Regular and Complex topologies, respectively.

Figure 6.8 shows the warning notification time using the three configurations in diverse scenarios, and Figure 6.9 depicts the average number of messages received per vehicle. The different configurations are compared in Figure 6.8 with an ideal situation, representing a scenario with a perfect channel where there are no collisions between wireless messages. Comparing our working modes to this ideal situation allows determining whether the available resources are efficiently used to maximize performance.

Focusing on Simple profile cities like Los Angeles, the *Full dissemination* mode produces a very high number of messages both in low and high vehicle density scenarios, thus being unsuitable for this environment. When the density of vehicles is low, the *Reduced dissemination* mode allows reducing the total amount of messages disseminated; however, the notification time and the percentage of blind vehicles is far greater than for the *Standard dissemination* mode, which is more balanced and more suitable for this situation. Thereby, this is the selected mode in low vehicle density scenarios. In high density scenarios, the differences in performance between these two modes diminish: the *Standard* mode only informs about 5% more vehicles, while the number of messages involved is reduced by a third part with the *Reduced dissemination* mode. This effect confirms its selection as the most suitable mode for this environment.

In Regular cities (e.g. Madrid), the *Reduced dissemination* mode does not ob-

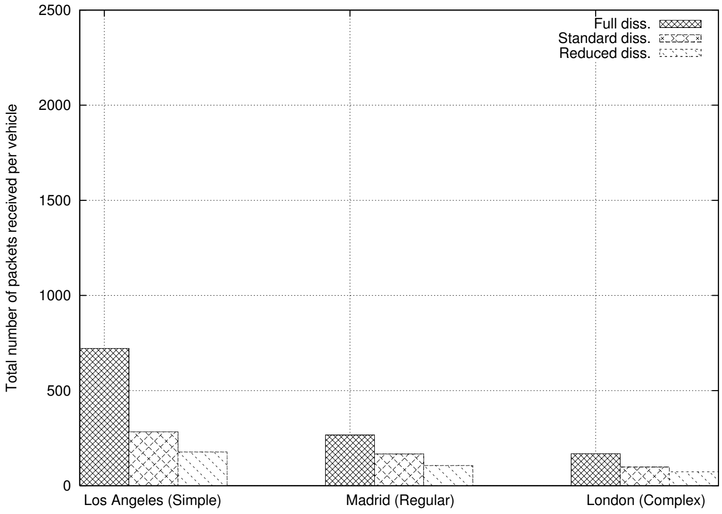


(a) (b)

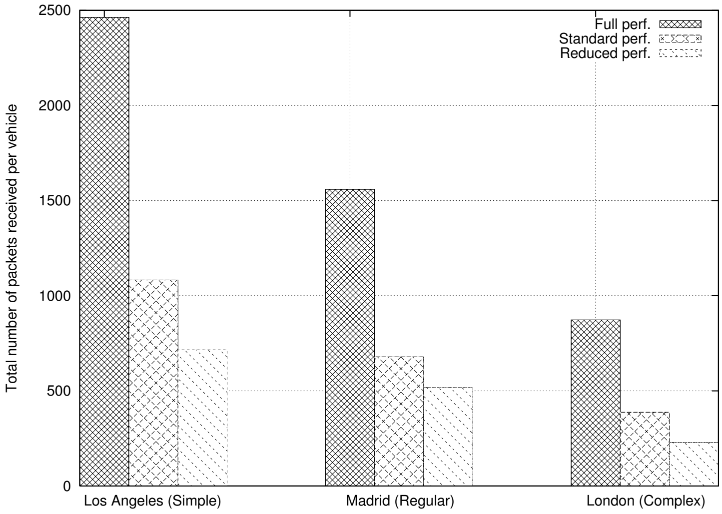
(c) (d)

(e) (f)

Figure 6.8: Warning notification time with the different PAWDS working modes compared to an ideal dissemination scheme without collisions in different cities: Los Angeles with (a) 100 and (b) 400 vehicles, Madrid with (c) 100 and (d) 400 vehicles, and London with (e) 100 and (f) 400 vehicles.



(a)



(b)

Figure 6.9: Number of messages received per vehicle with the different PAWDS working modes simulating (a) 100 and (b) 400 vehicles.

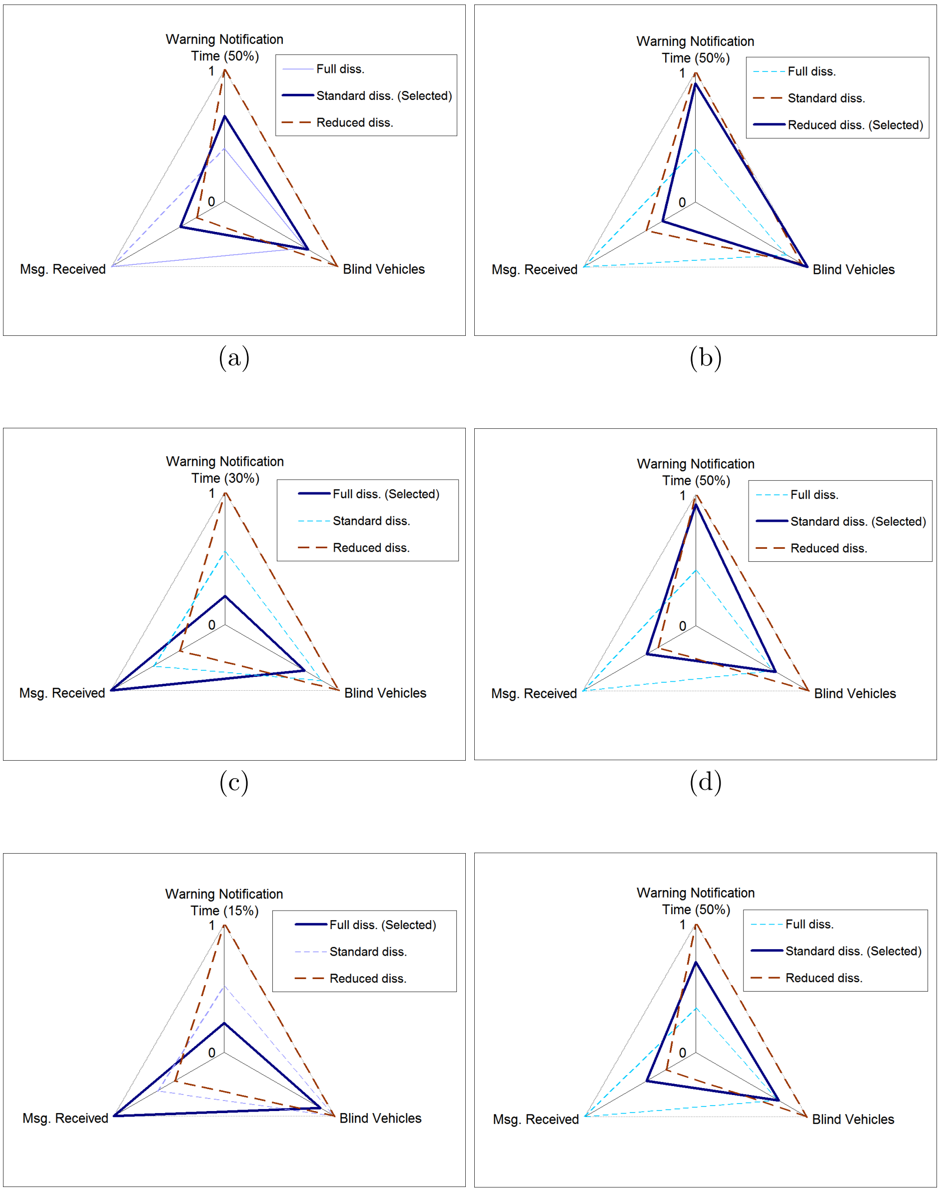
tain a good performance in terms of notification time and blind vehicles (about 30%-40% more blind nodes with respect to the rest of modes). In low vehicle density scenarios, using the *Full dissemination* mode yields a notable reduction of notification time and blind vehicles, without requiring a large amount of messages. Nevertheless, if the vehicular density is high, the number of messages grows excessively, and using the *Standard dissemination* mode allows reducing them by more than half with similar values for the percentage of blind nodes, and an affordable increment of the warning notification time. Hence, the most appropriate scheme would use the *Full dissemination* mode when there are few vehicles, and the *Standard* mode when their density increases.

Finally, in Complex profile cities (e.g. London), the *Full dissemination* mode selected by the PAWDS algorithm clearly outperforms the rest of the modes in terms of blind vehicles and warning notification time when only 100 vehicles are involved. In addition, the number of messages received is not very high (below 200 messages per vehicle), meaning that this mode would indeed be suitable for this environment. When the number of vehicles increases to 400, the *Reduced dissemination* mode remains unsuitable as it slows down the dissemination process and increases the percentage of blind nodes with respect to the other schemes in more than 30%. The *Full* and *Standard* modes present a similar behavior in percentage of blind vehicles, but the *Full dissemination* mode produces more than 850 messages per vehicle, which could yield broadcast storms. The *Standard* mode is slower during the first 5 seconds of the propagation process, but after this initial time the two schemes present very similar results, with less than half messages produced by the *Standard dissemination* scheme. Hence, in high vehicles density scenarios, this mode is the most appropriate when the roadmap profile is Complex.

Table 6.7 summarizes the average results after 30 runs and presents: (i) the warning notification time (WNT), (ii) the percentage of blind vehicles (BV), and (iii) the number of messages received (MR) per vehicle in the different studied situations. When the warning notification time is shown, the percentage in brackets represent how many vehicles were informed at that time, since some of the studied configurations produce very poor results and using a common basic percentage (for example, 50%) for all scenarios is very difficult. In Figure 6.10, all the results are normalized, i.e., divided by the highest value for each metric in each scenario, and thus the presented results vary between 0 and 1. The most balanced configurations are highlighted, matching with the specific operation mode used in our proposed scheme. When the vehicle density is low, the number of received messages is not critical (Figures 6.10c and 6.10e), whereas in high density scenarios the scheme tends to reduce messages by slightly increasing the other metrics.

6.7 Summary

In this chapter we introduced PAWDS, a new adaptive approach that allows increasing the efficiency of warning message dissemination processes using the information about the urban environment where the vehicles are moving. Our solution requires vehicles to make use of the information contained in their integrated maps to determine the profile type. Additionally, the beacons exchanged with neighbors



(a) (b)

(c) (d)

(e) (f)

Figure 6.10: Average simulation results after 30 runs in: Los Angeles with (a) 100 and (b) 400 vehicles, Madrid with (c) 100 and (d) 400 vehicles, and London with (e) 100 and (f) 400 vehicles. The working modes selected by our algorithm are represented using solid lines.

are used to estimate the density of vehicles in the area. By combining these two inputs, our algorithm is able to tune the parameters of the dissemination process and mitigate broadcast storm related problems. The objective is to find a balance among different performance metrics. With this aim, three different working modes (*Full*, *Standard* and *Reduced* dissemination) were proposed to be selected depending on their efficiency in each situation.

The PAWDS system has proven to be extremely effective when the density of vehicles is high, especially in maps with low density of streets and junctions. In those cases, selecting a balanced working mode allows maintaining an acceptable level of performance in terms of notification time and percentage of blind vehicles, while reducing the number of messages by more than 70% compared to other base configurations. In the rest of the maps, using the most suitable mode allows reducing message duplicates by about 60%. The effectiveness of the proposed system in scenarios with low density of vehicles becomes less meaningful as it is unlikely to find broadcast storm problems in such environments. Instead, the system is configured to reach as many vehicles as possible without concentrating on reducing the number of messages involved in the process.

Simulation results show that reducing the interval between messages increases the convergence speed of the system, but it also notably rises the number of messages received per vehicle. Hence, as future work, we plan to modify our approach to adapt the time between messages depending on the time elapsed since the last dangerous situation was detected.

Chapter 7

Improving Automatic Accident Detection and Assistance through Vehicular Networks

The symbiosis between communication technologies and vehicles offer a priceless opportunity to improve assistance to people injured in traffic accidents, providing information about the incident to reduce the response time of emergency services. Determining more accurately the required human and material resources for each particular accident could significantly reduce the number of victims.

This chapter presents our novel system prototype especially designed to detect and provide faster assistance for traffic accidents, thereby minimizing the consequences on the passengers' health. The proposed system requires each vehicle to be endowed with an On-Board Unit responsible for detecting and reporting accident situations to an external Control Unit that estimates its severity, allocating the necessary resources for the rescue operation.

The development of a prototype based on off-the-shelf devices, and its validation at the Applus+ IDIADA Automotive Research Corporation facilities, shows that our system could notably reduce the time needed to alert and deploy the emergency services after an accident takes place.

7.1 Introduction

During the last decades, traffic safety has become crucial in most countries around the world. The growth of the number of vehicles leads to more dangerous roads, which requires drivers to have higher levels of attention. This situation has dramatically increased the amount of traffic accidents, producing 2,478 fatalities in Spanish roads during 2010, which means one death for every 18,551 inhabitants [Dir10]; additionally, 34,500 people died in the whole European Union as a result of a traffic accident in 2009 [Eur12b].

Numerous efforts have been undertaken by automobile manufacturers to reduce road casualties, mainly focused on both active and passive safety systems. These initiatives have managed to increase traffic safety, achieving a reasonable reduction of road deaths. However, accidents can still occur, and a quicker response from emergency services could significantly decrease both the number of injured and dead passengers, as well as the impact and severity of such accidents.

The European Commission is currently funding several projects under the i2010 Intelligent Car Initiative, which promotes several efforts toward new safety systems. Cooperative Systems using vehicle-to-vehicle (V2V) communications are now considered necessary to accomplish these objectives, and will play an increasing role in the *Intelligent Transportation Systems* (ITS) area. Most ITS applications, such as road safety, fleet management, and navigation, will rely on information and communication technologies between the vehicle and the roadside infrastructure (V2I), or between vehicles (V2V).

In this chapter we present our prototype architecture called e-NOTIFY, a novel proposal designed to improve the chances of survival for passengers involved in car accidents. The proposed system offers automated detection, reporting, and assistance of passengers involved in road accidents by exploiting the capabilities offered by vehicular communication technologies. Our proposal does not directly focus on reducing the number of accidents, but on improving post-collision assistance with fast and efficient management of the available emergency resources, increasing the chances of recovery and survival for people injured in traffic accidents.

The rest of the chapter is organized as follows: Section 7.2 presents the motivation of this chapter. Section 7.3 presents the related projects focusing in inter-vehicular communications. Section 7.4 shows the overview of the e-NOTIFY architecture. Section 7.5 details the different parts of the On-Board Unit (OBU). Section 7.6 presents how the Control Unit consists of several modules. Section 7.7 shows the built prototype and its validation results. Finally, Section 7.8 concludes this chapter.

7.2 Motivation

When a traffic accident takes place, assisting injured passengers as soon as possible is crucial to minimize the negative effects on their health. Mortality from traffic accidents can be classified in three different stages [Rea10]:

- First phase: It involves casualties in the first few minutes or seconds after the accident (about 10% of all deaths).
- Second phase: The so-called *Golden Hour*, as it usually occurs during the first hour after the accident. It causes the highest mortality, i. e., 75% of all deceases. It is the phase in which the highest death rate can be avoided by proper initial health care.
- Third phase: It happens days or weeks after the traumatic incident, causing 15% of mortality. It takes hard work and a high amount of resources to reduce mortality in this phase.

As can be observed, the phase where more benefits can be achieved by reducing rescue response time is the second one. A fast and efficient rescue operation during

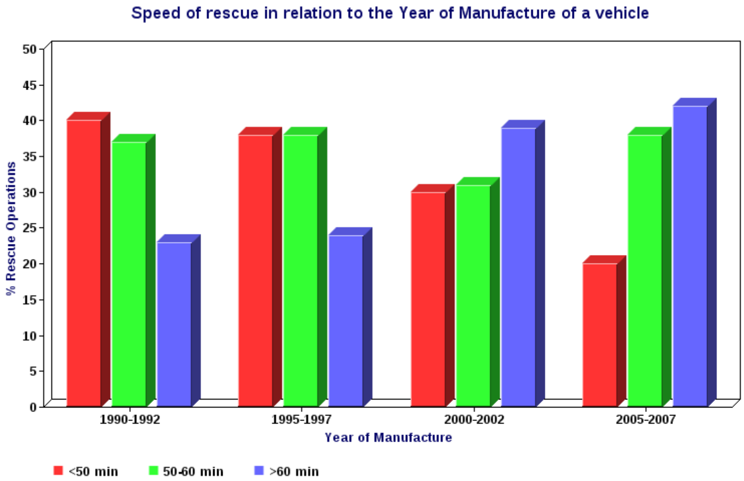


Figure 7.1: Impact of the year of manufacture of the vehicle in the rescue speed [All12].

the hour after a traffic accident significantly increases the probability of survival of the injured, and reduces the injury severity.

For a noticeable reduction in rescue time, two major steps must be taken: (i) fast and accurate accident detection and reporting to an appropriate Public Safety Answering Point (PSAP), and (ii) fast and efficient evacuation of occupants trapped inside a vehicle. The first of these objectives can be accomplished by using telecommunication technologies incorporated into the automotive world. There have been many advances in the development of technologies for communication between vehicles (V2V), also known as (*VANETs or Vehicular Ad hoc NETworks* [HL08]), offering support for cooperative security applications between vehicles. In fact, the 802.11p working group recently approved the IEEE 802.11p standard [IEE10], providing a viable solution for inter-vehicular security applications. This technology has been already studied to increase traffic safety in dangerous areas such as intersections [LFBZ09].

However, accomplishing the second goal is becoming harder and harder every year. Studies conducted by the ADAC German automobile club [All12] have proved that the rescue operation of injured people from a vehicle takes longer the more recent the vehicle is. This effect is clearly visible in Figure 7.1, where the impact of the year of manufacture of the vehicle in the rescue speed is shown. The increase of security equipment that makes vehicles safer also implies more complexity for the emergency teams. From the golden hour perspective, this is a serious threat to the successful rescue of injured persons.

Increasing the amount of information available about the accident and the vehicle involved could definitely contribute to the second goal [MTC+10]. In fact, the effectiveness of the assistance to passengers involved in a traffic accident could

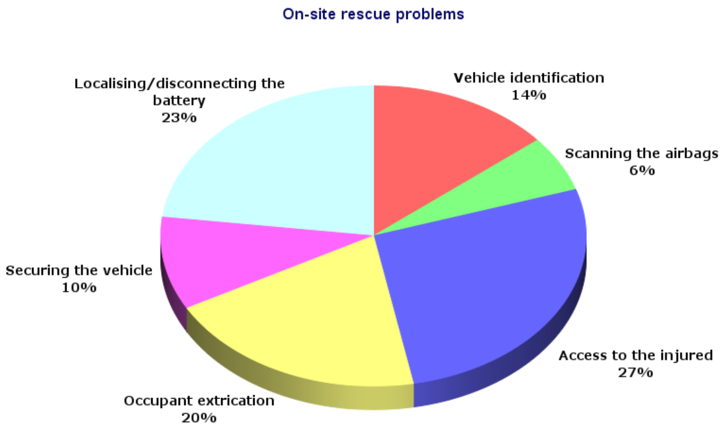


Figure 7.2: Main rescue problems at the accident site [All12].

be significantly improved if emergency services had available relevant information on the conditions under which the accident happened before moving to the area of the accident. As shown in Figure 7.2, up to 63% of all problems that rescue teams can find when facing an accident could be reduced by providing emergency services with additional information. This extra information, obtained from sensors inside the vehicle, would be used to estimate the severity of the occupants' injuries. Also, having more information would allow determining the optimal set of human and material resources to be sent to the accident location, with the consequent assistance quality improvement.

7.3 Related Projects

A number of research projects headed by different research institutes and car manufacturers around the world have been focusing on inter-vehicle communication systems. Some of the larger projects related to the e-NOTIFY system are listed below:

- *COMeSafety2* [BBE+09]: The COMeSafety2 project proposal aims at coordinating the activities towards the realization of cooperative systems on European roads, focusing on all issues related to vehicle-to-vehicle and vehicle-to-infrastructure communications. Its main goal consists of developing a European set of standards to support wide implementation and deployment of cooperative Intelligent Transport Systems.
- *eCall* [GMB+09]: The eCall system has been designed to improve transportation safety, providing rapid assistance to people involved in a collision anywhere in the European Union. A collision activates an emergency voice call to be established via the cellular network to local emergency agencies. In

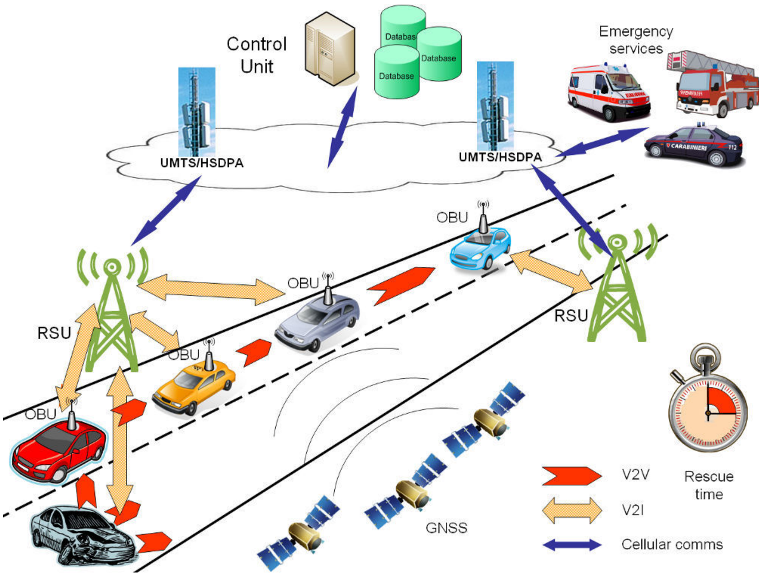


Figure 7.3: e-NOTIFY architecture based on the combination of V2V and V2I communications.

addition, e-Call transmits a *Minimum Set of Data* (MSD), including key information about the accident such as time, location and vehicle description. It is supposed that the eCall system will be operative by 2015.

- *OnStar* [OnS12]: It is an in-vehicle safety and security system created by General Motors (GM) for on-road assistance, which resembles the European eCall project. A collision activates an emergency voice call to report key information about the accident.
- *Campus Vehicular Testbed* (C-Vet) [CFG+10]: It is an effort by the UCLA university to deploy an open testbed that integrates ad hoc vehicle-to-vehicle communications and a wireless mesh to offer support for communications.

The most similar projects to e-NOTIFY are both the eCall and the OnStar projects, which are expected to be manually activated, or using the in-vehicle sensors for airbag deployment. However, our proposal goes one step beyond their aims. We are developing an autonomous intelligent system that allows automatically adapting the required rescue resources to each particular accident, allowing the rescue staff to work far more efficiently, and reducing the time associated to their tasks.

7.4 e-NOTIFY System: Architecture Overview

Figure 7.3 presents the basic structure of the e-NOTIFY system. The proposed system consists of several components with different functions. Firstly, the vehicles should incorporate an On-Board unit (OBU) responsible for detecting accidents and communicating about dangerous situations. Next, the notification of the detected accidents is made through a combination of both V2V and V2I communications. Finally, the destination of the information is the Control Unit (CU) that will handle the warning notification, estimating the severity of the accident and communicating the incident to the appropriate emergency services.

The OBU definition is of utmost importance for the proposed system. This device must be technically and economically feasible, as its adoption in a wide range of vehicles could become massive in a near future. In addition, this system should be open to future software updates. Although the design of the hardware to be included in vehicles initially consisted of special-purpose systems, this trend is heading towards general-purpose systems because of the constant inclusion of new services.

The information exchange between the OBUs and the CU is made through the Internet, either through vehicles providing Internet access (via UMTS, for example), or by reaching infrastructure units (*Road-Side Units*, RSU) that provide this service. If the vehicle does not get direct access to the CU on its own, it can generate messages to be broadcast by nearby vehicles until they reach one of the aforementioned communication paths. These messages, when disseminated among the vehicles in the area where the accident took place, also serve the purpose of alerting drivers traveling to the accident area about the state of the affected vehicle, and its possible interference on the normal traffic flow. An efficient warning message dissemination protocol should exploit the street and buildings layout of the surrounding area to carefully select the most appropriate forwarding node for the message [FGM$^+$12d]. This allows maximizing the percentage of informed vehicles and reducing the time elapsed between the accident occurrence and its actual notification to each specific vehicle (i.e. the warning notification time), while simultaneously reducing the amount of traffic generated in the wireless channel.

The goal of our proposal is to provide an architecture that allows: (i) direct communication between the vehicles involved in the accident, (ii) automatic sending of a data file containing important information about the incident to the Control Unit, and (iii) a preliminary and automatic assessment of the damage of the vehicle and its occupants, based on the information received from the involved vehicles, and a database of accident reports. According to the reported information and the preliminary accident estimation, the system will alert the required rescue resources to optimize the accident assistance.

7.5 On-Board Unit (OBU) Design

The main objective of the e-NOTIFY OBU lies in obtaining the available information from sensors inside the vehicle to determine when a dangerous situation occurs, and reporting that situation to the nearest Control Unit, as well as to other nearby vehicles that may be affected.

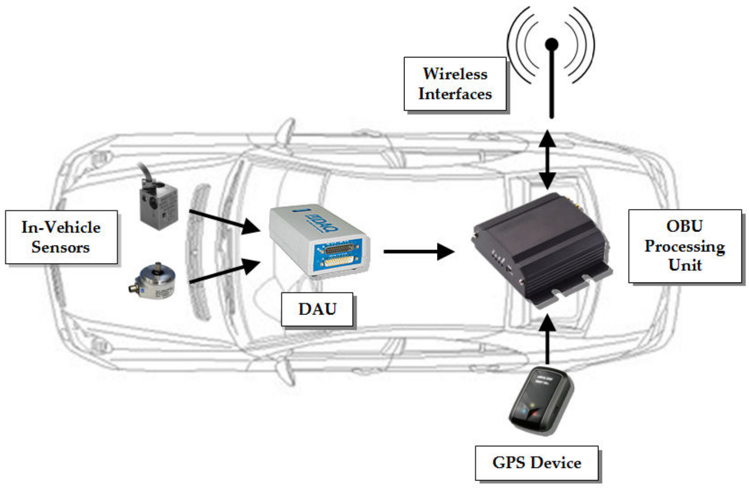


Figure 7.4: OBU structure diagram.

7.5.1 OBU Internal Structure

Figure 7.4 shows the e-NOTIFY OBU system, which relies on the interaction between sensors, the data acquisition unit, the processing unit, and wireless interfaces:

- *In-vehicle sensors*. They are required to detect accidents and provide information about its causes. Accessing the data from in-vehicle sensors is possible nowadays using the On-Board Diagnostics (OBD) standard interface [B&12], which serves as the entry point to the vehicle's internal bus. This standard is mandatory in Europe and USA since 2001. This encompasses the majority of the vehicles of the current automotive park, and the percentage of compatible vehicles will keep growing as very old vehicles are replaced by new ones.the processing unit, and wireless interfaces:

- *Data Acquisition Unit* (DAU). This device is responsible for periodically collecting data from the different sensors available in the vehicle (airbag triggers, speed, fuel levels, etc.), converting them to a common format, and providing the collected data set to the OBU Processing Unit.

- *OBU Processing Unit*. It is in charge of processing the data from sensors, determining whether an accident occurred, and notifying dangerous situations to nearby vehicles and to the Control Unit. The information from the DAU is gathered, interpreted and used to determine the vehicle's current status. This unit must have access to a positioning device (such as a GPS receiver), and also have access to different wireless interfaces, thereby enabling communication between the vehicle and the remote control center.

7.5.2 Accident Detection Algorithm

The first goal of the OBU consists of determining when a dangerous accident occurs. In the traffic accidents domain, there are two main events that could cause severe damage to the passengers in a vehicle: rollovers (overturns) and strong impacts. We are currently working with the Applus+ IDIADA Automobile Research Corporation [IDI12] to develop a realistic accident detection algorithm based on information which characterizes different types of accidents.

Crash tests held by IDIADA collect a huge amount of information about the collision (10,000 samples per second) which is unfeasible to be handled in real-time, thus it must be processed off-line after the accident. Nevertheless, for a really useful system, data must be processed in the moment of the accident to reduce the assistance time and the effects of the collision on the passengers. Moreover, the equipment used by IDIADA to record all this information is not affordable in a standard vehicle. Therefore, our detection system should be based on an affordable on-line system, but still accurate to detect when an accident occurs. So, e-NOTIFY OBUs use a reduced sampling frequency compared to the configuration under IDIADA tests. The new sampling frequency is selected so that it is possible to handle it in real-time, while being precise enough to classify the different types of accident pulses. Experiments showed that about 100 measurements per second are adequate to achieve a trade-off between accuracy and real-time processing.

When trying to detect an accident, a rollover in a vehicle is quite simple to recognize using a horizontal tilt sensor, since measurements deviating more than 90 degrees from the horizontal, or a constant value over 45 degrees (partial rollover), indicate that the vehicle overturned and needs to be rescued.

The interpretation of acceleration values is more complicated. The straightforward approach to classify collisions would consist of defining a series of acceleration thresholds. Nevertheless, this simple method is not valid for all tested situations, as shown in Figure 7.5. The graph contains different pulses corresponding to front crashes with different severities. As shown, the peak acceleration recorded in the minor accident exceeds the maximum value registered in the severe collision, although the duration of the pulse is much smaller. Therefore, it is clear that using simple acceleration thresholds to distinguish the acceleration pulses is not enough, and both their amplitude and duration should be considered to better estimate the severity of accidents.

To take into account both the amplitude and duration of the pulse, the e-NOTIFY system uses the area that the pulse forms with the Time axis, which can be obtained applying the integral of the function. Therefore, the integral value of the function is used to classify acceleration pulses and determine the preliminary severity of an impact.

The Data Acquisition Unit is configured to collect as much data as possible from the sensors during the intervals between sampling, calculating the average value measured during the period before sending it to the Process Unit. Hence, the most appropriate method for approximating the integral value during an interval will be the rectangle rule, calculated using Equation 7.1.

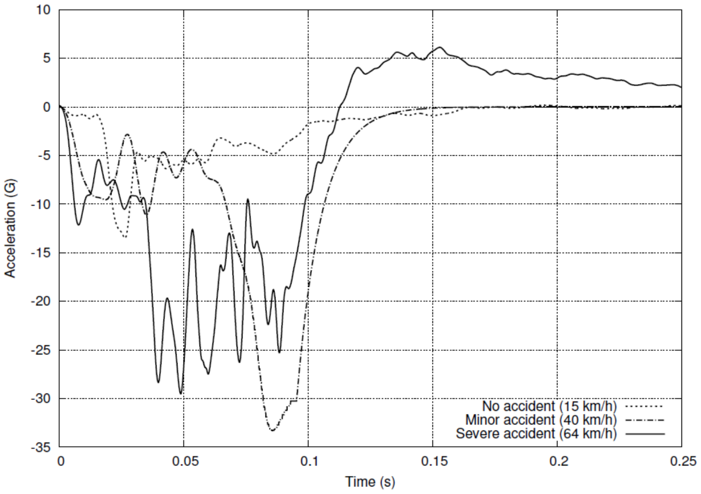


Figure 7.5: Acceleration pulses for different front crash ratings. Data provided by Applus+ IDIADA Corporation [IDI12].

$$\int_{x_0}^{x_n} f(x)dx \approx \sum_{n}^{i=1}(x_i - x_{i-1}) \cdot f_{avg}[x_{i-1}, xi] \qquad (7.1)$$

Where n is the number of intervals recorded, and f_{avg} is the average value of the function $f(x)$ in the interval $[x_{i-1}, x_i]$. The integration of the acceleration function starts when a value over 6G (for front collisions) or 3G (for side and rear-end collisions) is detected. These values were found and adjusted by using historical information about crash tests provided by Applus+ IDIADA.

7.5.3 OBU Design under the OSGi Environment

The e-NOTIFY OBUs make use of the OSGi (Open Services Gateway initiative) standard [OSG07], which enables the development of applications (in the form of bundles or modules for deployment) that can be installed, started, stopped, updated and uninstalled remotely without rebooting the system. Many car manufacturers have included the OSGi specification in their *Global System for Telematics* (GST) specification. Since OSGi is becoming the *de facto* standard for vehicular network systems, it has been chosen to be implemented in the e-NOTIFY system.

In the OSGi environment, a bundle is an application packaged in a JAR (Java ARchive) which is deployed in an OSGi platform. Therefore, the applications to be executed by the OBUs must be programmed in the Java language, and packaged in a JAR file that allows deployment as a module in the system. The inclusion of new services may be performed using a similar procedure, obtaining a highly scalable and updateable architecture.

The OSGi architecture is divided into layers, as shown in Figure 7.6. Their effect on the e-NOTIFY OBUs is the following:

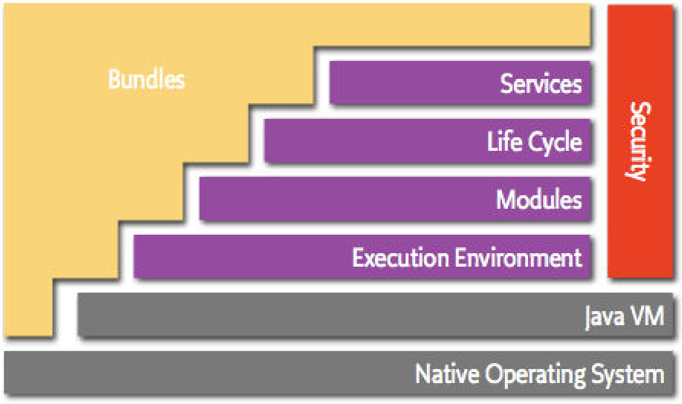


Figure 7.6: OSGi architecture.

- *Security Layer*: The objectives of this layer are two-fold: (i) ensuring that possible updates of the applications keep the system in a stable state, and (ii) ensuring that the programs installed on the OBU are from certified suppliers and they are installed under the user's consent.
- *Module Layer*: This layer makes possible to add new services (for example, downloaded from the Internet), encoded as independent JAR files, and included in the On Board Unit without requiring a reboot.
- *Life-Cycle Layer*: This layer determines the possible states of the bundles used on the OBUs: INSTALLED, RESOLVED, STARTING, ACTIVE, STOPPING, and UNINSTALLED.
- *Service Layer*: All the bundles incorporated into the OBU must provide information about the services provided: when to start and stop, number of instances, and so on. The lack of this information will refrain the service from being fully installed, in order to ensure the system remains in a stable state.

7.5.4 Warning message structure

The messages exchanged between the vehicles and the Control Unit should be concise, avoiding irrelevant information, but they should not ignore any possible information that might be useful for the emergency services to determine the necessary resources. Thus, the information delivered to the response point should include data about the conditions under which the accident occurred, the occupants of the vehicle and the different security systems included. These data are sent to the emergency services to provide a more detailed view of the conditions of the accident before they arrive to the affected area [MTC$^+$10]. For the designed

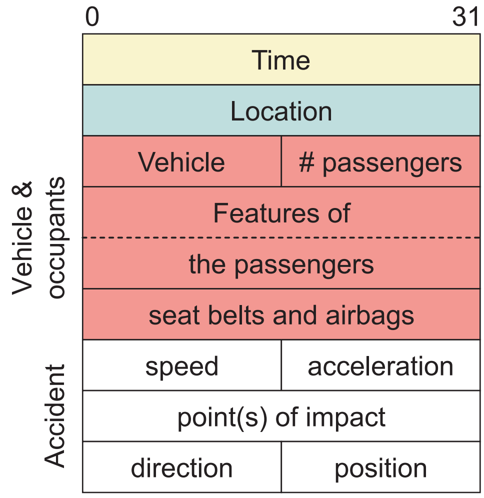


Figure 7.7: Warning packet format for the proposed system.

system, we implemented a message containing the following fields, accessible via the sensors included in the vehicle (see Figure 7.7):

TIME

- to inform exactly when the accident occurred.

LOCATION

- **geographical position of the vehicle**, to determine the exact location of the injured.

VEHICLE-OCCUPANTS

- **characteristics of the vehicle**, to adapt the equipment to send to the accident scenario and to warn the rescue team about the level of complexity and dangers. Critical areas at the vehicle which must be avoided by cutting procedures (e.g. gas inflators) are mostly not labeled and might cause critical/dangerous situations for rescue workers. (e.g. in modern electrical engines, etc.).

- **number of passengers**, to adequate the medical team required to attend them.

- **features of the passengers**: weight, height, age, etc. The more information, the better.

- **information about seat belts and airbags**, to estimate the severity of the injured ones, how the accident occurred and the severity of the accident.

ACCIDENT

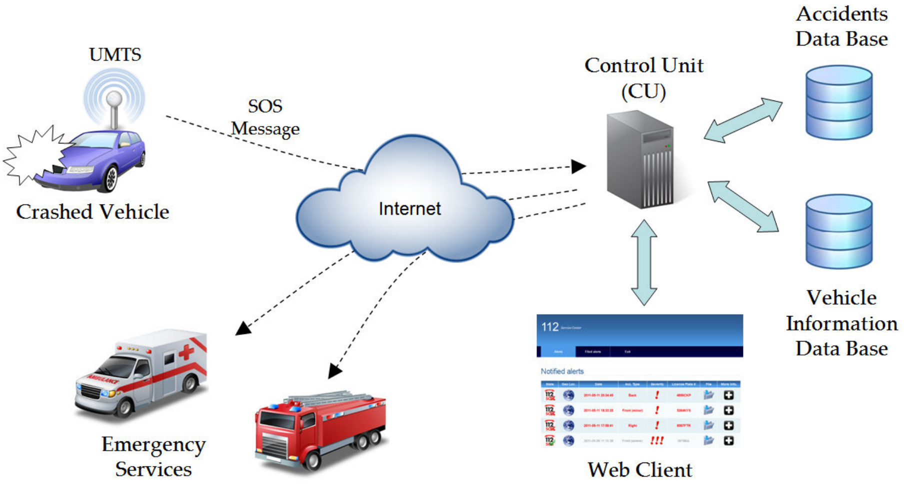


Figure 7.8: Control Unit in the e-NOTIFY system.

- **speed and acceleration** of the vehicle just before the accident, to estimate the severity of the accident.
- **point(s) of impact**, i.e. exactly where the impact(s) has been produced.
- **direction of impact force**. This is a mechanical concept. If we consider the top of the car as a clock, we can describe the direction of impact force as an hour. (12 for front side, 3 for right side, 6 for rear side, etc.).
- **position of the vehicle** after the crash to estimate the severity of the accident and to warn the emergency team about the level of complexity of the rescue.

7.6 Control Unit (CU) Design

The Control Unit (CU) is associated to the response center in charge of receiving notifications of accidents from the OBUs installed in vehicles. In particular, the Control Unit is responsible for dealing with warning messages, retrieving information from them, and notifying the emergency services about the conditions under which the accident occurred, as depicted in Figure 7.8.

7.6.1 CU Internal Structure

Figure 7.9 shows the modules included in the Control Unit to achieve all its objectives within the e-NOTIFY system:

- *Reception/interpretation module.* The first step for the CU is to receive a warning message from a collided vehicle, and so there must be a module waiting for the arrival of messages and obtaining their different fields.

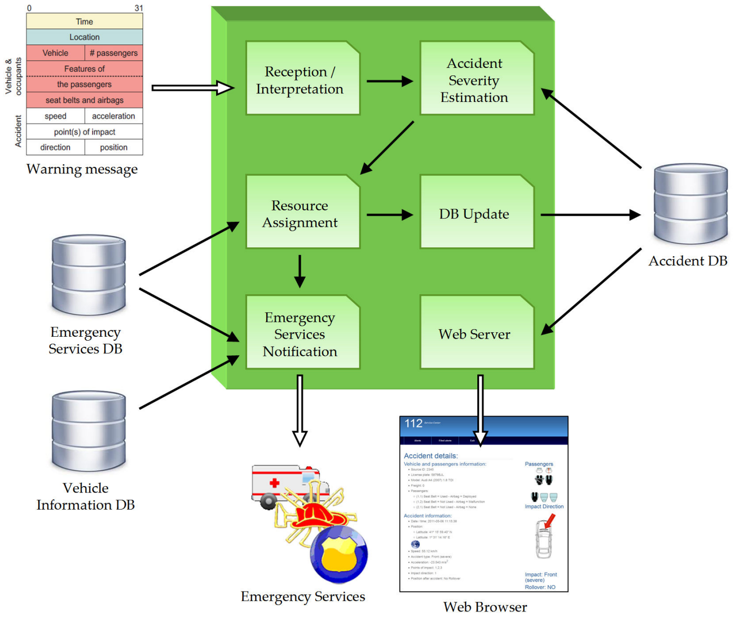


Figure 7.9: Control Unit modular structure.

- *Accident severity estimation module.* When a new accident notification is received, this module will determine how serious the collision was, and the severity of the passengers' injuries.

- *Resource assignment module.* After deciding the severity of the accident, an additional module is used to define resource sets adapted to the specific situation.

- Database update module. The data collected from the notified accident are stored into the existing database of previous accidents, increasing the knowledge about the accident domain.

- Web Server module. The Control Unit incorporates a Web Server to allow easy visualization of the historical information recorded and the current accident situations requiring assistance. A web interface was chosen in order to increase user friendliness and interoperability.

- Emergency services notification module. When the information has been correctly managed, the notification module sends messages to the emergency services including all the information collected, the estimated severity, the recommended set of resources, as well as additional information about the vehicles involved in the collision (for preliminary planning of the rescue operation). The information about vehicles consists of standard rescue sheets, which highlight the important or dangerous parts of a specific vehicle that

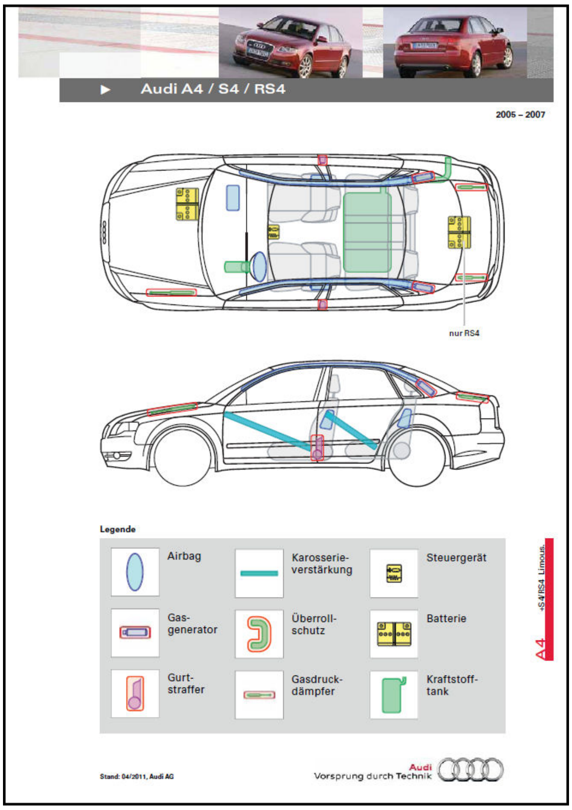


Figure 7.10: Example of standard rescue sheet.

should be taken into account during a rescue operation: batteries, fuel tanks, etc., as shown in Figure 7.10.

The Control Unit makes use of three different databases to handle accident notifications. The accident database contains historical data from past accidents detected by the system, and it is used to build the estimation models that predict the severity of new accidents. The vehicle information database provides, for each vehicle, available information about rescue procedures, dangerous components inside each car, etc. Finally, the emergency services database includes information about the rescue services available in the area of influence of the CU in order to determine the emergency services needed for each specific accident.

7.6.2 Accident Severity Estimation

After receiving an accident notification, the Control Unit must determine the severity of the traffic accident to adjust the available resources to each situation. In particular, the questions that must be answered to obtain useful information are: (i) how damaged are the vehicles involved in the accident? and (ii) how severe are the injuries suffered by the passengers? The first question will determine the need of machinery such as cranes to restore normal traffic flow, or the likability for the vehicle to catch fire and cause additional dangerous situations. The second one is related to the health equipment and vehicles necessary to increase the probability of survival of the vehicle occupants.

Developing a useful algorithm to estimate accident severity needs historical data to ensure that the criteria used are suitable and realistic. The National Highway Traffic Safety Administration (NHTSA) maintains the General Estimates System (GES) [Nat12a], a database with information about traffic accidents which began operating in 1988. The data for this database is obtained from a sample of Police Accident Reports (PARs) collected all over the USA roads. This database includes information about the crash characteristics and environmental conditions at the time of the accident, vehicles and drivers involved in the crash, and people involved in the collision.

Using the data contained in the GES database, we built a series of data mining classification algorithms to estimate the severity of the accident (*minor*, *moderate*, and *severe*) and the possible injuries of the passengers (*no injury*, *non-incapacitating injury*, and *incapacitating or fatal injury*). These estimations may be used to adapt the resources to the conditions of the accident, avoiding over-use and under-use of the available resources. Further details about the severity estimation and sanitary resource allocation, which are a very important part of the Control Unit, can be found in Chapters 8 and 9.

7.7 Prototype Implementation and Validation

A prototype for the e-NOTIFY system was built using off-the-shelf devices, allowing fast development and reduced cost, but including all the desirable characteristics of the e-NOTIFY architecture. This prototype was later validated in the Applus+ IDIADA facilities using real crash tests.

7.7.1 OBU Prototype

The Data Acquisition Unit in the initial prototype is built using an ARM *mbed NXP LPC1768* microcontroller [mbe12] programmed to periodically collect data from in-vehicle sensors. Basically, these sensors are accelerometers and gyroscopes that indicate the severity of the impacts received by the automobile or the occurrence of a rollover that might endanger the integrity of the occupants. Communication between the microcontroller and the Processing Unit is done by sending UDP packets through an Ethernet interface. Figure 7.11 shows the prototype build for the Data Acquisition Unit, providing the necessary sockets for the connection of the sensors and power the system, and a UTP cable used for the connection with the Processing Unit. Figure 7.12 shows the internal design of the circuit developed to read the analog data from the on-board sensors, transform them to a digital format, and finally send the corresponding packet to the Processing Unit. The design was provided by the DISCA department of the Universitat Politècnica de Valencia (UPV).

Figure 7.11: Data Acquisition Unit prototype.

The UDP packets sent by the DAU are small, containing six fields of 32 bit each, as depicted in Figure 7.13. Each field presents the following meaning:

- **Sequence #** (32-bit integer): sequence number of the packet, to ensure their reception in order and possibly missing packets.
- **Timestamp** (32-bit integer): time (in milliseconds) when the value was measured.
- **AccX, AccY, AccZ** (32-bit float): values recorded for the acceleration in the 3 axis. These values are measured in Volts, since they represent the measurements of the analog sensors. The posterior conversion to real acceleration (measured in Gs) will be performed in the Processing Unit.
- **Roll** (32-bit float): values recorded by the gyroscope installed the vehicle, again measured in Volts and requiring a subsequent conversion to degrees in the Processing Unit.

The values sent by the DAU are no converted to their final units to increase the flexibility of the system. Programming the Processing Unit is more simple, making easy to implement the conversion algorithms in them. Moreover, the computing power of the Processing Unit is greater than the power of the DAU, thus reducing the amount of work to be done in it and allowing a faster processing of the analog signal.

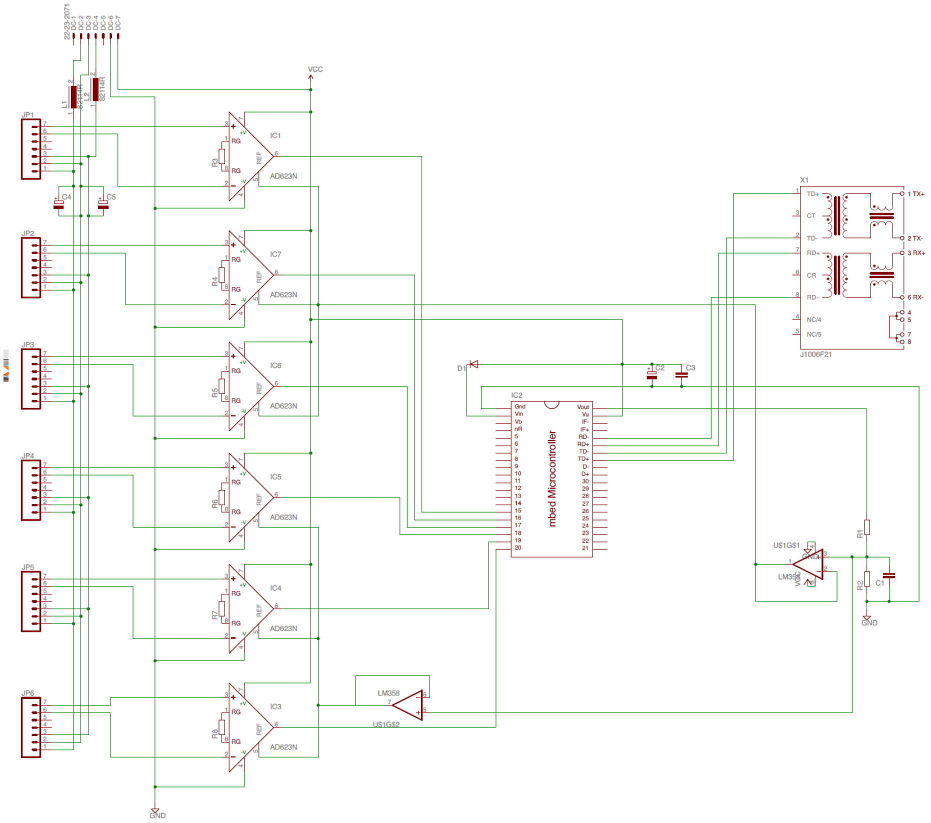


Figure 7.12: Logical design of the circuit in charge of reading the data from the in-vehicle sensors.

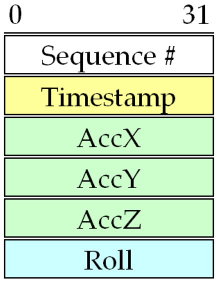

0 31
Sequence #
Timestamp
AccX
AccY
AccZ
Roll

Figure 7.13: Format of the packet sent by the DAU prototype.

The OBU Processing Unit in our prototype is a general-purpose Asus Eee PC netbook [Asu11], equipped with solid state disk (SSD) to minimize the possibility of damage due to impact in crash tests. The vehicle position and speed are obtained using a GPS device *Qstarz BT-Q818XT* [Qst12] accessible via Bluetooth.

7.7.2 CU Prototype

The Control Unit prototype for the initial tests was built using common software components, allowing fast prototyping with little cost.

The reception/interpretation module was implemented using the Java programming language [AGH05]. This module acts as a concurrent server, creating different execution threads to handle each message received, which allows exploiting multiprocessor or multicomputer architectures.

Databases are managed using the MySQL relational database management system [Ora12]. MySQL was selected because of its scalability and easy integration with the rest of components of the Control Unit.

The Web server for the visualization module is Apache. To support dynamic content, we use the PHP (Hypertext Preprocessor) technology [PHP12], which is easily integrated into Apache [The12]. By combining these technologies and MySQL, users can visually check the system status, as shown in Figure 7.14.

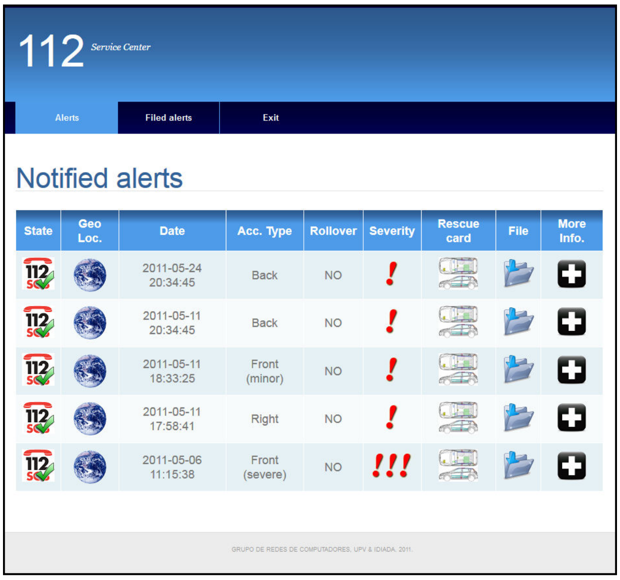
7.7.3 Prototype Validation

The prototype was validated at the Applus+ IDIADA [IDI12] Passive Security Department facilities in Santa Oliva (Tarragona, Spain). These facilities house one of the most sophisticated crash test laboratories in the world, and constitute an official center for approval under the Euro NCAP program.

Due to the cost of using real vehicles in the collision experiments, the e-NOTIFY prototype tests were performed using a platform (known as "sled") that moves on rails in order to collide against a series of metal bars that simulate the deformation suffered by a vehicle body to absorb the impact. The speed of the stroke and the configuration of bars used in the test determine, respectively, the kind of accident detected and the segment the simulated vehicle belongs to (family car, off-road, etc.). Tested speeds are determined by European standards and vary from 10 km/h to 64 km/h to represent different accident severities.

Figure 7.15 shows the sled used in the tests. Validation experiments consisted of front, side, and rear-end crash tests, accounting for both accident and no accident situations. The classification of the severity of the collision is dictated by the parameters used in Applus+ IDIADA in automotive standard tests. The specific tests performed during the validation phase appear in Table 7.1.

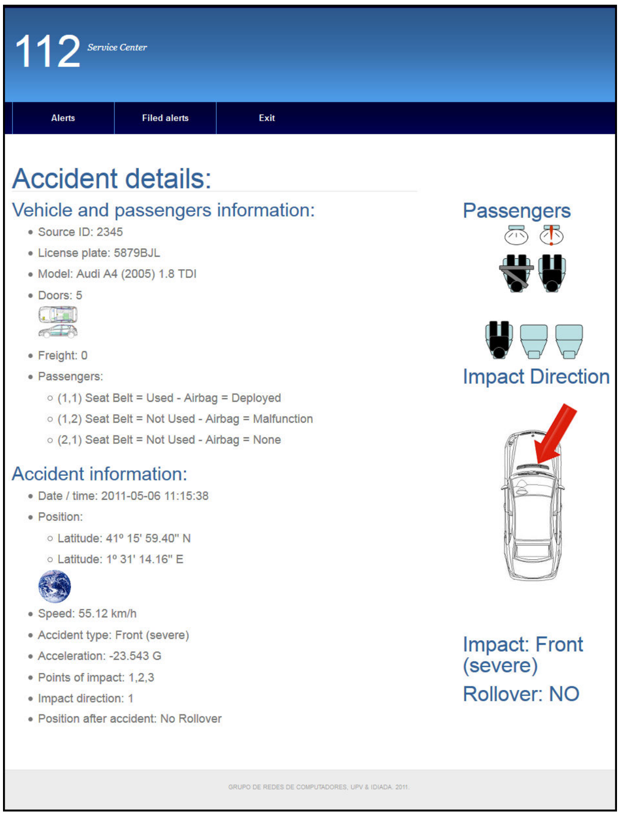
The test system included an external computer receiving regular information from the sled (via a wireless network) of the measurements recorded by the OBU to ensure the proper behavior of the sensor reading module, along with a Control Unit in charge of receiving alert messages and applying the corresponding algorithms. The real trials were performed with two different objectives: proving that the OBU prototype was solid enough to resist a dangerous impact and thus it could



Notified alerts

State	Geo Loc.	Date	Acc. Type	Rollover	Severity	Rescue card	File	More Info.
112 SOS ✓		2011-05-24 20:34:45	Back	NO	!			✚
112 SOS ✓		2011-05-11 20:34:45	Back	NO	!			✚
112 SOS ✓		2011-05-11 18:33:25	Front (minor)	NO	!			✚
112 SOS ✓		2011-05-11 17:58:41	Right	NO	!			✚
112 SOS ✓		2011-05-06 11:15:38	Front (severe)	NO	!!!			✚

GRUPO DE REDES DE COMPUTADORES, UPV & IDIADA, 2011.



Accident details:

Vehicle and passengers information:

- Source ID: 2345
- License plate: 5879BJL
- Model: Audi A4 (2005) 1.8 TDI
- Doors: 5
- Freight: 0
- Passengers:
  - (1,1) Seat Belt = Used - Airbag = Deployed
  - (1,2) Seat Belt = Not Used - Airbag = Malfunction
  - (2,1) Seat Belt = Not Used - Airbag = None

Accident information:

- Date / time: 2011-05-06 11:15:38
- Position:
  - Latitude: 41º 15' 59.40'' N
  - Latitude: 1º 31' 14.16'' E
- Speed: 55.12 km/h
- Accident type: Front (severe)
- Acceleration: -23.543 G
- Points of impact: 1,2,3
- Impact direction: 1
- Position after accident: No Rollover

Passengers

Impact Direction

Impact: Front (severe)

Rollover: NO

GRUPO DE REDES DE COMPUTADORES, UPV & IDIADA, 2011.

Figure 7.14: Web interface screenshots with information about notified accidents.

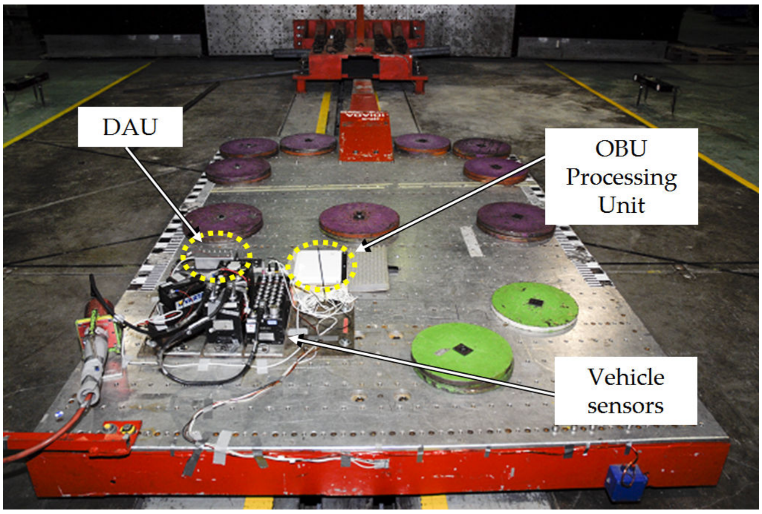


Figure 7.15: Sled with the e-NOTIFY prototype installed before a crash detection test.

Table 7.1: Validation tests performed on the e-NOTIFY system

Accident type	**Vehicle segment**	**Accident severity**	**Pulse duration**	**Acceleration**
Front acc.	Large Family Car	Severe accident	110 ms	23-28 G
	Large MPV	Minor accident	100 ms	15-21 G
	Small Family Car	No accident	110 ms	4-9 G
Side acc.	Small Off-Road 4x4	Accident	90 ms	14-21 G
	Supermini	No accident	90 ms	3-6 G
Rear-end acc.	Small MPV	Accident	110 ms	5-7 G
	Supermini	No accident	70 ms	2-6 G

continue working after the accident, and also ensuring the proper function of the system under a realistic crash situation.

All the tests produced very positive results, since the OBU did not suffer from noticeable damage even in the strongest impacts. The experiment helped to show that the OBU was able to correctly detect both the magnitude and direction of the impact. Figure 7.16 summarizes how acceleration pulses were handled by the e-NOTIFY system in two of the experiments. As shown, using a reduced sampling frequency a similar pulse shape is obtained with less than 10% variation in the integral value (approximated by the sum of smaller rectangle areas) compared to the area obtained using the highest sampling frequency.

In addition, the OBU generated an appropriate warning message from the sensor data and send it using UMTS technology to the Control Unit in all accident configurations, as shown in Figure 7.17. The latter properly processed the accident details, generating a correct estimation of the severity of the accident.

7.8 Summary

In this chapter we presented the e-NOTIFY system, which allows fast detection of traffic accidents, improving the assistance to injured passengers by reducing the response time of emergency services through the efficient communication of relevant information about the accident using a combination of V2V and V2I communications. The proposed system requires installing On-Board Units in the vehicles, in charge of detecting accidents and notifying them to an external Control Unit, which will estimate the severity of the accident and inform the appropriate emergency services about the incident. This architecture replaces the current mechanisms for notification of accidents based on witnesses, who may provide incomplete or incorrect information after a much longer time. The development of a low-cost prototype shows that it is feasible to massively incorporate this system in existing vehicles. We validated our prototype at the Passive Security Department of Applus+ IDIADA Corporation, and showed how it can successfully detect traffic accidents, reporting all the detailed information to a Control Alert System on time. Future work in this area includes deploying the system in a real environment with the OBUs installed in real vehicles to check the system behavior when moving at high speeds.

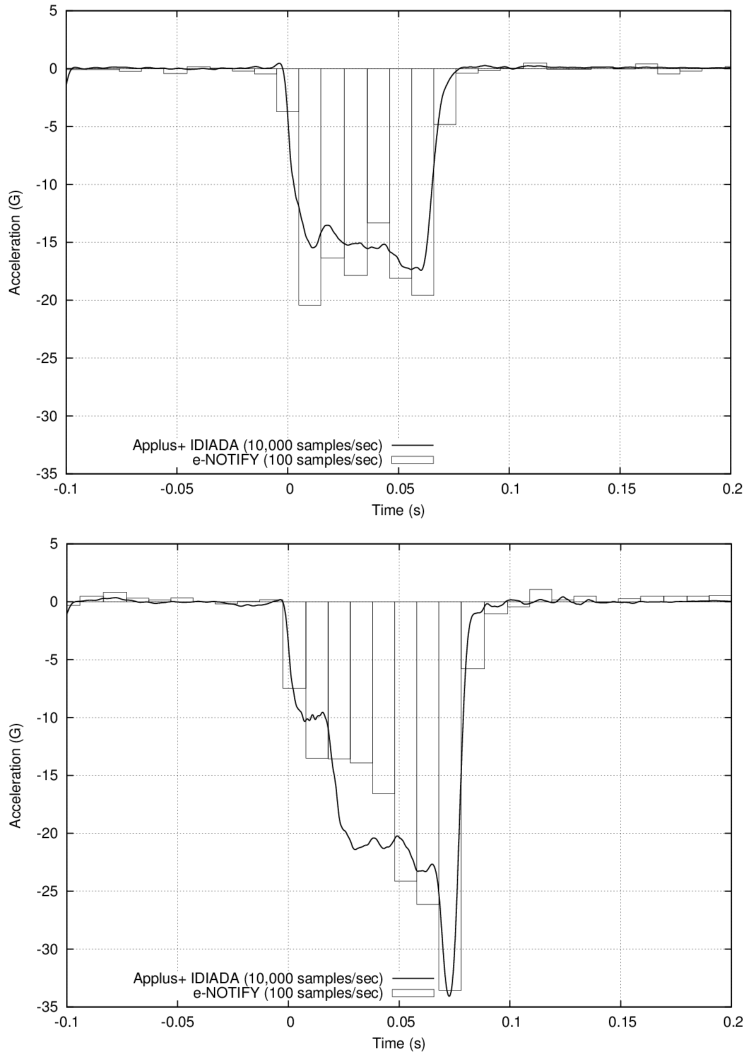


Figure 7.16: Acceleration pulses collected by Applus+ IDIADA compared to the samples obtained by the e-NOTIFY system in the same experiments: (a) front minor accident (top), and (b) front severe accident (bottom).

Connection state: Connected (1043 ms)

Front accident state: SEVERE ACCIDENT (1146)

Side accident state: No accident (0)

Back accident state: No accident (0)

LogSalida_15.dat

10 x

Notified alerts

State	Geo Loc.	Date	Acc. Type	Rollover	Severity	Rescue card	File	More Info.
112 ✗	🌐	**2011-05-25 13:48:58**	**Front (severe)**	**NO**	!!!		📁	✚
112 ✓	🌐	2011-05-24 20:34:45	Back	NO	!		📁	✚
112 ✓	🌐	2011-05-11 20:34:45	Back	NO	!		📁	✚
112 ✓	🌐	2011-05-11 18:33:25	Front (minor)	NO	!		📁	✚
112 ✓	🌐	2011-05-11 17:58:41	Right	NO	!		📁	✚
112 ✓	🌐	2011-05-06 11:15:38	Front (severe)	NO	!!!		📁	✚

Figure 7.17: Images of the crash test results: (a) Accident pulse recorded by the OBU (top), and (b) the same accident notified and received by the CU (bottom).

Chapter 8

Improving Accident severity estimation through Knowledge Discovery in Databases

New communication technologies integrated into modern vehicles offer an opportunity for better assistance to people injured in traffic accidents. Recent studies show how communication capabilities should be supported by artificial intelligence systems capable of automating many of the decisions to be taken by emergency services, thereby adapting the rescue resources to the severity of the accident and reducing assistance time. To improve the overall rescue process, a fast and accurate estimation of the severity of the accident represent a key point to help the emergency services to better adapt the quantity of required resources.

This chapter proposes a novel intelligent system which is able to automatically estimate the severity of traffic accidents based on the concept of data mining and knowledge inference. Our system only considers the most relevant variables that can characterize the severity of the accidents (variables such as the vehicle speed, the type of vehicles involved, the impact speed, and the status of the airbag).

Results show that a complete Knowledge Discovery in Databases (KDD) process, with an adequate selection of relevant features, allows generating estimation models able to predict the severity of new accidents. Classification based on Bayesian networks was able to outperform algorithms based on decision trees and Support Vector Machines (SVMs), and a prior division of collisions depending on the impact direction increased the accuracy of the system.

8.1 Introduction

To reduce the number of road fatalities, vehicular networks will play an increasing role in the *Intelligent Transportation Systems* (ITS) area. Most ITS applications such as road safety, fleet management and navigation, will rely on data exchanged between the vehicle and the roadside infrastructure (V2I) or even directly between vehicles (V2V) [MCC^{+}09]. The integration of sensoring capabilities on-board of vehicles, along with peer-to-peer mobile communication among vehicles, are expected to provide significant improvements in terms of safety in the near future.

Before arriving to the zero accident objective on the long term, a fast and efficient rescue operation during the hour following a traffic accident (the so-called *Golden Hour*) significantly increases the probability of survival of the injured, and reduces the injury severity [MTC$^+$10]. Hence, to maximize the benefits of communication systems between vehicles, the infrastructure should be supported by intelligent systems capable of estimating the severity of accidents, and automatically deploying the actions required, thereby reducing the time needed to assist injured passengers. Many of the manual decisions taken nowadays by emergency services are based on incomplete or inaccurate data, which may be replaced by automatic systems that adapt to the specific characteristics of each accident. A preliminary assessment of the severity of the accident will help emergency services to adapt the human and material resources to the conditions of the accident, with the consequent assistance quality improvement [FGM$^+$11e].

In this chapter, we take advantage of the use of Vehicular Networks to collect precise information about road accidents that are used to estimate the severity of the collision, using the e-NOTIFY architecture presented in Chapter 7. The accident severity estimation was one of the most important modules in the Control Unit structure of the proposed architecture, and this chapter contains the efforts towards algorithms able to predict how dangerous an accident has been. We propose an estimation based on data mining classification algorithms, trained using historical data about previous accidents, which will serve as an input for the resource allocation algorithms presented in Chapter 9. Note that our proposal does not focus on reducing the number of accidents, but on improving post-collision assistance.

The rest of the chapter is organized as follows: Section 8.2 reviews the related work on data mining for accident severity estimation. Section 8.3 presents the architecture of our proposed automatic system to improve accident assistance, providing details of our KDD model adapted to the traffic accidents domain. Finally, Section 8.4 concludes this chapter.

8.2 Previous Approaches towards Accident Severity Estimation using Data Mining

Despite the interest that may arise from understanding the influence of various factors on road accidents, the number of works about this topic in the literature is not particularly large. In addition, most attempts to carry out a data mining process related to traffic accidents only considered data from a single city or a very small area, making results little representative.

Several works are based on data obtained from the Traffic Office of Ethiopia, since this country presents one of the largest number of accidents per capita. [BH10] used data from 18,288 accidents around Addis Ababa as the basic data set. This study uses Naïve-Bayes, decision trees, and k-nearest neighbors (KNN) algorithms to classify the data using a cross-validation methodology, with accuracy values close to 80%. However, the authors only provided estimations for the whole accident, not for single occupants. Data from Ethiopia was also used to build regression tree models for accident classification by [TAG05]. Only 13 out of 36 variables available in the data were used to build the classification models, but the selection process was not shown, and again only estimations about the whole accident were provided.

The area of South Korea was also used to develop classification models based on artificial neural networks, decision trees, and logistic regression [SS01]. The data set involved 11,564 accidents, and the authors concluded that the different classification algorithms obtain similar results in terms of accuracy, being the use of protection devices, such as the seat belt and the airbag, the most relevant factor to classify accidents. This work was extended by [SL03] using ensemble methods (i.e., multiple models to obtain better predictive performance than could be obtained from any of the constituent models) combined with a prior assignation of instances through clustering, attaching a different classification model to each cluster, which produced a better class assignment.

More recently, [CAP05] selected data from all the United States obtained during the 1995-2000 period to propose a set of models based on artificial neural networks, decision trees and Support Vector Machines (SVMs). All the classification models presented similar accuracy results, and they were highly effective at recognizing fatal injuries.

Finally, some authors have focused on the characteristics of specific road segments, instead of using the data from individual vehicles. Clustering of accident hotspots were performed by [And09] in order to determine effective strategies for the reduction of high density areas of accidents. She studied the spatial patterns of injury related to road accidents in London (UK), and she found several hotspots with relevant significance using K-means clustering. [NEWP11] used a road-based approach for modeling the crash proneness of road segments using available road and crash attributes, classifying the road depending on their “crash proneness”. They also used a prior clustering of the accidents with similar features, and a consequent classification of the data by means of decision trees. However, they did not use different severity levels on the accidents studied.

From previous works, we detected significant shortcomings when attempting to combine their results with vehicular networks, since existing works about estimating the severity of road accidents have not been used to improve the assistance to injured passengers. All these papers used a whole variety of attributes to build the classification models, whereas only some of them could be effectively extracted from the vehicle itself (e.g., the driver’s inebriation level). In addition, none of them used an adequate feature selection algorithm to select the optimal variable subset. Finally, some of the models are extensively used (decision trees), while other interesting methods received little attention (SVMs and Bayesian networks).

8.3 Our Proposal

Our approach collects information available when an accident occurs, captured by sensors installed in the vehicle the previously proposed e-NOTIFY architecture. Based on this information, we plan to directly estimate the accident severity by we comparing the obtained data with information coming from previous accidents stored in a database. This information can be used, for example, to determine the most suitable set of resources in a rescue operation. Since we want to consider the information obtained just when the accident occurs, to estimate its severity immediately, we are limited by the data automatically retrievable, omitting other information, e.g., about the driver's degree of attention, drowsiness, etc.

8.3.1 Estimating Traffic Accidents Severity using a KDD-based approach

The KDD [FPSS96] can be defined as the nontrivial process of identifying valid, novel, potentially useful, and understandable patterns from existing data. The KDD process begins with the understanding of the application specific domain and the necessary prior knowledge. After the acquisition of initial data, a series of phases are performed:

1. Selection: This phase determines the information sources that may be useful, and then it transforms the data into a common format.
2. Preprocessing: In this stage, the selected data must be cleaned (noise reduction or modeling) and preprocessed (missing data handling).
3. Transformation: This phase is in charge of performing a reduction and projection of the data to find relevant features that represent the data depending on the purpose of the task.
4. Data mining: This phase basically selects mining algorithms and selection methods which will be used to find patterns in data.
5. Interpretation/Evaluation: Finally, the extracted patterns must be interpreted. This step may also include displaying the patterns and models, or displaying the data taking into account such models.

Previous proposals do not develop a complete KDD process. In fact, the only phase of the KDD process that has received widespread attention is the data mining phase, while the rest has been overlooked or summarized as much as possible. Although data mining is a very important phase, the results obtained when omitting the previous phases can loose their interest or utility. Therefore, we propose to develop a complete KDD process, starting by selecting a useful data source containing instances of previous accidents. The data collected will be structured and preprocessed to ease the work to be done in the transformation and data mining phases. The final step will consist on interpreting the results, and assessing their utility for the specific task of estimating the severity of road accidents. The phases from the KDD process will be performed using the open-source Weka collection, which is a set of machine learning algorithms [HFH$^+$09]. Weka is open source software issued under the GNU General Public License which contains tools for data pre-processing, classification, regression, clustering, association rules, and visualization.

We will deal with road accidents in two dimensions: (i) damage on the vehicle (indicating the possibility of traffic problems or the need of cranes in the area of the accident), and (ii) passenger injuries. These two dimensions seem to be related, since heavily damaged vehicles are usually associated with low survival possibilities of the occupants. Consequently, we will use the estimations obtained with our system about the damage on the vehicle to help in the prediction of the occupants' injuries.

Finally, our system will benefit from additional knowledge to improve its accuracy, grouping accidents according to their degree of similarity. We can use the criteria used in numerous studies about accidents, including some tests such as the Euro NCAP [Eur12a], in which crashes are divided and analyzed separately depending on the main direction of the impact registered due to the collision. The following sections contain the results of the different phases of our KDD proposal.

8.3.2 Data acquisition, Selection and Preprocessing Phases

Developing a useful algorithm to estimate accident severity needs historical data to ensure that the criteria used are suitable and realistic. The *National Highway Traffic Safety Administration* (NHTSA) maintains a database with information about road accidents which began operating in 1988: the General Estimates System (GES) [Nat12c]. The data for this database is obtained from a sample of Police Accident Reports (PARs) collected all over the USA roads, and it is made public as electronic data sets [Nat12b].

In the traffic accidents domain, the most relevant sets of information in GES are: (i) *Accident*, which contains the crash characteristics and environmental conditions at the time of the accident, (ii) *Vehicle*, which refers to vehicles and drivers involved in the crash, and (iii) *Person*, i.e., people involved in the crash. We will integrate the data harvested during the year 2011 into two different self-built sets: one for the vehicles and another one for the occupants.

Using the data contained in the GES database, we classify the damage in vehicles in three categories: (i) *minor* (the vehicle can be driven safely after the accident), (ii) *moderate* (the vehicle shows defects that make it dangerous to be driven), and (iii) *severe* (the vehicle cannot be driven at all, and needs to be towed). Focusing on passenger injuries, we will also use three different classes to determine their severity level: (i) *no injury* (unharmed passenger), (ii) *non-incapacitating injury* (the person has minor injuries that does not make him lose consciousness, or prevent him from walking), and (iii) *incapacitating or fatal injury* (the occupants' wounds impede them from moving, or they are fatal).

After preprocessing the selected GES data, no noise or inaccuracies were detected as all the nominal and numerical values contained reasonable values. Due to the large number of records available in the database, we decided to only use those accident records with all the required information complete. After removing incomplete instances, our data sets consist of 14,227 full instances of accident reports (5,604 front crashes, 4,551 side crashes, and 4,072 rear-end crashes).

8.3.3 Transformation Phase

This phase consists on developing a reduction and projection of the data to find relevant features that represent the characteristics of the data depending on the objective. We selected a potential subset of variables which could be obtained from the on-board sensors of the vehicle or auxiliary devices such as the GPS. Those variables include the type of vehicle, the speed just before the accident, and the airbag status. Concerning passengers, there are specific characteristics for each person that are not directly accessible, but might help to improve the prediction accuracy. We added two of these personal variables to our data -age and sex-, which will be used to study their relevance on the injuries suffered.

Weka provides a wide variety of feature selection algorithms. Among them, we selected three of the most commonly used:

- Correlation-based Feature Selection (*CfsSubsetEval*) [Hal08]: This filtering algorithm considers that the selection of attributes for classification tasks can be performed from the degree of correlation between attributes. The basic idea is to consider an appropriate subset of attributes that contains features highly correlated with the class (accident severity), but not correlated with each other.

- Information gain selection (*InfoGainAttributeEval*): The information gain metric is one of the most commonly used to evaluate the discriminatory power of an attribute. It is based on the entropy (measure of the uncertainty associated with a random variable) of a set of training examples, and it aims at verifying the entropy change when introducing knowledge about the values of a variable to determine the degree of reduction of uncertainty about the class.

- Wrapper technique (*WrapperSubsetEval*) [KJ97]: This method is based on a search through all the space of possible variable subsets, aimed at finding the state presenting the highest score determined by a guiding heuristic (accuracy, for example). A learning scheme or induction algorithm is required to calculate the score for any given subset. The wrapper approach normally requires more computing time, but it usually improves accuracy.

We determined the optimal variable subset with the three different schemes, and we chose for our final subset those variables selected by, at least, two of the previous algorithms. All the tested variables and the results of the feature selection process appear in Table 8.1. The top part of the table contains variables about the vehicle involved in the accident, and hence also applicable to the occupants of that vehicle. The bottom part shows variables only applicable to individual occupants. We compared the results of the process when using the whole data set available (*Full Set*), and dividing these data into three subsets depending on the direction of the impact.

As shown, we find noticeable differences between the sets determined for the full set of accident data, and for each of the divisions depending on the direction of the impact. The most relevant attributes (in almost all cases) are the body

Table 8.1: Most relevant variables for vehicle damage and passenger injury estimation.

Attribute	Vehicle damage				Passenger Injury			
	Full Set	Front	Side	Rear-end	Full Set	Front	Side	Rear-end
Body Type	✓		✓	✓	✓	✓	✓	✓
Light Condition	✓	✓		✓				✓
Model Year				✓				
Point of Impact	✓		✓		✓			
Road Align[a]						✓		
Road Profile[b]		✓				✓		
Rollover	✓	✓	✓	✓	✓		✓	✓
Speed	✓	✓	✓	✓	✓	✓	✓	
Speed limit	✓	✓	✓	✓	✓		✓	✓
Surface condition				✓				
Trailer			✓	✓	✓		✓	✓
Vehicle role[c]		✓	✓					✓
Weather			✓	✓				
Airbag					✓	✓	✓	✓
Age								
Restraint system					✓	✓	✓	
Seat position							✓	
Sex							✓	
Veh. damage estim.					✓	✓	✓	✓

[a] Roadway alignment just prior to the vehicle's critical precrash event (straight, curve)

[b] Roadway profile just prior to the vehicle's critical precrash event (level, grade, hillcrest, sag)

[c] Determines whether the vehicle was the striking or the struck one

type, the occurrence of rollover, the speed, the speed limit, the presence of a trailer, the airbag status, and the estimation on vehicle damage. When we divide the instances, new important values appear, like the road profile when considering front accidents, or the light condition for rear-end crashes, which were not detected when using the full data set.

For accidents in which the vehicle strikes another urban infrastructure of the road, the attribute that offers a better approximation to determine the accident severity is the speed of the vehicle before the impact. Nevertheless, if you want to estimate the damage when the vehicle is struck by another one, the type of vehicle and the speed limit in the area are more important variables than the speed itself, as deduced by studying side and rear-end accidents. The speed limit in the area of the accident is a good estimator of the speed of other vehicles, and usually accidents occurring in highways are more severe than those in residential areas where the speed limit is lower.

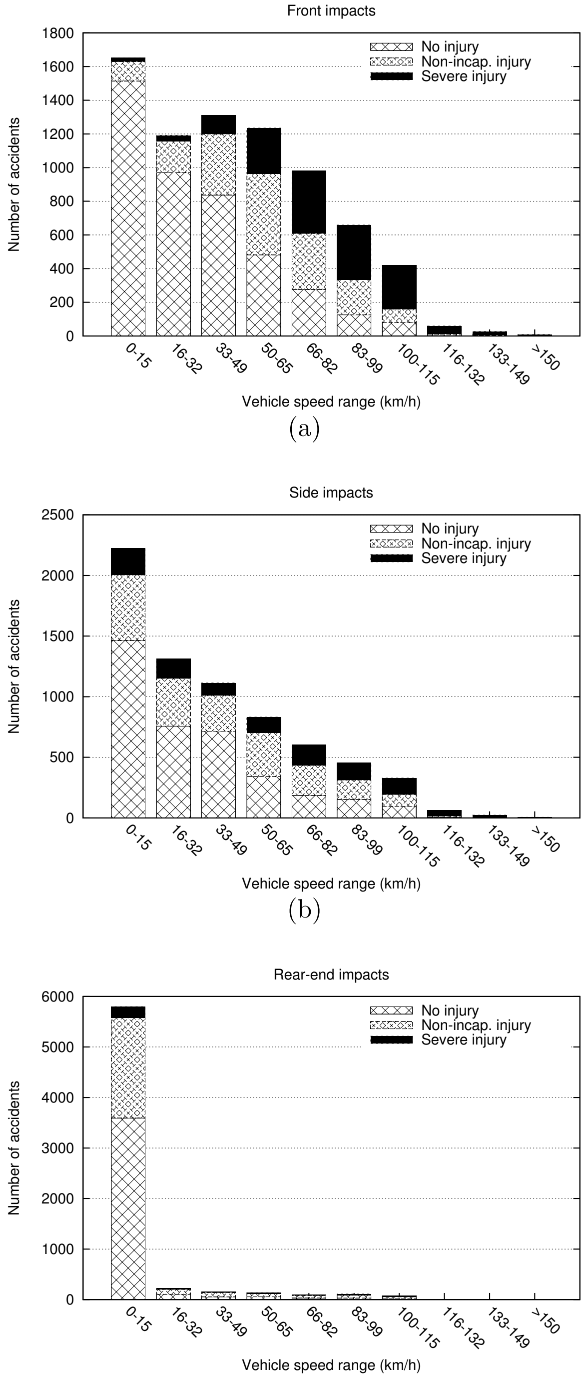
This effect is shown in Figures 8.1 and 8.2, which highlight the influence of the speed of the vehicle and the speed limit on the severity of the passengers' injuries, respectively. The severity of front collisions is clearly dependent on the speed of the vehicle itself, since more than half of the registered accidents occurred at speeds greater than 80 km/h resulted on severe injuries to the passengers. However, this dependence is less visible for side impacts, where the proportion between injury levels remains more stable, and especially for rear-end impacts, where almost 85% of the accidents happened when the vehicle was moving at speeds below 15 km/h. Using the speed limit as an indicator, Figure 8.2(c) shows that minor accidents are the dominant type for speed limits under 60 km/h, and that collisions above this speed were associated with different levels of severity on the passengers' injuries.

The selection of most of these variables is quite intuitive, but there are some important and non obvious considerations. The restraint system is not selected in all cases, as it would be reasonable, since it is not usually critical for the security of the passengers in rear-end collisions. Also, the year when the vehicle involved in the crash was manufactured is only relevant to determine the damages to the vehicle in rear-end collision. The presence of a trailer is also important, especially when the vehicle is struck by another one, which can cause dangerous situations such as uncontrolled articulation or *jackknife*.

8.3.4 Data Mining and Interpretation/Evaluation Phases

The most adequate data mining task for our interests is classification. Each instance has a record indicating its class membership, while the rest of the available attributes are used to predict the class of new instances. We selected three of the classification algorithms provided by Weka to study which one obtains the best results in terms of prediction accuracy:

- Decision trees: *J48* is an open source Java implementation of Quinlan's C4.5 algorithm [Qui93] found in Weka, designed to build decision trees from a training data set. At each node of the tree, this algorithm selects the attribute that most effectively separates the sample set into subsets with a

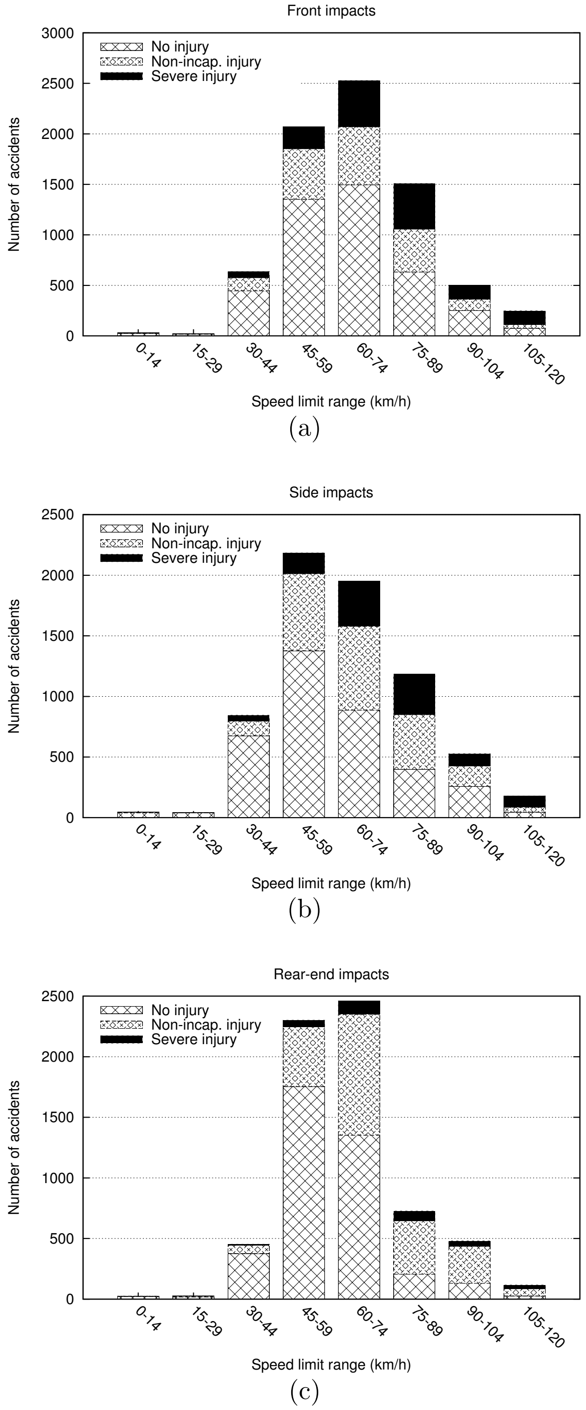


(a)

(b)

(c)

Figure 8.1: Influence of the speed of the vehicle on the distribution of the severity of the passengers' injuries in (a) front, (b) side, and (c) rear-end impacts.



(a)

(b)

(c)

Figure 8.2: Influence of the speed limit on the distribution of the severity of the passengers' injuries in (a) front, (b) side, and (c) rear-end impacts.

predominant class value. Most existing works in this area makes use of this tool to classify road accidents, and thus we will use it as well as reference.

- Bayesian networks: Bayesian networks allow modeling a phenomenon with a set of random variables and the dependency relationships between them. Those variables represent qualitative knowledge of the model by a directed acyclic graph in which the variables are represented as nodes, and the relationships of dependence and conditional independence between them are shown as arcs between the nodes. They also allow to express the strength of the relationship through probability distributions. We will use the *BayesNet* implementation of Bayesian networks, available in Weka, along with the K2 algorithm [CH92] to find the graph that best represents the set of dependence or independence in the data. This model has been rarely used in this domain, despite its power to represent complex phenomenons.

- Support Vector Machines: SVMs are a set of supervised learning algorithms that are based on the construction of a set of hyperplanes in a high dimensional space (generated by a kernel function) to separate instances from different classes. We will use the SMO algorithm [Pla99] to train the SVMs from the GES database.

These algorithms present different parameters that must be tuned to maximize the accuracy of the built models. The specific parameters used for each algorithm are: the prune level in decision trees, the number of parents in Bayesian networks, and the specific kernel function used in SVMs. We carried out several tests to obtain the sets of values that produce the best performance for the selected metrics, corresponding to the results shown.

The effectiveness of the classification can be measured using different metrics. One of the most used ones is the True Positive Rate (TP Rate) or percentage of instances correctly classified by the algorithm. Nevertheless, this metric could lead to wrong impressions, since those classifiers which focus their attention on the most frequent class would get a good value on this metric, but their utility is low as they are not able to differentiate among the existing classes properly. The False Positive Rate (FP Rate), i.e., the percentage of classification errors with respect to the total number of instances belonging to the right class, should also be considered to determine the efficiency of the classification process.

To cope with the deficiencies of the TP Rate metric, we will also use the area under the ROC (Receiver Operating Characteristics) curve, abbreviated as AUC [Faw04]. The possible values of this metric vary between 0.5 (for random classifiers with low efficiency) and 1.0 (for a perfect classifier), and it is computed using both the True Positive Rate and the False Positive (FP) Rate. Hence, the AUC metric presents some desirable features when compared to the overall accuracy [Bra97]: (i) it provides an increased sensitivity in Analysis of Variance (ANOVA) tests because the standard error decreases as both AUC and the number of test samples increase, (ii) it is invariant to *a priori* class probabilities, and (iii) it offers an indication of the amount of work done by a classification scheme, providing low scores to both random and “one class only” classifiers.

8.3.4.1 Results of the classification

Figures 8.3 and 8.4 show the results of the selected algorithms for both the TP Rate and the AUC metrics. Results were obtained by using 10-fold cross validation, which reduces the dependence of the result from the classification process in terms of the partition made for training and validation.

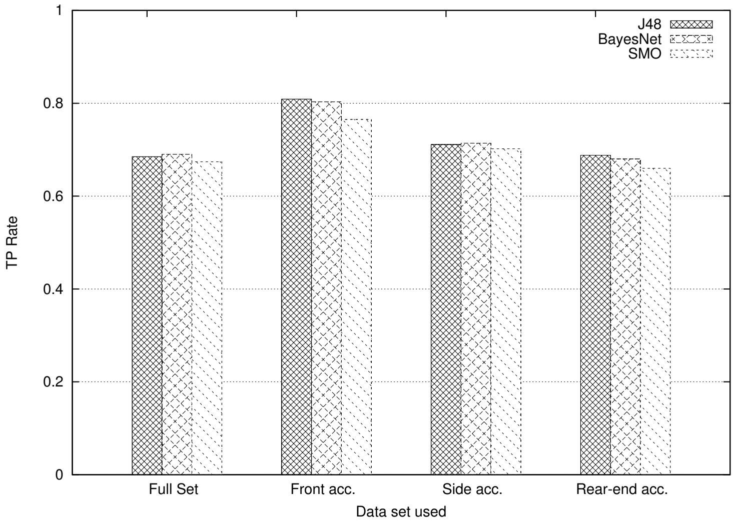
When estimating the damages in vehicles (see Figure 8.3), the three algorithms showed similar performance using the TP Rate metric (though *SMO* is slightly worst in all cases), with an overall accuracy about 70 or 80%. However, there are noticeable differences between the schemes under the AUC metric, showing a clear advantage for the *BayesNet* algorithm. This means that Bayesian networks are more robust when facing doubtful cases, and they are not so focused in the majority class. When we divide the accidents depending on the direction of the impact, we obtain a relevant increase on the accuracy for both metrics, showing average results much higher than those achieved with the full data set. Rear-end impacts were the most difficult to estimate, since there was a high proportion of instances where the car itself was struck by another vehicle, making it harder to estimate the damage without knowing all the details of the other vehicle.

If we try to estimate the injuries on passengers (see Figure 8.4), we observe a very similar trend. All the algorithms are very close in terms of the TP Rate metric (even closer than estimating the damage in the vehicle), and again the overall accuracy ranges from 70% to 80%. The differences between the three algorithms increase when we select the AUC metric, and *BayesNet* outperforms the other algorithms as well. Dividing the accident data in subsets also considerably improves the results under both metrics. However, when studying rear-end collisions, we obtain high values of TP Rate but lower results of AUC. This effect is due to the proportion of classes of this subset, since there are very few cases where passengers suffered from very severe injuries. In those cases, the algorithms reduce the probability of belonging to this class, and, even if the number of instances correctly classified is high, the AUC metric penalizes any excessive focus on a subset of the classes. This situation might improve if we were provided with additional information about the colliding vehicle, which will be possible using vehicular networks, including both V2V and V2I.

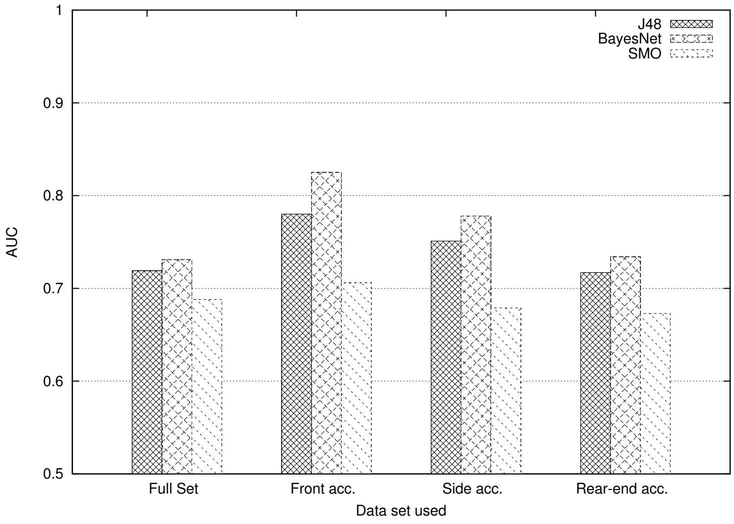
8.3.4.2 Bayesian models for accident severity estimation

Tables 8.2 and 8.3 show the conditional dependences found on the variables selected when estimating the severity of a road accident. In the Bayesian models, all the variables have at least one parent: the value of the class (severity of the damage on the vehicles or the passengers' injuries, respectively).

By studying the tables, we can find some intuitive connections, present in almost all cases. The type of vehicle (body type) presents strong connections with the presence of trailer, since more than 80% of the instances where the vehicle was towing a trailer, the vehicle was a heavy truck. The speed of the vehicle is the variable presenting more connections with other variables: speed limit (the speed is usually higher as the speed limit increases, representing an upper limit to the speed in most cases), rollover (only 15% of the registered overturned vehicles

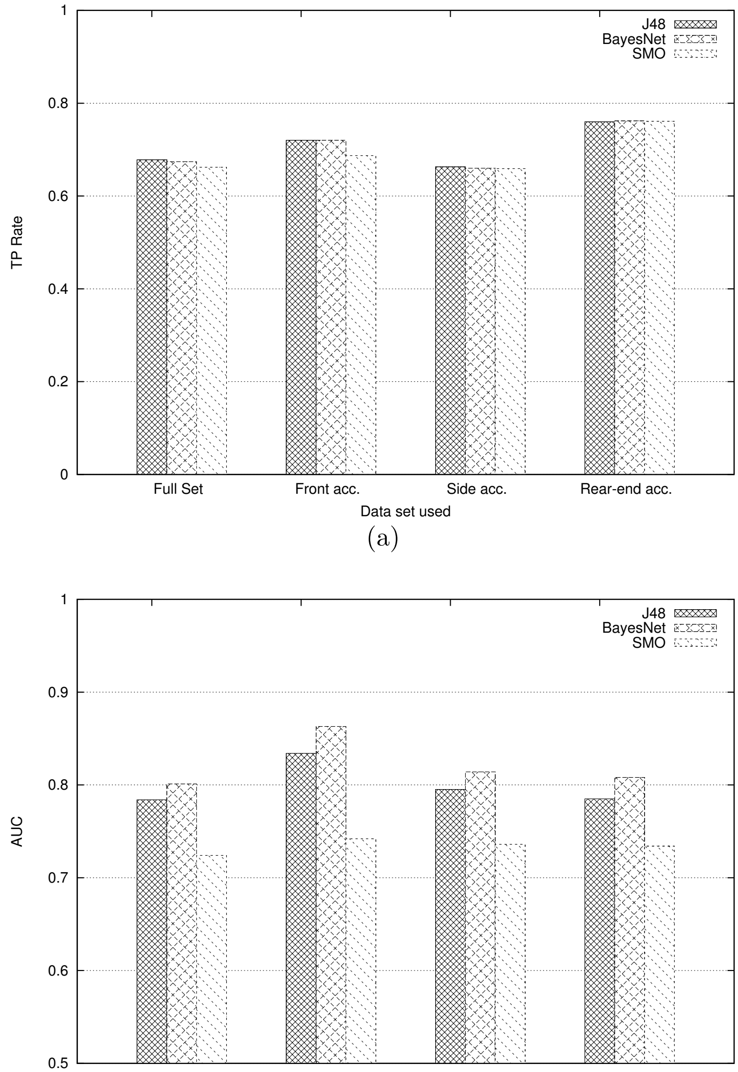


(a)



(b)

Figure 8.3: Comparison of different data mining classification algorithms in the estimation of the damage on the vehicle due to the accident: (a) using the TP Rate metric, and (b) using the AUC metric.



(a)

(b)

Figure 8.4: Comparison of different data mining classification algorithms in the estimation of the injuries of the passengers in the vehicle: (a) using the TP Rate metric, and (b) using the AUC metric.

Table 8.2: Main conditional dependences between variables used to estimate the damage on the vehicles.

Accident type	**Dependences**
Front accident	*Light condition, Speed limit ⟶ Speed*
	Speed ⟶ Rollover, Vehicle role
Side accident	*Body type ⟶ Speed, Trailer, Rollover*
	Speed limit ⟶ Speed
	Speed ⟶ Rollover, Vehicle role
Rear-end accident	*Light condition, Surface condition, Speed limit ⟶ Speed*
	Speed ⟶ Rollover
	Body type ⟶ Trailer
	Weather ⟶ Surface condition

Table 8.3: Main conditional dependences between variables used to estimate the injuries of the passengers.

Accident type	**Dependences**
Front acc.	*Speed ⟶ Restraint system, Vehicle damge*
	Body type ⟶ Speed, Airbag
Side acc.	*Speed limit ⟶ Speed, Restraint system, Vehicle damage*
	Speed ⟶ Rollover, Vehicle damage
	Body type ⟶ Airbag, Restraint system, Trailer, Seat position
Rear-end acc.	*Speed limit ⟶ Vehicle damage, Vehicle role, Light condition, Body type*
	Body type ⟶ Airbag, Rollover

occurred at speeds under 60 km/h), light condition (vehicles usually reach the highest speed under good visibility conditions), and so on. Seat belts and airbags are found more often in touring cars; thus, the airbag status and the restraint systems usage is strongly related to the type of vehicle.

However, we find that some of the probabilities generated are not so intuitive. For example, the probability tables associated to front and rear-end impacts for passengers' injuries estimation show that, under daylight conditions, the majority of accidents are not very severe, while at dawn and dusk the probability of severe accidents increases up to 60%. This means that, when the light begins to decline but it is still not enough to use car lighting systems, accidents tend to be more severe.

The airbag status becomes the most determinant value for determining the injury severity on the passengers in front and side collisions. When the airbag does not need to be deployed, the impact is not usually dangerous for the passengers, whereas strong collisions where the airbags have to be deployed present a greater magnitude that could affect the passengers' health. To prove this observation, about 70% of the registered cases where the airbag was not deployed, resulted in few injuries on the passengers, and the occupants suffered from severe injuries in more than 60% of the instances with deployed airbag. In rear-end collisions, the airbag is rarely deployed (less than 5% of the available instances), making the body type and the speed limit the most relevant features in the classification.

8.4 Summary

The new communication technologies integrated into the automotive sector offer an opportunity for better assistance to people injured in traffic accidents, reducing the response time of emergency services, and increasing the information they have about the incident just before starting the rescue process. However, the effectiveness of this technology can be improved with the support of intelligent systems which can automate the decision making process associated with an accident. A preliminary assessment of the severity of an accident is needed to adapt resources accordingly. This estimation can be done by using historical data from previous accidents using a Knowledge Discovery in Databases process.

Most of the existing work focused on data mining in traffic accidents was based on data sets where a very limited preprocessing and transformation were performed. After a careful selection of relevant attributes, we showed that the vehicle speed is a crucial factor in front crashes, but the type of vehicle involved and the speed of the striking vehicle are more important than speed itself in side and rear-end collisions. The status of the airbag is also very useful in the estimation, since situations where it was not necessary to deploy the airbag rarely produce serious injuries on the passengers.

The studied classification algorithms do not show remarkable differences in terms of percentage of instances correctly classified, with an accuracy in the range 70-80%. However, since the AUC metric takes into account both the true and false positive rates, we found that Bayesian networks were able to outperform decision trees and support vector machines. Dividing the accidents depending on the types of impacts allows noticeably increasing the accuracy of the system, especially for front crashes where the vehicle itself is usually the striking one. The accuracy estimation of the severity of side and rear-end crashes could be significantly increased if we were provided with data from other vehicles involved in the collision, which will be possible using inter-vehicles communication technologies.

The estimation of the severity of a road accident is invaluable for the emergency services to improve the assistance after a collision. The immediate use of this information is to determine the most appropriate resource set for the deployment of a rescue operation.

Chapter 9

Improving Traffic accidents sanitary resource allocation based on Multi-Objective Genetic Algorithms

The development of communication technologies integrated in vehicles allows creating new protocols and applications to improve assistance in traffic accidents. Combining this technology with intelligent systems will permit to automate most of the decisions needed to generate the appropriate sanitary resource sets, thereby reducing the time from the occurrence of the accident to the stabilization and hospitalization of the injured passengers. However, generating the optimal allocation of sanitary resources is not an easy task, since there are several objectives that are mutually exclusive, such as assistance improvement, cost reduction, and balanced resource usage.

In this chapter, we propose a novel approach for the sanitary resources allocation in traffic accidents. Our approach is based on the use of multi-objective genetic algorithms, and it is able to generate a list of optimal solutions accounting for the most representative factors. The inputs to our model are: i) the accident notification, which is obtained through vehicular communication systems, and ii) the severity estimation for the accident, achieved through data mining.

We evaluate our approach under a set of vehicular scenarios, and the results show that a memetic version of the NSGA-II algorithm was the most effective method at locating the optimal resource set, while maintaining enough variability in the solutions to allow applying different resource allocation policies.

9.1 Introduction

The elapsed time from the accident occurrence to the moment where the affected passengers are stabilized and hospitalized is critical to increase their survival probability, while reducing the severity of their injuries. This concept is commonly known as the *Golden Hour* [MTC$^+$10]. ITS services and communication technologies may definitely help at reducing this time by providing fast accident notification to the control centers in charge of traffic surveillance; however, those services still demand an accurate estimation of the severity of the accident, and the potential danger for the occupants to generate an adequate emergency response to assist the injured. Therefore, communication between vehicles should be supported by an infrastructure providing intelligent systems, capable of automatically deploying the set of actions required for each specific accident.

A preliminary assessment of the accident severity will help emergency services to adapt the human and material resources to the conditions of the accident, with the consequent assistance quality improvement. Data mining and vehicular networks can be successfully used together to notify and make a preliminary estimation of the severity of the accident, both in the injuries produced on the passengers and the damages on the vehicles, as shown in Chapter 8. However, it is still necessary to define how this information can be used to automatically achieve optimal resource allocation for the emergency operatives assigned to a crash. In this chapter, we propose a novel approach based on: (i) the information collected by vehicular networks, and (ii) the severity estimations provided by data mining. Our solution provides: (i) the most adequate set of resources for a specific traffic accident scenario, and (ii) information about which suppliers should provide these resources depending on factors like their proximity to the affected area, available resources, and experience dealing with similar accident situations. Our proposal is able to increase the chances of survival for the affected people, focusing on improving post-collision assistance.

The rest of the chapter is organized as follows: Section 9.2 presents a sanitary resource classification for traffic accidents. Section 9.3 shows the basis of the Multi-objective Optimization problems and how Genetic Algorithms (GA) can solve these problems. Section 9.4 presents the *Genetic Algorithm for Traffic Accidents Resource Allocation* (GATARA), our proposal for resource allocation. Section 9.5 evaluates the obtained results using a set of traffic accident scenarios. Finally, Section 9.6 concludes this chapter.

9.2 Sanitary resources required in a traffic accident

In every traffic accident involving injured people, it is essential to provide health care as soon as possible to minimize the potential damage to the occupants of the affected vehicles. However, not all the available ambulances and rescue teams incorporate the same equipment and medical staff, meaning that there are different types of vehicles with different medical attention capabilities [Spa98].

A preliminary classification of sanitary vehicles divides them into assistance and non-assistance vehicles. The former allow providing health care during the transport of the patients, including the necessary sanitary equipment and staff, whereas the latter are merely able to transport patients on stretchers, being not specifically equipped for medical care. However, a closer look to the different types of assistance ambulances shows that, depending on the severity of injuries they are prepared to handle, they can be classified in the following groups (see Figure 9.1):

- Non-assistance Ambulances: also known as transport-only or support ambulances, consist of vehicles designed for the evacuation of patients alone, thereby not being specially equipped for providing assistance. The staff usually consists of one or two technicians, and the equipment is very basic, being unsuitable for the transportation of urgent patients. They usually include a stretcher and two seats in the rear area of the ambulance.

- Basic Life Support (BLS) Assistance Ambulances: vehicles equipped with all the equipment required to provide basic life support to the patient, reducing the risk of death or other consequences resulting from the injury or from the transport conditions. They are known as basic ambulances, or just BLS. The staff includes two trained technicians equipped with the basic equipment for the patient assistance and stabilization, i.e., material for first aid and immobilization, and oxygen. They can be used for first aid, as well as for the treatment and transportation of patients with minor injuries.

- Advanced Life Support (ALS) or Mobile Intensive Care Ambulances: vehicles with elements able to provide advanced life support, and the practice of surgery to the patient. The staff includes a doctor, a nurse, and at least one trained driver. In addition to the material of BLS ambulances, they include medication and electromedical equipment, providing all the needed material to treat patients with serious injuries while being carried to a hospital.

- Fast Intervention Vehicles (FIV): also known as medical vehicles, they are usually SUVs or large cars equipped with sanitary equipment to attend areas with rough terrain, under adverse weather conditions or in cases where special services are carried. The staff includes a a doctor and/or a nurse and a paramedic, and the available equipment is the same as for ALS units; however, they are unable to move patients, since they do not include stretchers. They are useful for their agility and speed, but they require an extensive network of BLS ambulances to provide transportation capabilities.

- Health Emergency Helicopters (HEH): air vehicles especially useful for reaching areas far away from hospitals. The staff includes a pilot, a mechanic, a doctor, a nurse, and sometimes a medical technician. The equipment is the same as for ALS ambulances, but they may not be used in urban areas due to the difficulty of finding adequate landing areas, and they require the existence of heliports at the final destination hospitals.

9.2.1 Features of the different sanitary vehicles

The existing sanitary vehicles used to provide support for traffic accidents can be classified according to several factors, related to the type of injured passengers they are able to assist, their ability to reach the crash site, and so on.

(a) (b) (c) (d) (e)

Figure 9.1: Classification of sanitary vehicles needed in a traffic accident: (a) Non-assistance ambulance, (b) BLS ambulance, (c) ALS ambulance, (d) FIV vehicle, and (e) HEH helicopter.

9.2.1.1 Severity of injuries supported

The injury severity or assistance category indicates the type of injuries for which the vehicle includes medical supplies and human resources. This assistance category is divided into three levels:

- Non-assistance: the vehicle does not include enough material to heal any type of wound that can not be stabilized by first aid. This type of vehicle can only be used for the transportation of passengers without serious injuries, and when the transportation time is not especially important. Non-assistance ambulances belong to this category.

- Basic Life Support (BLS): the vehicle contains additional material to stabilize the patient (immobilization equipment and oxygen), so it is possible to transport passengers with moderately severe injuries, or those which can be stabilized on the way to the hospital. BLS ambulances belong to this category.

- Advanced life support (ALS): the vehicle incorporates intensive care material and allows practicing surgery for severely injured patients. This type of transportation is particularly suitable for occupants who have suffered a severe accident, and so a fast intervention is crucial to ensure their survival. This category includes ALS ambulances, FIV vehicles, and HEH helicopters.

9.2.1.2 Passenger capacity

The capacity of a vehicle is expressed by the maximum number of passenger that can be transported in a standard service (depending on the seriousness of injuries). Passengers with severe injuries should be evacuated individually in different vehicles, due to the difficulty to stabilize them.

The maximum passenger capacity for the different medical vehicles is usually:

- Non-assistance Ambulance: 1 or 2 occupants

- BLS Ambulance: 1 or 2 occupants

- ALS Ambulance: 1 occupant

- Fast Intervention Vehicle (FIV): 0 occupants

- Helicopter (HEH): 1 occupant

Vehicles in charge of evacuating people with minor injuries would be able to carry more than one person at once, if they have been previously stabilized. FIV vehicles can not transport any patients. Finally, both ALS ambulances as HEMS helicopters are capable of transporting seriously injured passengers.

Table 9.1: Average speeds of sanitary vehicles

Vehicle type	Area type		
	Urban	**Interurban**	**Rough terrain**
Non-assistance Ambulance	50 km/h	100 km/h	40 km/h
BLS Ambulance	50 km/h	100 km/h	40 km/h
ALS Ambulance	50 km/h	100 km/h	40 km/h
Fast Intervention Vehicle (FIV)	60 km/h	120 km/h	70 km/h
Helicopter (HEH)	250 km/h	250 km/h	250 km/h

9.2.1.3 Accessible areas

According to the characteristics of the vehicles, there are areas where access may be more or less complicated, or that directly impede their use in that area. The different zones can be classified as urban (cities or environments with a high density of buildings), interurban (roads and highways between cities or small towns with few buildings), and rough terrain (difficult road conditions and mountain area, among others). If an accident happens in an area with rough terrain, vehicles will find difficult reaching the accident area, and therefore their speed may be considerably reduced. Ambulances should generally move more slowly to reach an area of difficult access, whereas FIV vehicles are less affected and helicopters are not affected at all by the terrain. However, helicopters are not usually able to land with enough security in urban areas with many buildings.

9.2.1.4 Average speed

Each vehicle presents different speed depending on the area where it is moving, mostly due to the road conditions or the traffic laws. Our approach will consider the average speeds for the sanitary vehicles shown in Table 9.1.

9.2.1.5 Cost of service

Each vehicle type has different costs associated with its use, due to fuel consumption, required staff, operation licenses requirements, maintenance and insurance. The total cost depends on the total time of use and the distance traveled. Hence, we can divide the cost in three different items: a fixed usage cost, a staff cost depending on the required time for the emergency operation, and a variable cost per kilometer. For each sanitary vehicle, we define the cost of service in Table 9.2, obtaining the total cost as the sum of the values for each column. The data shown in Table 9.2 was obtained from an existing sanitary transport company in Spain [Amc12].

9.2.2 Sanitary vehicles allocation policy

To correctly decide the sanitary resources required to assist a traffic accident, it is convenient to do an *a priori* classification of the accident in order to optimize

Table 9.2: Cost of use of sanitary vehicles

Vehicle type	Cost		
	Fixed	**Medical Staff**	**Distance Traveled**
Non-assistance Ambulance	29 €	36 €/hour	0.68 €/km
BLS Ambulance	29 €	72 €/hour	0.68 €/km
ALS Ambulance	156 €	81 €/hour	1.56 €/km
Fast Intervention Vehicle (FIV)	156 €	45 €/hour	1.56 €/km
Helicopter (HEH)	468 €	81 €/hour	4.68 €/km

the resource usage. In our model, accidents are classified and handled according to the percentage of injured passengers, including their corresponding severity [FGM$^+$12e].

In general, there is no standardized method to allocate sanitary vehicles to accidents. Traditionally, resources are over-allocated, in anticipation of a particularly severe accident. However, some guidelines are provided in [Med12], where it is always recommended that the rescue operation includes a nurse and/or doctor, and at least one of the ambulances should be an ALS. Thus, the medical staff will have the corresponding medical equipment to adequately assist serious injuries. However, for minor injuries, a BLS ambulance is enough to provide the required first aid. Therefore, each accident should be individually studied to define the required equipment and personnel depending on the severity of the accident.

This issue will be included into our system by distinguishing three levels for accident classification:

- **Minor accidents**: Situations where there has been a minor collision and there is no risk of death for the occupants. In this type of accidents, there might be slight injuries among the passengers, but most occupants are considered unharmed. Since it is highly unlikely that this type of collisions need medical supplies beyond first aid, at least a BLS ambulance should be sent containing enough material for 3 passengers estimated to have minor injuries. The rest of the ambulances to be sent can be of the non-assistance type, allowing to evacuate the passengers to a hospital for further exploration. Many of these injuries will not even require transportation, being assisted in the accident site, so the allocated ambulances should be enough to transport 50% of the injured. We obtained this percentage by studying the accidents in the *General Estimates System* (GES) database [Nat12b] maintained by the *National Highway Traffic Safety Administration* (NHTSA), showing that accidents with these characteristics usually present about 30-50% of people involved with possible injuries greater than the initially estimated. However, the percentage is mainly orientative and it could be adapted to better represent accidents happening in a specific area if we had enough information collected using our system.

- **Intermediate accidents**: These accidents are not the most severe ones, although they may be potentially lethal for some of the passengers. Often, most passengers suffer from minor injuries, but there is at least one of them with a high probability of severe injuries. The rescue operation should include an ALS unit with material for every 3 injured passengers, as well as enough additional ALS vehicles to correctly evacuate the severely injured occupants individually. Due to the higher probability of dangerous injuries, it would be convenient to send enough BLS vehicles to transfer at least 75% of the rest of injured passengers. Again, the selection of this percentage is based on data from the GES database.

- **Severe accidents**: They represent the highest severity for a traffic accident. The collision was important enough to produce very severe injuries to the passengers. Hence, most of the occupants in the vehicles are estimated as severely injured. The rescue operation requires sending ALS vehicles for every passenger with potentially lethal injuries. Additional ALS units with support material should also be sent for every 3 people with minor injuries. To avoid unexpected complications on the affected passengers, all of them should be transfered to the nearest hospital by using BLS vehicles.

The selected resources for each accident will also depend on the conditions of the accident itself. Hence, for minor or intermediate accidents, the use of rescue helicopters should only be acceptable if they occur in areas located very far away from health centers. If the accident happens in a poor access area, it could be convenient to send a FIV vehicle in charge of the stabilization of the affected people before the arrival of other emergency vehicles.

Another possibility consists of sending vehicles with less assistance category than needed, due to the proximity to the crash site. This would be beneficial if it is possible to correctly evacuate the injured passengers to a health center faster than the required resources would need to reach the accident.

9.2.3 Objectives of the resource allocation

The greatest difficulty of the resource allocation problem resides in the different conflicting objectives when obtaining an optimal set. We would want to select the nearest resources from the accident area, but this is not always possible due to the cost of some of the resources: sending a helicopter to an accident without serious injuries would not be affordable, even though it is the fastest of all the available vehicles. Hence, the optimal solution must offer a balance between different objectives, often contradictory. We defined the following objectives for traffic accident assistance:

- **Assistance quality**: The first and most obvious of the objectives to be met is based on the assistance quality received by those injured in the accident. This parameter is measured in terms of the time it takes for medical teams to access the crash site, as well as the type of injuries they are able to attend. Thus, if a seriously injured passenger requires advanced life support to maximize his survival chances, and the system selects a basic life support equipment instead, this should be reflected in the assistance quality with a penalty.

- **Cost**: The second parameter to consider is the cost of the rescue operation. As we showed in the classification of resources, the cost for each resouce can be subdivided into several elements: licenses, insurance, travel, staff, etc. The value used to represent the cost will come from the sum of the individual costs of all vehicles, with their corresponding medical staff, dispatched to the scene of the accident.

- **Reduced resource overuse**: To avoid excessive wearing out of the equipment and vehicles, and fatigue in medical personnel involved in rescue missions, the equipment and human resources of the different suppliers should be used in the most equitable manner possible. This parameter has lower priority, since the care of the equipment should never overcome the health of the passengers, but there may be situations where different solutions provide similar assistance quality, and then this parameter may be used to choose between one or the other.

- **Balanced resource deployment**: The last factor to be considered avoids having any of the existing health centers deprived from all its resources at a given time, thereby preventing situations where a serious accident could occur in the vicinity.

It is easy to observe that these objectives are contradictory, since increasing the quality of the assistance to the injured is often only possible by increasing the cost of the emergency operative. The most adequate solution to the problem should take into account all these factors to reach an acceptable balance, that will also depend on the scenario and the economical and social environment.

9.3 Multi-objective Optimization: Search through Genetic Algorithms

The problem of resource allocation to traffic accidents is considered an optimization problem, since we know the model representing the system, and the goals to achieve. So, the objective is to find the input that achieves the given goals, i.e., the set of selected resources to be sent to the accident site. However, the goal is not simple, since we have four different objective functions: assistance quality, cost, reduced resource overuse, and balanced resource deployment. We propose to address this issue using an optimization problem approach following a multi-objective optimization based on genetic algorithms.

The rest of the Section is organized as follows: Section 9.3.1 presents the different existing approaches to multi-objective optimization. Section 9.3.2 introduces the evolutionary algorithms with their main features. Section 9.3.3 shows why evolutionary algorithms are appropriate for multi-objective optimization problems. Finally, Section 9.3.4 presents the Memetic Algorithms (MAs).

9.3.1 Multi-objective Optimization

The problem we face has a special feature compared to standard optimization approaches, where there is only one objective function to optimize and selecting the best solution is the common approach. Multi-objective problems are those having several objectives which are usually mutually exclusive, so that all of them can not be optimized at the same time. Those kind of problems are very common in engineering, where in most cases the performance or reliability is maximized with minimum cost.

Several approaches can be followed to address multi-objective optimization problems. The straightforward method consists on combining the individual objective functions into a single composite function, using methods such as utility theory or weighted averages. This approach has the advantage of being simple, not requiring changes in the optimization algorithm used with a single objective function. However, the selected weights or utility functions must be carefully tuned to characterize the preferences of the entity responsible for making decisions. In addition, very small changes in the weights may lead to very different solutions.

However, during a decision-making process, it may be preferable to have a good set of potential solutions on which to decide which better address each particular situation, rather than having just a single solution as obtained with the methods presented so far. This approach relies on generating a Pareto set of optimal solutions, also called Pareto front or Pareto frontier [Tei01].

The concept of Pareto efficiency was initially defined in the area of economy. According to Pareto, a situation Y is superior or preferable to a situation X when the change from X to Y is an improvement for all the members of the society; or an improvement for some, but no one is adversely affected [Par09]. This concept can be also applied to multi-objective optimization problems. Therefore, a solution $S1$ is Pareto-optimal when no other solution $S2$ improves an objective without worsening at least one of the other objectives. This is defined on the concepts of Pareto dominance and Pareto optimality:

- **Pareto dominance**: Given a vector $\mathbf{u} = (u_1, \cdots, u_k)$, it dominates another vector $\mathbf{v} = (v_1, \cdots, v_k)$ if:

$$\forall i \in \{1, \cdots, k\}, \ u_i \leq v_i \quad \wedge \ \exists i_0 \in \{1, \cdots, k\} \mid u_{i_0} < v_{i_0} \tag{9.1}$$

- **Pareto optimality**: A solution $\mathbf{x}^*$ is Pareto-optimal if there is no different vector $\mathbf{x}$ so that $\mathbf{v} = f(\mathbf{x}) = (v_1, ..., v_k)$ dominates $\mathbf{u} = f(\mathbf{x}^*) = (u_1, ..., u_k)$.

In general, the solution to a problem of multi-objective optimization is not unique: the solution will consist of the set of all non-dominated vectors, which are known as the non-dominated set, Pareto front or Pareto frontier. The Pareto frontier may have different sizes (even infinite), and the Pareto set size usually grows while increasing the number of objective functions (as a result of increased dimensionality of the problem). As a result, obtaining the full set of optimal solutions is not feasible for many problems. Thus, for practical purposes, the aim is to investigate a rough set of solutions that represent the best possible Pareto optimal set, leading to several conflicting objectives [ZDT00]:

- The approximate Pareto frontier should be as close to the true Pareto set as possible. Ideally, this approximate boundary should be a subset of the actual border. This requires intensifying the search in a particular region of the Pareto frontier.
- Solutions in the rough set should be evenly distributed along Pareto frontier, to provide decision-makers a clear picture of the sacrifices to be made to achieve the different solutions.
- The approximate set should capture the full spectrum of the Pareto frontier, which requires investigating the solutions at the ends of the space of objective functions, extending the set of Pareto.

In the existing literature, we can find different analytical and numeric algorithms to approximate the Pareto front, such as *Normal Boundary Intersection* (NBI) [ID98], *Normal Constraint* (NC) [MIYM03, MM04], and *Directed Search Domain* (DSD) [EU10]. However, these methods present several shortcomings due to the significant number of redundant solutions that they can generate [UFG09], and the problems that arise when the Pareto frontier is not continuous [SD07]. Nowadays, most of the existing related work about multi-objective optimization is based on the use of evolutionary algorithms, which could overcome those important drawbacks.

9.3.2 Evolutionary algorithms

Evolutionary algorithms have the ability to simultaneously search different regions of the solution space, including those with non-convex spaces, discontinuous, or multi-modal. Although there are different variants of evolutionary algorithms, the idea behind them all is the same: given a population of individuals, the environmental pressure produces a natural selection process that causes an increase in the adaptation level of the individuals to the environment. For each generation, some of the best candidates are chosen to create a new generation by applying the recombination and mutation operators, producing new individuals that will compete again in the environment. The general scheme of an evolutionary algorithm [ES03] is shown in Algorithm 4.

The recombination or crossover operator is usually the most important factor in this type of algorithms. It is based on combining two or more genotypes, i.e., gene sequences, called parents to form new genotypes, the offspring. Parents are selected from existing individuals based on their level of adaptation or fitness, so you can expect that the offspring inherits the good genes that make their parents the fittest. Applying iteratively this operator, it is more likely that the best chromosome genes appear more frequently in the population, ultimately leading to a convergence towards the best solutions.

The mutation operator is responsible for introducing random changes in the characteristics of the chromosomes, and it is usually applied at the gene level. As a rule, the mutation rate (probability of change in a gene) is usually very small and dependent on the length of the genotype, so that the new genotypes produced after the mutation will not be very different from the originals. The

Algorithm 4 General scheme for an evolutionary algorithm

```
BEGIN
INITIALISE population with random candidate solutions;
EVALUATE each candidate;
REPEAT UNTIL ( TERMINATION CONDITION is satisfied ) DO
1 SELECT parents;
2 RECOMBINE pairs of parents;
3 MUTATE the resulting offspring;
4 EVALUATE new candidates;
5 SELECT individuals for the next generation;
OD
END
```

role of the mutation in the evolutionary algorithms is also very relevant, since the recombination operator makes the individuals converge rapidly toward the best solutions found so far. However, there may be a region of the state space not previously explored, and so the mutation is used to reintroduce genetic diversity in the population, thereby avoiding local optima.

9.3.3 Multi-objective Optimization based on Evolutionary Algorithms

Through an appropriate use of the recombination and mutation operators of evolutionary algorithms, it is possible to obtain good solutions with respect to different objectives, obtaining new non-dominated solutions in the Pareto frontier. In addition, most of the developed evolutionary algorithms do not require the objective functions to be prioritized over each other, to be scaled, or to use weights to find weighted aggregate functions. For that reason, most optimization algorithms are multi-objective meta-heuristics based on an underlying evolutionary algorithm [JMT02].

The classical (and straightforward) approach to the problem of multi-objective optimization was based on assigning a weight (w_i) for each normalized objective function (f_i'), so the problem is reduced to a single objective formed as the weighted sum of these values. This method is known as *a priori*, since the user has to supply the values for the weights. A unique solution is obtained for each weight vector. However, as discussed above, the major drawback of this approach is that small variations in the weight vector can lead to completely different solutions.

More sophisticated versions of these algorithms approximate the Pareto frontier using different approaches. The first multi-objective genetic algorithm that appeared to approximate the Pareto frontier was the *Vector Evaluated Genetic Algorithm* (VEGA) [Sch85]. VEGA divides the population into subpopulations and assigns a different objective function to each of them. This approach could be easily implemented; however, the solutions tend to converge towards the extremes of the objective functions, achieving good results for one function but behaving very poorly for the rest.

The posterior *Multi-Objective Genetic Algorithm* (MOGA) [FF93] uses the fitness sharing concept, so that the search towards unexplored sections of the Pareto frontier is favored by penalizing the fitness value of the solutions in densely populated areas. The fitness value is obtained by assigning ranks to the different solutions, depending on whether they are in the Pareto front, and their distance to it. MOGA is an extension of a standard genetic algorithm, but it has slow convergence and requires additional parameters specification, which is not always easy and may require several tests to find them.

The *Pareto Envelope-based Selection Algorithm* (PESA) [CKO00] divides each dimension of the objective space into cells, where the cell size is defined by the user. The number of solutions in each cell is defined as the cell density, and this density information is used to achieve diversity in the individuals. PESA is easy to implement and efficient, but its performance depends on the size of the cells in each dimension, requiring prior knowledge of the objective space to decide how to divide it efficiently. The PESA-II extension [CJKO01] selects cells instead of individual solutions, but the cell size problem persists.

The *Nondominated Sorting Genetic Algorithm* (NSGA) [SD94] is a fitness-sharing algorithm characterized by its fast convergence towards the Pareto front. The population is classified as non-domination fronts, and each one receives a value of fitness that penalizes the nearest solutions. Similarly to other methods based on fitness sharing, it is difficult to adjust the parameters. To overcome this problem, a new version called NSGA-II [DPAM02] was proposed, which employs a crowding distance for a uniform distribution of the solutions in every front. This algorithm is very efficient and does not require additional parameters in the search, although the concept of crowding distance can be only applied to the objective function space, not to the solution space.

The different algorithms proposed were designed to guide the evolutionary process in order to obtain the optimal solution to a specific problem, being the NSGA-II algorithm, in theory, the most efficient variant in the literature. However, we still need to define the rest of the parameters needed to achieve proper results, such as the representation of individuals, and the crossover and mutation operators.

9.3.4 Hybridization with other techniques: Memetic Algorithms.

In practice, evolutionary algorithms are frequently applied to a problem in which a considerable amount of experience and knowledge is available. This information can then be used as specialized operators to produce performance benefits. In these cases, it is usual that the combination of evolutionary algorithm and a heuristic method performs better than either of the two original algorithms separately.

This type of hybrid algorithms, combining evolution with heuristics, are often based on the idea of “memes” [Daw76], which can be seen as units of cultural transmission, in the same way that genes are units of biological transmission. These memes are selected according to their utility, and transmitted through interpersonal communication. The idea of using information not encoded in the genes, increasing the evolutionary search process with different local search processes, makes these hybrid algorithms to be often known as Memetic Algorithms (MAs) [Mos89].

Hybridization of genetic algorithms with local search algorithms are frequently applied in single-objective approaches. Generally, a local search algorithm proceeds as follows: (i) start with an initial solution x, (ii) generate a set of neighboring solutions around the solution x using a simple rule of variation, and (iii) if the best solution on the set of neighbors is better than x, replace x with this solution and return to the second step, otherwise stop the search.

Hybridization in the multi-objective algorithms has not been extensively studied so far. There have been only few attempts in problems with two objective functions [PS03] or applying local search only to the final solutions to ensure their dominance [DG01]. A more comprehensive attempt to generate a multi-objective memetic algorithm was developed in [KC00], which presents the algorithm M-PAES (memetic version of PAES), employing the concept of dominance to evaluate local solutions. When a neighboring solution is created, it is only compared with the set of nondominated solutions. The local search is finished after a number of local movements without any improvement.

9.4 Genetic algorithm for sanitary resource allocation

We propose a novel method to improve the resource allocation process in a traffic accident: *Genetic Algorithm for Traffic Accidents Resource Allocation* (GATARA). Our model will provide a set of resources (final solution) to be sent to the accident area, based on the necessary resource types defined by the allocation policy presented in Section 9.2.

To accomplish that, our model makes use of the Genetic Algorithm (GA) subtype among the general Evolutionary Algorithms. In the problem of sanitary resource allocation for traffic accidents, we must consider that the final solution will consist of a set of selected resources, and therefore the search process should determine, for each available resource, if it is sent or not. We are facing a problem where we must be decided for a number of elements, which can be represented in a vector, whether they are selected or not. This situation could be expressed as *selected = true* or *selected = false*. In other words, each possible solution can be represented by a vector of Boolean values, and each element is associated with a resource. The Genetic Algorithms (GA) represent the candidate solutions as strings over a defined alphabet, making them the most appropriate type of algorithm.

Our algorithm is based on the execution cycle performed by the *Nondominated Sorting Genetic Algorithm, Fast version* (NSGA-II) [DPAM02], which allows efficiently searching the solution space to generate uniform Pareto front approximations. However, we will include a hybridization of this algorithm to improve its convergence speed towards the optima. The results of our proposal will be compared with other genetic algorithms that could be adopted, making use of the simple *a priori* approach, or approximating the Pareto front: *Vector Evaluated Genetic Algorithm* (VEGA) [Sch85], and *Multi-Objective Genetic Algorithm* (MOGA) [FF93].

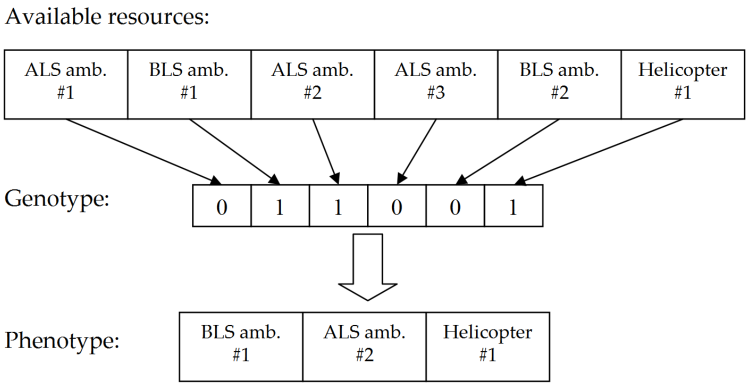


Figure 9.2: Representation of individuals in the genetic algorithm for resource allocation.

9.4.1 Parameter Definition for the Genetic Algorithm

Our genetic algorithm require a series of components that need to be defined to determine their functioning, which are dependent on the specific problem to solve. In our case, we must adapt the general parameters of genetic algorithms to the sanitary resource allocation problem.

- **Representation of individuals:**

The first step in defining the algorithm is to determine how to represent real-world situations in our genetic algorithm. The representation of the individuals is the link between genotypes, i.e., chromosomes containing genetic information for each of the individuals, and the phenotypes, the different solutions to the original problem.

The phenotype for the search of medical resources consists of a set of vehicles to be sent to the crash site for treatment and stabilization of the injured before being evacuated to hospital to complete their assistance. Each individual, i.e., possible solution, is represented in the population by using a vector of bits where each position is associated with an available resource. A value of 1 indicates that the resource associated to that position is selected; otherwise, the value in the vector is 0. Figure 9.2 shows an example with 6 available resources.

- **Evaluation functions:**

When determining the most appropriate sanitary resources for a traffic accident, we must take into account that different providers may have different priorities, being the closest resources not always the most appropriate ones. There are many factors that may be important in the decision of the final set. The objective functions used are designed to transform the problem in a minimization one, and hence greater values are considered as penalties and they should be reduced. The four evaluation functions defined are:

Algorithm 5 Pseudo-code representing the calculation of the assistance quality penalty for transport resources.

```
Input: The set of selected $resources$, and a target passenger $p$
Output: Assistance quality penalty for passenger $p$
$r \leftarrow$ determine_assigned_resource($resources$, $p$)
if $r = undefined$ then
    // 5 hours penalty
    $time = 5$
else if $r.category < p.severity$ then
    // Inappropriate resource:  penalization with double time
    $time =$ compute_arrival_time($r$) * 2
else
    $time =$ compute_arrival_time($r$)
$penalty = time^2$
```

1. *Assistance quality penalty* (f_1): The assistance quality is measured as the time required for the medical teams to access the crash site, and the type of injuries they are able to handle. Thus, if a serious injury requires advanced life support to maximize their survival chances, and if our algorithm selects a basic life support equipment, the assistance quality should be penalized. Since the rescue time is the most critical factor in a traffic accident, the penalty in the assistance quality due to the time past since the notification of the accident will be quadratic. In addition, we differentiate between two types of resources: transport vehicles, needed to transfer the injured passengers to a hospital in a safe way; and support vehicles, that provide additional equipment and medical staff. The arrival time of the sanitary vehicles is computed using a map representing the streets and roads around the crash site. Road vehicles are supposed to use the shortest path from their locations to the accident area, whereas helicopters use a straight line for their route. Algorithms 5 and 6 show our proposed scheme, which is used to assign assistance quality penalties for each type of resource. These algorithms allow obtaining the final value for the assistance quality function, defined as:

$$f_1(R) = \sum_{i=1}^{m} w_i \cdot assistance\_quality(R, p_i) + \sum_{j=1}^{n} w_j \cdot support\_quality(R, a_j) \tag{9.2}$$

   Where R is the set of selected resources, m is the number of passengers (p_i), n is the number of required support resources (with assistance category a_j). The weights w depend on the category requested, being defined as 1 for non-assistance vehicles, 2 for BLS resources, and 4 for ALS vehicles to reflect the higher importance of ALS equipment for severe injuries.

2. *Cost* (f_2): The total cost of the rescue operative, representing the overall cost of all the individual resources selected to be deployed at the crash site. The values to determine the cost of each resource are obtained from Table

Algorithm 6 Pseudo-code representing the calculation of the assistance quality penalty for support resources.

```
Input: The set of selected resources, and the assistance category required
Output: Assistance quality penalty for the resource
$r \leftarrow$ determine_support_resource($resources$, $category$)
if $r = undefined$ then
    // 5 hours penalty
    $time = 5$
else if $r.category < p.severity$ then
    // Inappropriate resource:  penalization with quad time
    $time$ = compute_arrival_time($r$) * 4
else
    $time$ = compute_arrival_time($r$)
$penalty = time^2$
```

9.2, and it is calculated using Equation 9.3, where n is the number of selected resources.

$$f_2(R) = \sum_{i=1}^{n} cost(r_i) \tag{9.3}$$

3. *Resource overuse penalty* (f_3): In an ideal situation, the resources from the different suppliers would be used in an equitable manner to avoid an overusing on the equipment and vehicles, as well as reducing fatigue in the medical personnel. The calculation of this value is done by determining the time elapsed since the last time when the resource was used. The smaller this value, the greater the penalty provided by the resource when used again. Equation 9.4 shows how this function is calculated for n selected resources and the time being indicated in hours.

$$f_3(R) = \sum_{i=1}^{n} \frac{2}{current\_time - r_i.last\_use\_time + 2} \tag{9.4}$$

4. *Emergency threshold penalty* (f_4): This function tries to avoid health care centers to be deprived of all their resources at any given time, so maintaining their clinical operatives in case of nearby accidents. Each health care center has thresholds defined for BLS and ALS resources, and a penalty is added if the number of resources available is lower than the corresponding threshold. The final value is the sum of the penalties for each of the k health centers:

$$thr\_penalty(hc) = 0.4 \cdot \frac{bls\_thr - bls\_units}{bls\_thr} + 0.6 \cdot \frac{als\_thr - als\_units}{als\_thr}$$

$$f_4(R) = \sum_{i=1}^{k} thr\_penalty(hc_i) \tag{9.5}$$

- **Population:**

The population contains the possible candidate solutions to be evaluated at a particular time (generation). We will use populations with a fixed number of individuals, which have been commonly used. Although there are algorithms with a variable number of individuals in the population [AWW07], the benefits are purely spatial, since it allows storing fewer individuals in memory. However, the convergence speed of the algorithm does not change significantly.

In general, the population size influences the speed of the problem solving algorithm. Reducing the population size increases the speed optimization to some extent, from which a premature convergence occurs reducing the speed [KA06]. In addition, the reliability of the optimization, i.e., the ability to find the optimal value, normally increases monotonically with the size of the population. We selected 10 individuals for populations based on the *a priori* approach, and 30 individuals when the objective is to find the Pareto front, since more solutions should give a more detailed idea of the shape of the frontier.

- **Parent selection:**

The main purpose of the parent selection phase is to determine which individuals are best suited to have children and pass their genes to the next generation. Most algorithms (such as VEGA, MOGA and *a priori* approaches) do not define a specific mechanism for parent selection. However, NSGA-II is specifically designed to use a binary deterministic tournament mechanism ($k = 2$) [B9̈6]. In the comparisons of the different algorithms, all of them will be configured to make use of this mechanism.

- **Crossover operator:**

Crossover or recombination is a binary operator that joins the information from the genotypes of two parents in one or more offspring genotypes. There are several types of recombinations in genetic algorithms. The classical operator has been the 1-point crossover. Given two parent genotypes, a cutoff point is chosen and the offspring genotype genes take values from the first parent before the cut, and from the second parent after the cut. In our case, we will employ an extension of this scheme using two cutoff points, in order to increase the variability on the genotype of the offspring, as shown in Figure 9.3.

- **Mutation operator:**

Mutation in genetic algorithms has been traditionally defined as the probability of change for a single gene. This probability is usually low to avoid excessive changes in the offspring that could move the individual away from the area that it is currently exploring, but this mechanism should exist to successfully avoid local optima. In our proposal we will use a probability of 0.02, i.e., one change for every 50 genes on average.

- **Survival selection:**

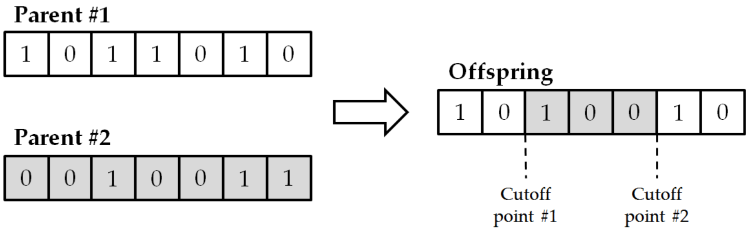


Figure 9.3: Example of crossover operator using two cutoff points.

The selection of survivors, or environmental selection, is aimed at selecting individuals depending on their quality to create the next generation. It is usual to use a standard generational replacement, where the new offspring completely replaces the individuals from last generation. However, NSGA-II and GATARA are elitist schemes, thus the best individuals from the last generation are included in the next generation to keep track of the best solutions found so far.

9.4.2 Constraint handling

In optimization problems where the variable values are not subject to any restriction, i.e., those in which the variables can take any value in the domain, the concept of Pareto dominance presented so far is sufficient to compare two solutions. However, most engineering problems have restrictions that may cause some of the obtained solutions to be unfeasible.

If we analyze our problem of resource allocation, all possibilities are feasible in terms of sets of resources to be sent to an accident area. However, some of them are clearly more suitable than others. The simplest example is the solution that sends no resources to the crash site. It is easy to see that this solution will never be dominated by any other, since the objective functions based on cost, overuse penalty, and emergency threshold violation would present the minimum value, although the assistance quality will be null. Therefore, we must prevent solutions excessively neglecting the assistance of the injured.

An interesting approach [DPAM02] makes use of the constraint-dominance concept, where a solution i dominates another solution j if any of these conditions is true:

1. Solution i is feasible, while solution j is not.
2. Both solutions are unfeasible, but solution i presents less violation to the feasibility condition.
3. Both solutions are feasible, but solution i dominates over j.

In our algorithm for sanitary resource allocation, a solution is considered feasible if it provides at least the amount of resources required by the accident using the proposed allocation policy, even when their assistance category is not optimal. That is, the number of vehicles sent should allow evacuating all the person according to the allocation policy, which also depends on the accident severity estimation. Thus, the solution of not sending any resources will be dominated by any other solution subject to these restrictions. Between two unfeasible solutions, the solution able to evacuate a greater number of occupants is preferred. Finally, from two feasible solutions, we would select the Pareto-dominating one.

9.4.3 Hybridization of the NSGA-II Algorithm in GATARA

The original NSGA-II algorithm could be improved by adding knowledge about the problem that could help to find better solutions in fewer generations. When a hybrid, or memetic, multi-objective algorithms is developed, we should take into account the solutions to which local search will be applied, and how to identify a solution in the vicinity as the new best solution when there are multiple local non-dominated solutions.

Generating neighboring solutions to the problem at hand can be simple using inversion of bits, or *bit-flipping*, since the new solution only differs from the original one in a single resource to be added or removed from the rescue team. Moreover, local search must be applied selectively to be computationally efficient. Hence, instead of checking all solutions of the offspring, GATARA only investigates those that are not dominated by any other solution, also know as *rank 1* solutions, after all the solutions have been assigned to different domination fronts in NSGA-II. The local search process will finish when the first better solution is found in the vicinity, or when there are no more neighbors left to explore.

9.5 Algorithm evaluation

The proposed model will now be evaluated using a series of pre-generated scenarios representing accidents occurring in different situations. The data for the accidents is taken from the GES database to represent realistic situations.

9.5.1 Definition of the evaluation problem

To evaluate the chosen algorithms, we generated two situations in which, for the same accident, the number of providers is different. The specific accident is a multiple collision set in an interurban road which took place in the minute 3,000. The potential resources for the accident are searched in the 10,000 km^2 surrounding area. That is, we consider a 100 km × 100 km square area in which the accident is located in the central coordinates (50, 50). The collision involved the following vehicles and passengers:

- A tourism with severe damage estimation. Three passengers were in the vehicle at the time of the accident, where two of them are estimated to present severe injuries, and the third one just minor injuries.
- A truck with minor damage, having the driver as the only passenger, with minor injuries estimation as well.
- A small vehicle with severe damage, occupied by 3 passengers with severe injuries estimation.

Table 9.3: Parameters for the Resource Allocation Genetic Algorithm

Representation	Binary strings
Recombination	2-point crossover
Recombination probability	90%
Mutation	Bit-flipping
Mutation probability	2%
Parent selection	Tournament $k = 2$
Survival selection	Generational
Population size	10 (*a priori*), 30 (Pareto Front approach)
Initialization	Random
Termination condition	200 generations (*a priori*), 300 generations (Pareto Front approach)
Number of executions	20

Table 9.4: Weight sets used in the *a priori* approach

Objective Function	**Weight**	Weight set #				
		1	**2**	**3**	**4**	**5**
Assistance Quality Penalty	w_1	0.7	0.5	0.5	0.4	0.3
Cost	w_2	0.15	0.2	0.2	0.4	0.5
Resource Overuse Penalty	w_3	0.075	0.05	0.25	0.1	0.1
Emergency Threshold Penalty	w_4	0.075	0.25	0.05	0.1	0.1

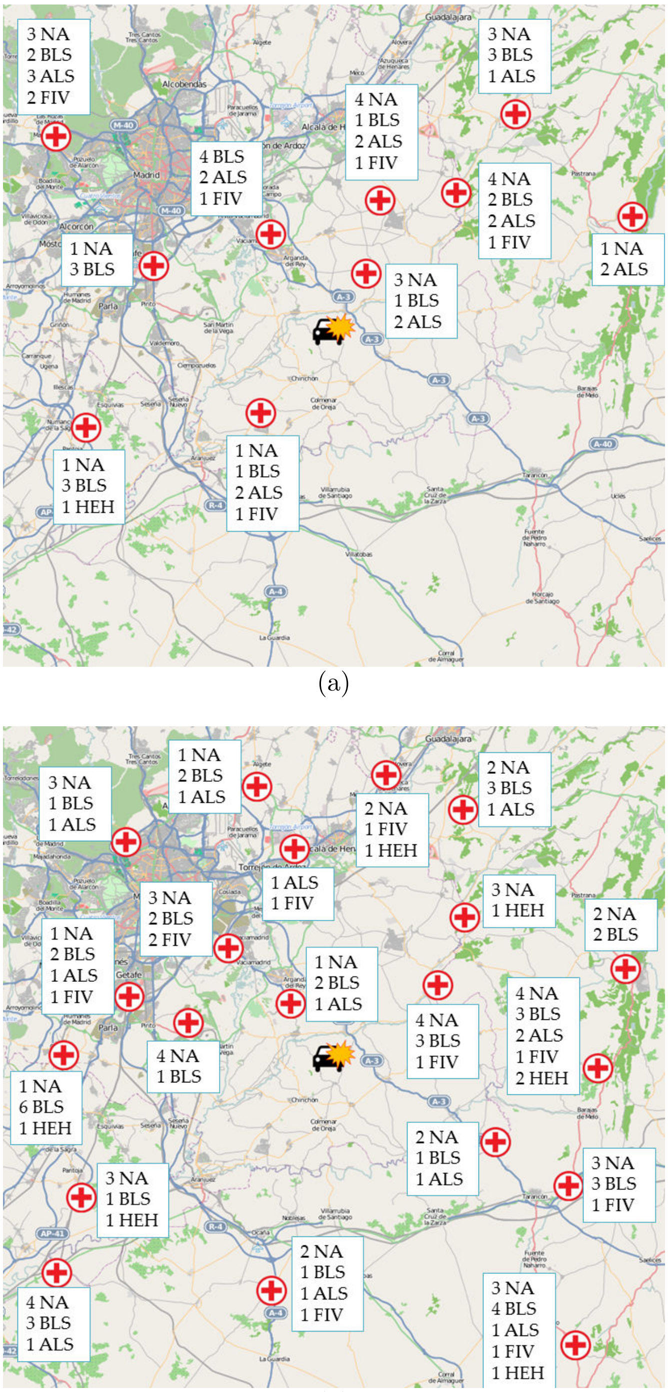
According to our resource allocation model, the incident would be classified as severe, and the estimated resources for assistance would consist of:

- 5 Advanced Life Support vehicles for the possible transport of the seriously injured in the collision.
- 2 Basic Life Support vehicle for the possible transport of minor injured passengers.
- 1 Advanced Life Support vehicle to support BLS vehicles (for example, to provide additional material).

In our case, our scenarios will include several sanitary resource suppliers, such as rescue centers and hospitals. As shown in Figure 9.4, we generated two random scenarios with potential suppliers around the crash site: the first one includes 10 suppliers, and the second one involves 20 suppliers. The available resources for each of them were also generated randomly. The map was obtained from the area around Madrid (Spain), using OpenStreetMap [osm09]. The parameters of the executions of the selected genetic algorithms are shown in Table 9.3.

9.5.2 Drawbacks of the simple *a priori* approach

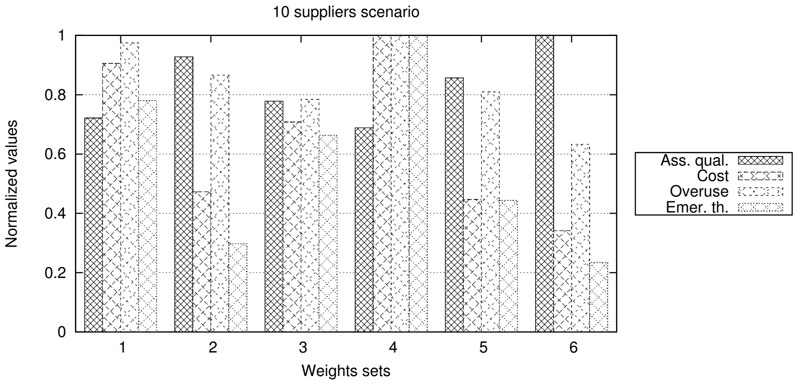
The straightforward method for adapting a genetic algorithm to be multi-objective is to generate a new function resulting from the combination of the multiple chosen



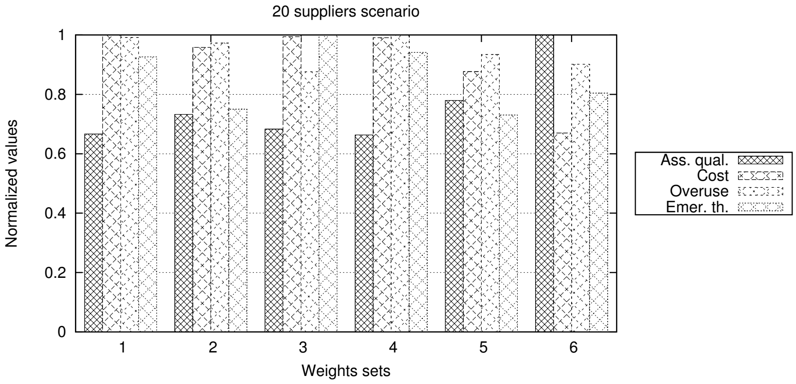
(a)

(b)

Figure 9.4: Example scenarios for a traffic accident resource allocation in a 100 km × 100 km area with (a) 10 suppliers, and (b) 20 suppliers.



(a)



(b)

Figure 9.5: Different solutions obtained using different weight sets for the *a priori* approach in the (a) 10 suppliers scenario, and (b) 20 suppliers scenario.

objective functions. We may perform a weighted mean using the normalized values from the four functions, with a set of weights varying depending on the relative importance of each function. Hence, the fitness value for each individual i of the population at time t will be obtained through the following formula:

$$f(i,t) = \sum_{j=0}^{4} w_j \cdot f_j(i,t) \tag{9.6}$$

where w_j represents the weight assigned to the objective function f_j.

We performed several executions using the weight sets included in Table 9.4, which represent different allocation policies with more preference for one or more objective function. For example, the weight set 1 presents a clear preference towards assistance quality, while the weight sets 4 and 5 try to achieve a balance between assistance quality and cost, probably indicating a situation where the cost could be highly reduced. These weights must be manually included into the algorithm, meaning that the specific weight for each function is an approximation of the intentions of the entity in charge of the decision.

The optimal solutions found using the *a priori* approach after 20 executions of 200 generations are shown in Figure 9.5. The differences between the five weight sets presented are very noticeable. Even when two weight sets that are not too different, like sets 2 and 3, where only the two functions with less priority change their weight values, totally different solutions are obtained, making it very difficult to adjust them to represent a given allocation scheme. We can observe in Figure 9.5(a) how the values for the functions change noticeably for them, obtaining a totally different shape in the graph bar. A similar effect is appreciated when studying weight sets 4 and 5, where the cost function is reduced by greatly increasing the assistance quality and the overuse penalty.

In addition, comparing Figures 9.5(a) and 9.5(b), it is shown that the differences between the solutions found is more important when fewer suppliers are taken into account. Therefore, having less options makes the solution vary significantly, which may be a problem in areas with few health centers available. This undesirable effect makes this simple scheme less useful when we need to define a precise allocation policy, and using the Pareto front approach becomes an option to overcome this drawback.

9.5.3 Comparison between GATARA and other algorithms approximating the Pareto front

Given the limitations observed in the *a priori* approach for multi-objective search, we conclude that it is more beneficial to present a set of non-dominated solutions representing the Pareto front, instead of just selecting a single solution with the *a priori* approach. Our proposed scheme GATARA is based on the NSGA-II algorithm, and we will compare it to the original version of this algorithm, as well as other existing multi-objective genetic algorithms: VEGA and MOGA. These algorithms will be evaluated using the scenarios previously presented, both with 10 suppliers and 20 suppliers.

Figure 9.6 shows the results obtained with the four algorithms in the 10 suppliers scenario. The data series indicate the mean value of the four objective functions while increasing the number of generations of the population. The three schemes obtain very similar results in terms of assistance quality and cost. It is noticeable how they treat the assistance quality, since VEGA and MOGA are approximately constant during all the execution, whereas NSGA-II and GATARA worsen their results during the first generations to explore the solutions space, and later they stabilize with results that are similar to the other two algorithms. There are more differences related to the overuse penalty function, with clear advantage for GATARA, and the emergency threshold penalty function, where VEGA is the winner.

The convergence speed of the three schemes is similar, even if GATARA reaches a stabilization point sooner than the rest of the approaches, thus making difficult to select the best algorithm. That is the reason why we study the distribution of the final solutions obtained in the four dimensions after 300 generations, as shown in Figure 9.7. Among the four algorithms, GATARA and NSGA-II generate fewer extreme values, with a fairly even distribution of solutions in all dimensions. In fact, since GATARA mainly increases the convergence speed of the NSGA-II algorithm, it is logical to obtain such similarity in the distribution of solutions for both algorithms. VEGA achieves very good results for the emergency threshold penalty, but several of the values for the assistance quality are too high or too close to each other. MOGA is not able to achieve enough variety in the assistance quality, with little differences between the solutions, although there is considerable diversity in the other functions. Our proposal is the most appropriate algorithm to obtain a variety of solutions with acceptable quality, allowing decisions to be flexible enough to adapt to different situations and priorities.

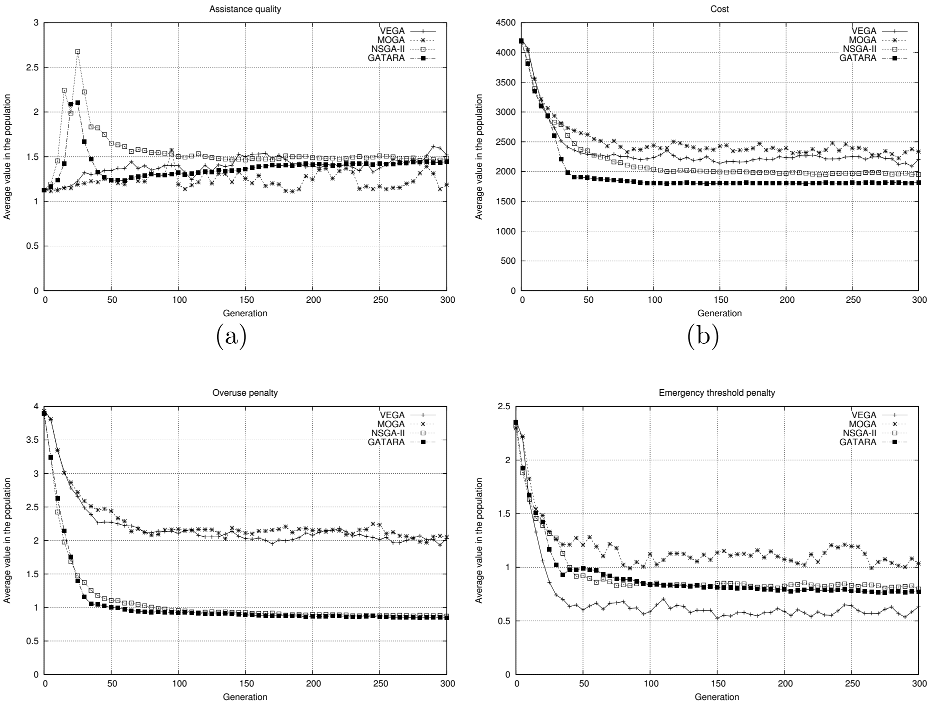
Since the behavior of the algorithms may vary in different environments, we studied how the results are affected by using the scenario with 20 suppliers. As shown in Figure 9.8, GATARA clearly outperforms the rest of schemes after 300 generations for all the functions, except the assistance quality penalty, where all the algorithms behave similarly. The convergence speeds of the four schemes is similar during the first 50 generations. Surprisingly, NSGA-II presents problems to reach the optimum solutions for the cost and emergency threshold functions, requiring more than 150 generations to stabilize. Again, this behavior indicates that NSGA-II explores the search space during the first few generations to later focus on the best areas detected. The hybridization allows GATARA to overcome this drawback, achieving the best solution set in less than 80 generations.

Finally, Figure 9.9 represents the distribution of the values for the four objective functions in the 20 suppliers scenario. Both VEGA and MOGA present excessively high values for the cost and overuse functions, while MOGA again shows deficiencies in terms of variety of values for the assistance quality function. The values for the assistance quality penalty function are also very high in NSGA-II, whereas GATARA is able to find a set of solutions with values that are reduced and diverse enough for all the penalty functions. Therefore, GATARA is a suitable algorithm to generate approximations to the Pareto front with a high degree of uniformity.

9.6 Summary

Intelligent Transportation Systems are beginning to be implemented in vehicles from different manufacturers, as a combination of communication systems between vehicles (V2V), and between vehicles and the external infrastructure (V2I). Using this technology together with Artificial Intelligence (AI) systems can be helpful at reducing the assistance time of the injured people in an accident. In this work we showed how Multi-objective Genetic Algorithms make it possible to generate optimal resource sets automatically when an accident is notified and its severity estimated.

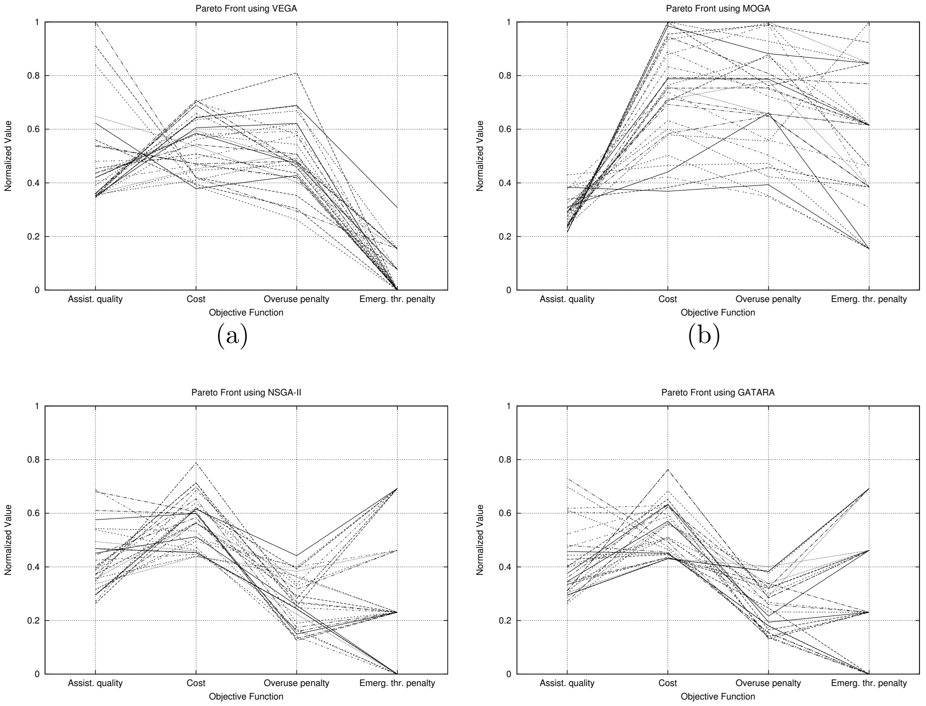
Using the resource model presented, there are different multi-objective algorithms that can be used to select the most appropriate resource set, taking into account four main objectives: maximizing the assistance quality, minimizing cost, minimizing the penalty for overuse of resources, and minimizing the penalty for



(a) (b)

(c) (d)

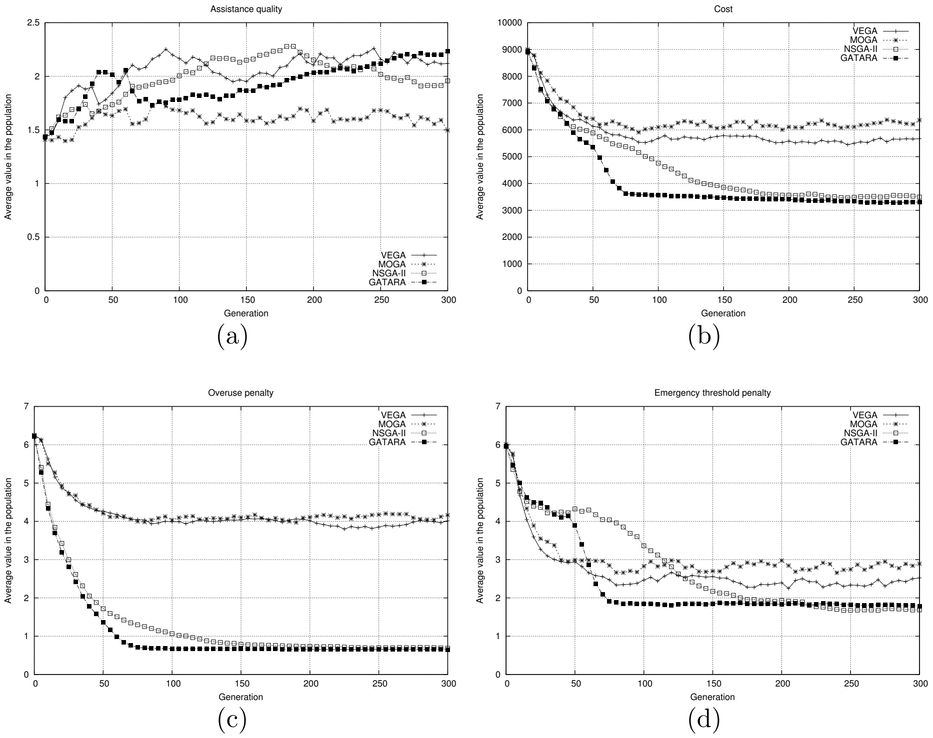
Figure 9.6: Evolution of the mean value of the objective functions for the individuals in the population when varying the genetic algorithm in the 10 suppliers scenario.



(a) (b)

(c) (d)

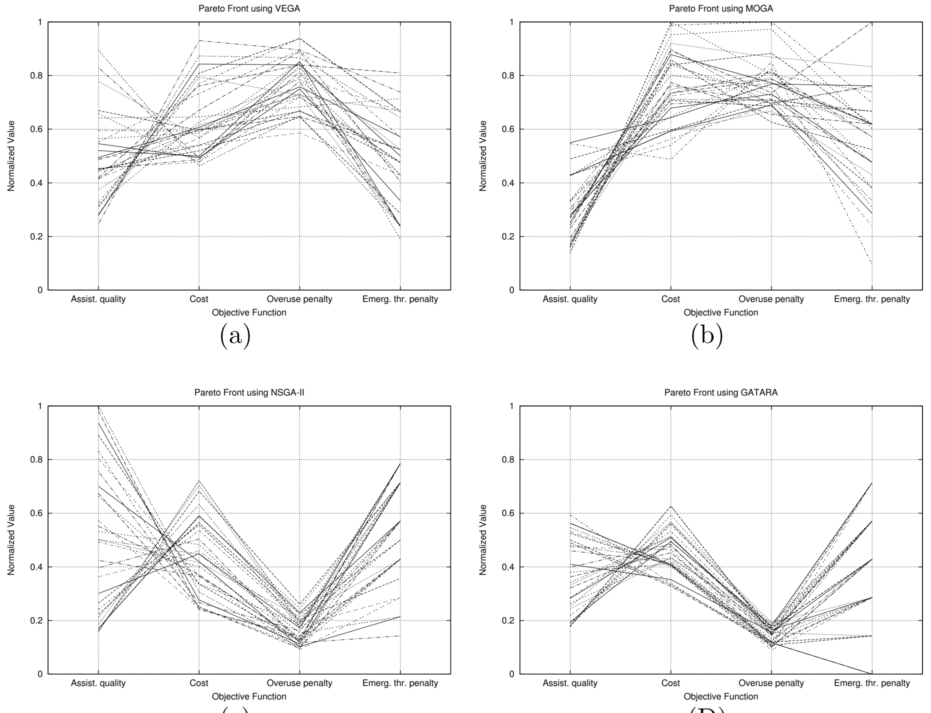
Figure 9.7: Pareto front obtained when varying the genetic algorithm in the 10 suppliers scenario: (a) VEGA, (b) MOGA, (c) NSGA-II, and (d) GATARA.



(a) (b)

(c) (d)

Figure 9.8: Evolution of the mean value of the objective functions for the individuals in the population when varying the genetic algorithm in the 20 suppliers scenario.



(a) (b)

(c) (D)

Figure 9.9: Pareto front obtained when varying the genetic algorithm in the 20 suppliers scenario: (a) VEGA, (b) MOGA, (c) NSGA-II, and (d) GATARA.

violation of the emergency threshold. We propose a Genetic Algorithm for Traffic Accidents Resource Allocation (GATARA), based on the existing NSGA-II algorithm, modifying it to include hybridization through memetics to increase the convergence speed towards the Pareto front. GATARA still has the advantages of the original NSGA-II approach with respect to other algorithms, such as VEGA and MOGA, since our proposal does not give preference to one function over others, and it is very efficient at obtaining a uniform distribution for solutions using the different objective functions. However, the memetic version of NSGA-II allows for a faster search by improving the non-dominated suboptimal solutions found during the search process.

As future work, it would be interesting to study the system for a long time period to assess its behavior once deployed in a real environment. The simulation would include the modeling of traffic accidents in terms of their frequency and other factors, such as vehicles involved, average number of occupants, etc.

Chapter 10

Conclusions, Publications and Future Work

Throughout this thesis several contributions have been made to the area of Intelligent Transportation Systems. Our purpose was to design a system for reducing the Emergency Services Responsiveness, in order to improve the chances of survival for passengers involved in car accidents. Hence, we proposed a warning message dissemination scheme that uses information about the street map to select the most appropriate forwarding node, increasing the efficiency of the dissemination process. In addition, after studying the most important factors that affect warning message dissemination, we proposed a protocol that adapts the broadcast scheme to be used depending on the vehicular density and the characteristics of the roadmap where the dissemination takes place. Using our proposal, we are able to reduce the number of messages produced when the environment allows an easy propagation, and to increase the number of messages sent when the probability of reaching all the map area is lower.

Since the objective of this thesis includes the efficient dissemination of warning messages, their handling, and the optimal decisions to be taken after their reception, we proposed an architecture that fulfills all these objectives. Vehicles in our system incorporate an On-Board Unit responsible of the notification of the accident to an external Control Unit. Using the information of the warning messages, we developed a series of algorithms able to estimate the severity of the accident and the most appropriate rescue resources that should be sent to the crash site. The automation of the decision process will help to reduce the time between the occurrence of the accident, and the time when the emergency services arrive to the affected area, with the associated improvement in the survival chances of the people affected.

We now proceed to summarize the most relevant contributions of this work:

- Proposal of a system for reducing the Emergency Services Responsiveness in order to improve the chances of survival for passengers involved in car accidents. It includes the *enhanced Message Dissemination for Roadmaps* (eMDR), designed to use the information about the roadmap to reduce the warning notification time and percentage of blind nodes in urban environments, as well as the *Profile-driven Adaptive Warning Dissemination Scheme* (PAWDS), a novel approach that adapts the broadcast scheme depending on the type of street layout, allowing more flexible warning dissemination processes.

- Classification of city profiles using information about their street and junction density, dividing them into three possible profiles by means of clustering. The cities from the same cluster present similar performance using a specific dissemination scheme, whereas there are noticeable differences between cities from different clusters.
- Development of an architecture for traffic accident automatic notification based in V2V and V2I communications. We created a prototype using off-the-shelf devices, to ensure the feasibility of the system, which was successfully validated using real crash tests experiments.
- Development of a complete Knowledge Discovery in Databases (KDD) process, with an adequate selection of relevant features, that allows increasing the accuracy of the models used to estimate the severity of a traffic accident using a prior division depending on the main direction of the impact.
- Proposal of a sanitary resource model that can be used to determine the most adequate resources for each specific accident, using the information notified by means of V2V and V2I communications, and the accident severity estimation algorithm proposed. This input is then fed into our proposed *Genetic Algorithm for Traffic Accidents Resource Allocation* (GATARA), which will select the suppliers that should provide each needed resource depending on factors such as the closeness to the crash site, the cost, and the balanced resource usage.

Having accomplished all of our predefined goals, we consider that the ultimate purpose of this thesis has been achieved successfully, and so we conclude this dissertation.

10.1 Publications Related to the Thesis

The research work related to this thesis has resulted in 19 publications; among them we have 6 journal articles (all of them indexed by the Journal Citation Reports (JCR) database), and 13 conference papers (6 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.

10.1.1 Journals

[FGM$^+$12c] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, “An Adaptive System Based on Roadmap Profiling to En-

hance Warning Message Dissemination in VANETs", IEEE/ACM Transactions on Networking. 2012.
Available at: http://dx.doi.org/10.1109/TNET.2012.2212206

In recent years, new applications, architectures and technologies have been proposed for Vehicular Ad hoc Networks (VANETs). Regarding traffic safety applications for VANETs, warning messages have to be quickly and smartly disseminated in order to reduce the required dissemination time and to increase the number of vehicles receiving the traffic warning information. In the past, several approaches have been proposed to improve the alert dissemination process in multi-hop wireless networks, but none of them was tested in real urban scenarios, adapting its behavior to the propagation features of the scenario.

In this paper, we present the Profile-driven Adaptive Warning Dissemination Scheme (PAWDS) designed to improve the warning message dissemination process. With respect to previous proposals, our proposed scheme uses a mapping technique based on adapting the dissemination strategy according to both the characteristics of the street area where the vehicles are moving, and the density of vehicles in the target scenario. Our algorithm reported a noticeable improvement in the performance of alert dissemination processes in scenarios based on real city maps.

[FGM$^+$13] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "A Novel Approach for Traffic Accidents Sanitary Resource Allocation Based on Multi-Objective Genetic Algorithms", Expert Systems With Applications, vol. 40, issue 1, pp. 323336. January 2013. ISSN 0957-4174. Available at: http://dx.doi.org/10.1016/j.eswa.2012.07.056

The development of communication technologies integrated in vehicles allows creating new protocols and applications to improve assistance in traffic accidents. Combining this technology with intelligent systems will permit to automate most of the decisions needed to generate the appropriate sanitary resource sets, thereby reducing the time from the occurrence of the accident to the stabilization and hospitalization of the injured passengers. However, generating the optimal allocation of sanitary resources is not an easy task, since there are several objectives that are mutually exclusive, such as assistance improvement, cost reduction, and balanced resource usage.

In this paper, we propose a novel approach for the sanitary resources allocation in traffic accidents. Our approach is based on the use of multi-objective genetic algorithms, and it is able to generate a list of optimal solutions accounting for the most representative factors. The inputs to our model are: i) the accident notification, which is obtained through vehicular communication systems, and ii) the severity estimation for the accident, achieved through data mining. We evaluate our approach under a set of vehicular scenarios, and the results show that a memetic version of the NSGA-II algorithm was the most effective method at locating the optimal resource set, while maintaining enough variability in the solutions to allow applying different resource allocation policies.

[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. 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.

[FGM$^+$12a] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Automatic Accident Detection: Assistance through Communication Technologies and Vehicles", in *IEEE Vehicular Technology Magazine*, vol. 7, issue 3, pp. 90-100. September, 2012. ISSN 1556-6072.
Available at: http://dx.doi.org/10.1109/MVT.2012.2203877

This paper presents in-depth our prototype architecture called e-NOTIFY, a novel proposal designed to improve the chances of survival for passengers involved in car accidents. The proposed system offers automated detection, reporting, and assistance of passengers involved in road accidents by exploiting the capabilities offered by vehicular communication technologies. Our proposal does not directly focus on reducing the number of accidents, but on improving post-collision assistance with fast and efficient management of the available emergency resources, increasing the chances of recovery and survival for people injured in traffic accidents.

This architecture replaces the current mechanisms for notification of accidents based on witnesses, who may provide incomplete or incorrect information after a much longer time. The development of a low-cost prototype shows that it is feasible to massively incorporate this system in existing vehicles. We validated our prototype at the Passive Security Department of Applus+ IDIADA Corporation, and showed how it can successfully detect traffic accidents, reporting all the detailed information to a Control Alert System on time.

[FGM$^+$12d] 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", in *Transportation Research Part C: Emerging Technologies*, Elsevier, vol. 25, pp. 61-80. December 2012. ISSN: 0968-090X. Available at: http://dx.doi.org/10.1016/j.trc.2012.04.017

In this paper, we propose a novel scheme called *enhanced Message Dissemination based on Roadmaps* (eMDR), which uses location and street map information to facilitate an efficient dissemination of warning messages in 802.11p based VANETs. We evaluate the performance of our eMDR proposal in realistic urban scenarios, that is, obtained from real maps of existing cities, and demonstrate how our approach could benefit drivers on the road.

The proposed eMDR scheme is specially suitable in situations where there are few vehicles able to forward messages, which can be due to either the low vehicle density or the low market penetration rate of wireless devices. Thus, the eMDR scheme may be successfully used during the first steps of the mass implantation of 802.11p compliant devices on vehicles. Moreover, by studying the time evolution of the message propagation process, we find that our proposal can be useful to transmit critical messages that should be spread out as soon as possible; in particular, we show that eMDR clearly outperforms all the studied proposals.

[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", in *Wireless Personal Communications Journal*, Springer, 2012. Available at: http://dx.doi.org/10.1007/s11277-012-0594-6

When taking into account visibility schemes, the topology of the map used to constrain vehicle movement is very important. Using complex layouts implies more computational time, but the obtained results are expected to be closer to the real ones. Typical simulation topologies used are highway scenarios (the simplest layout, without junctions) and Manhattan-style street grids (with streets arranged orthogonally). Layouts obtained from real urban scenarios are rarely used, although they should be chosen to ensure that the obtained results are likely to be similar to those obtained in realistic environments. In this paper, we present our novel Topology based Visibility model, which enables a more precise warning message propagation process, taking into account both attenuation and visibility in real urban scenarios.

We then validate our proposed model, evaluating the process of message dissemination in several real VANET scenarios to detect variations under different topologies. City maps (and hence road topologies) have little effect on warning notification time and number of received packets in scenarios with low vehicle density, but they affect warning message dissemination performance at high vehicle density scenarios. Simulations results also revealed that the Manhattan topology (i.e., the map with the longest streets) yields the highest warning coverage across all vehicle densities. Thus, results obtained under such topologies are optimistic, and not applicable to cities with different topologies.

10.1.2 Indexed Conferences

[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.

[FGM$^+$11d] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, “Using Roadmap Profiling to Enhance the Warning Message Dissemination in Vehicular Environments”, in *36th IEEE Conference on Local Computer Networks Conference (LCN 2011)*, Bonn, Germany, pp. 18-25, October 2011. ISSN: 0742-1303.
Available at: http://dx.doi.org/10.1109/LCN.2011.6115184

In this work, we focus on efficient warning message dissemination to be used in traffic safety applications. The main goal is to reduce the latency and to increase the accuracy of the information received by nearby vehicles when a dangerous situation occurs. We present an adaptive algorithm that improves warning message dissemination by modifying the broadcasting strategy depending on the features of the environment, especially the estimated density of vehicles and the type of street map of the surrounding area.

Our solution requires vehicles to make use of the information contained in their integrated maps to determine the profile type. Additionally, the beacons exchanged with neighbors are used to estimate the density of vehicles in the area. By combining these two inputs, our algorithm is able to tune the parameters of the dissemination process and mitigate broadcast storm related problems. The objective is to find a balance among different performance metrics. With this aim, three different working modes were proposed to be selected depending on their efficiency in each situation.

[FGM$^+$11c] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, “PAWDS: A Roadmap Profile-driven Adaptive System for Alert Dissemination in VANETs”, in *10th IEEE International Symposium on Network Computing and Applications (NCA'11)*, Cambridge, MA USA, pp. 1-8, August 2011. Available at: http://dx.doi.org/10.1109/NCA.2011.25

In this paper, we show how adapting to the specific environment where the vehicles are located can be beneficial in order to reduce broadcast storm related problems, and also to increase the efficiency of the warning message dissemination process. Existing adaptive techniques for VANETs only make use of the vehicle density to adapt the process; however, this information in not enough in many situations to determine the most effective configuration. We propose PAWDS, a *Profile-driven Adaptive Warning Dissemination System* that dynamically modifies some of the key parameters of the propagation process, such as the interval between notifications and the selected broadcast scheme, to achieve an optimal performance depending on the features of the roadmap in which the propagation takes place.

The PAWDS system proved to be extremely effective when the density of vehicles is high, especially in maps with very high density of streets and junctions. In those cases, selecting a balanced working mode allows to maintain an acceptable level of performance in terms of notification time and percentage of blind vehicles, while reducing the number of messages by more than 90% compared to other base configurations. In the rest of the maps, using the most suitable mode allows reducing message duplicates by about 60%. The effectiveness of the proposed system in scenarios with low density of vehicles becomes less meaningful as it is unlikely to find broadcast storm problems in such environments.

[FGM$^+$11b] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, “Analysis of the most representative factors affecting Warning Message Dissemination in VANETs under real roadmaps”, in *The 19th annual meeting of the IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS)*, Singapore, pp. 197-204, July 2011.
Available at: http://dx.doi.org/10.1109/MASCOTS.2011.25

This paper presents a statistical analysis based on the 2k factorial methodology to determine the most representative factors that govern the warning message dissemination performance in 802.11p-based VANETs. The aim of this methodology is to reduce the simulation time required to analyze the performance of a given VANET system, since it allows researchers to focus on the key factors affecting their proposals.

The key factors affecting the delivery of warning messages were found to be the radio propagation model, the density of vehicles, and the roadmap used. Some other factors, such as the broadcast scheme used, the channel bandwidth, and the priority and the periodicity of messages, did not have a significant impact on the metrics considered in our study.

[MFC$^+$10b] F. J. Martinez, M. Fogue, M. Coll, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Assessing the Impact of a Realistic Radio Propagation Model on VANET Scenarios using Real Maps", in *IEEE International Symposium on Network Computing and Applications (IEEE NCA'10)*, Cambridge, MA USA, pp. 132-139, July 2010.
Available at: http://doi.ieeecomputersociety.org/10.1109/NCA.2010.24

In this paper we present a new Radio Propagation Model (RPM), called Real Attenuation and Visibility (RAV), proposed to simulate more realistically both attenuation of wireless signals (signal power loss) and the radio visibility scheme (presence of obstacles interfering with the signal path). We evaluated this model and compared it against existing RPMs using real scenarios. We then carried out further studies to evaluate the impact of combining different attenuation and visibility schemes. Simulation results confirmed that our proposed RAV scheme can better reflect realistic scenarios, and significantly affects the percentage of blind vehicles, the channel contention, and the warning notification time.

[MFC$^+$10a] F. J. Martinez, M. Fogue, M. Coll, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Evaluating the Impact of a Novel Warning Message Dissemination Scheme for VANETs Using Real City Maps", in *IFIP Networking*, Chennai, India, pp. 265-276, May 2010.

In this paper we present the enhanced Street Broadcast Reduction (eSBR), a novel scheme for VANETs designed to mitigate the broadcast storm problem in real urban scenarios. We evaluate the impact that our scheme has on performance when applied to VANET scenarios based on real city maps.

Simulation results show that eSBR outperforms other schemes in high density urban scenarios, yielding a lower percentage of blind vehicles while drastically alleviating the broadcast storm problem, being thus suitable for real scenarios. Our experiments also highlight that the message propagation behavior in realistic scenarios based on maps of actual cities differs greatly from more traditional Manhattan-style scenarios. Thus, we consider that the results obtained using unrealistic scenarios should be revised, and we recommend the adoption of real maps whenever possible.

10.1.3 International Conferences

[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", International Workshop on IPv6-based Vehicular Networks (Vehi6), collocated with the 2012 IEEE Intelligent Vehicles Symposium, Alcalá de Henares, Spain, 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.

[FGM$^+$12e] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Using Data Mining and Vehicular Networks to Estimate the Severity of Traffic Accidents", in *International Symposium on Management Intelligent Systems (IS-MiS)*, Salamanca, Spain, pp. 37-46, July 2012. Available at: http://dx.doi.org/10.1007/978-3-642-30864-2_4

This paper shows how vehicular networks can be used to collect precise information about road accidents that are later used to estimate the severity of the collision. We show the efforts towards algorithms able to predict the severity of an accident, based on data mining classification algorithms trained using historical data about previous accidents, which will serve as an input for resource allocation algorithms.

The different classification algorithms studied do not show remarkable differences in terms of percentage of instances correctly classified, with an accuracy in the range 70-80%. However, we found that Bayesian networks were able to outperform decision trees and support vector machines in terms of the AUC metric. Dividing the accidents depending on the types of impacts allows noticeably increasing the accuracy of the system, especially for front crashes where the vehicle itself is usually the striking one. The accuracy estimation of the severity of side and rear-end crashes could be significantly increased if we were provided with data from other vehicles involved in the collision, which will be possible using inter-vehicle communication technologies.

[FGM$^+$12b] 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)*, Desenzano del Garda, Italy, pp. 37-46, March 2012.

In this paper we present a complete simulation framework specially designed to simulate vehicular networks, in order to assess novel proposals. Specifically, we have designed and implemented Citymob for Roadmaps (C4R), a mobility generator for vehicular networks. Moreover, we have introduced several enhancements to ns-2, a widely used network simulator. All these enhancements allow simulating vehicular networks using real maps while reducing the time required to prepare the simulated scenarios. Compared to other similar proposals, our vehicular simulation framework accounts for the effect of obstacles in radio signal propagation when using the IEEE 802.11p in real urban maps.

All these enhancements allow researchers to simulate vehicular networks using real maps, thus obtaining far more accurate results than using other available simulation frame works. In addition, C4R allows to significantly reduce the time required to prepare the simulation scenarios.

[**FGM$^+$11e**] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Prototyping an Automatic Notification Scheme for Traffic Accidents in Vehicular Networks", in *4th IFIP Wireless Days Conference*, Ontario, Canada, pp. 1-5, October 2011.
Available at: http://dx.doi.org/10.1109/WD.2011.6098139

In this paper, we present the basic implementation of the prototype developed to assess the operation of the e-NOTIFY system, with the goal of improving post-collision assistance by the reduction of the arrival time of the emergency services, and the increased amount of information regarding the accident.

We show the different parts of the system: OBU, message format, and Control Unit, and how they can be implemented using low-cost general-purpose devices. Finally, we show the validation tests performed to the system in the facilities of Applus+ IDIADA, that proved the correct operation of the system as a whole and its robustness in case of accident.

10.1.4 National Conferences

[**SFG$^+$12**] J. A. Sanguesa, M. Fogue, P. Garrido, F. J. Martinez, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Estimación en tiempo real de la densidad de vehículos en entornos urbanos", in *XXIII Jornadas de Paralelismo*, Elche, Spain, septiembre 2012.

In vehicular networks, communication success usually depends on the density of vehicles, as a higher density allows having shorter and more reliable wireless links. However, vehicle density is highly variable in time and space. Thus, knowing the density of vehicles in a vehicular communications environment is important, as better opportunities for wireless communication can show up. This paper studies the importance of predicting the density of vehicles in vehicular environments to take decisions for enhancing the dissemination of warning messages between vehicles. Moreover, we propose a mechanism which allows the estimation of the vehicular density within a certain urban environment, using as parameters the number of beacons received per vehicle, and the topological characteristics of the environment where the vehicles are located. Simulation results indicate that our approach accurately estimates the vehicular density, and therefore it may be used by researchers in order to design adaptive dissemination protocols for vehicular environments, or to improve previously proposed schemes.

[**FGM$^+$11a**] M. Fogue, P. Garrido, F. J. Martinez, J.-C. Cano, C. T. Calafate, and P. Manzoni, "Desarrollo de un Prototipo para la Notificación Automática de Accidentes de Tráfico usando Redes Vehiculares", in *XXII Jornadas de Paralelismo*, La Laguna (Tenerife), Spain, pp. 367-372, septiembre 2011.

This paper presents the efforts towards obtaining a working prototype of the e-NOTIFY system, based on the data provided by Applus+ IDIADA about historical accidents and crash tests performed under the Euro NCAP programme. We detail the components of the different parts of the system and the algorithm for accident detection, and we present a message format with all the relevant information about the crash.

We evaluated the prototype in real crash tests representing different scenarios: front, side, and rear-end impact. In all the studied cases, the prototype was able to detect the impact, generate an adequate warning, and forward it to a Control Unit. The Control Unit was able to recover the information and use it to generate an estimation of the severity of the accident.

[**FGM$^+$10**] M. Fogue, P. Garrido, F. J. Martinez, C. T. Calafate, J.-C. Cano, and P. Manzoni, "Reducing the Emergency Services Response Time using Vehicular Networks", in *XXI Jornadas de Paralelismo*, Valencia, Spain, pp. 821-828, September 2010.

In this paper, we present the basics of the e-NOTIFY system, focusing on our motivation and the overall structure of the architecture, with the objective of reducing the response time of rescue teams and optimizing automatically the medical and rescue resources needed. We compare our proposal to other existing projects related to the increase of the security in current vehicles, such as Fleetnet, eCall, SafeSpot and OnStar.

10.2 Future work

In the development of this thesis several issues emerged which deserve further scrutiny in a future. The ones we consider most relevant are the following:

- To increase the flexibility of the adaptive warning message dissemination scheme, applying fuzzy techniques to avoid that a roadmap profile only belongs to one cluster or another. Instead of this, it would be interesting to define different "degrees of membership" to the different clusters, and adapt the broadcast scheme consequently.

- To make use of concepts already used in Delay-Tolerant Networks to improve the dissemination process in urban environments, allowing the vehicles to store the received packets until they find the optimal conditions for their forwarding.

- To develop a Dynamic Mobility Model generator. Such application would generate more realistic traffic mobility patterns, making it possible that vehicle's movements could change "on-the-fly" when a warning message is received.

- To assess the performance of the e-NOTIFY system in a real environment, with vehicles moving at high speed and external infrastructure to provide access to the corresponding services.
- To study the performance of the resource allocation policy in a time period, simulating a number of accidents with data provided by the GES database, and the real deployment of health care centers in a specific area. This would require modeling the time between accidents and their severity.

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