Universidade do Minho
Escola de Engenharia
Departamento de Informática

Bruno Martins Pereira

Improving the Response Time of Emergency Vehicles

Using V2X communications

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Using V2X communications

Master dissertation
Master Degree in Computer Science

Dissertation supervised by
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December 2019

STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

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ABSTRACT

Emergency vehicles are bound to lose unnecessary time on their response. Furthermore, research shows that emergency vehicles are prone to fatal crashes while on an emergency call. Emergency vehicle's response time is commonly affected by factors unbeknownst to it, such as traffic, traffic lights, road conditions, and accidents.

The overall goal of this dissertation project was to improve the response time of an emergency vehicle, while improving its safety along the route. Thus, V2X communications was used to obtain knowledge from the environment, so that the emergency vehicle can choose the best decisions to reduce the response time. The emergency vehicle issued alerts to all of the entities of the road system so that these can adapt their behaviour collaboratively. In this context, V2X communications may occur between vehicles and every other entity of the system, such as infrastructures, pedestrians, vehicles, and the network.

The present document describes the research and development work that aimed to establish a comparison between two scenarios: with and without support on a vehicular network simulator, namely Veins, incorporating the American standard WAVE. The V2X scenario benefited from use cases as emergency avoidance, dynamic routing, intersection and traffic light's logic. Alternatively, the non-V2X communications setup did not have access to communications, simulating a current context for urban road environments. The evaluation of the V2X benefits was made by analysing the most relevant criteria like response time, stop time, distance covered by the emergency vehicle.

The performance of the system prototype based on these metrics showed a clear improvement when using V2X communications. In particular, the response time was reduced by 41% using V2X, guaranteeing that the use of V2X is a step forward in this context. Since the results from the tests using a full simulated setup were positive, a pair of additional experiments integrating real Bosch V2X communication boards were planned: one with the integration of these boards into the already simulated environment and another with the integration of these boards on real Bosch prototype vehicles. While this later experiment was not possible to realize during this dissertation work time, the former was conducted with successes proving that the it is already possible to develop RD projects that use real V2X communications boards, which is a step closer to test these new technologies on real environments or, at least, on controlled environments that better emulate real environments.

RESUMO

Os veículos de emergência tendem a perder tempo desnecessário na sua resposta de emergência. Além disso, estudos revelam que os veículos de emergência estão propensos a ter acidentes fatais e, considerando a natureza dos mesmos, que é suposto ajudarem os pacientes, não devem estar envolvidos do outro lado da ajuda médica. Além disso, o tempo de resposta é sempre afetado por fatores que o veículo de emergência não consegue controlar, tal como trânsito, semáforos, STOPs, acidentes.

Este projeto tem como objetivo principal melhorar o tempo de resposta de um veículo de emergência, enquanto aumenta a segurança do sistema. Assim, as comunicações V2X foram utilizadas para obter conhecimento sobre o ambiente, para que o veículo de emergência consiga escolher as melhores decisões para minimizar o tempo de resposta, enquanto alerta todas as restantes entidades, para que se possam adaptar e não ser um obstáculo para a emergência. Neste contexto, comunicações V2X são comunicações entre veículos e todos os outros constituintes do sistema, tal como infraestruturas, pedestres, veículos, e a rede.

Este documento descreve o trabalho de investigação e desenvolvimento através de uma comparação entre um cenário com e outro sem V2X, cenários feitos num simulador rodoviário e de comunicações veiculares, o Veins, utilizando o protocolo americano WAVE. O cenário com V2X irá usar funcionalidades como as rotas dinâmicas, veículos desviarem-se do veículo de emergência, e lógica dos semáforos e dos STOPs. Entretanto, o cenário sem V2X não terá acesso a quaisquer comunicações, simulando um cenário atual rodoviário. A avaliação dos benefícios do V2X irá resultar da comparação entre o tempo de resposta de um veículo de emergência, o tempo que esteve parado, a distância percorrida, e a emissão de CO_2.

A avaliação do protótipo desenvolvido recai na análise das métricas consideradas, que indica uma clara melhoria utilizando comunicações V2X. Analisando o tempo de resposta, este foi reduzido em 41% utilizando V2X, garantindo que o uso do V2X é uma mais valia neste contexto. Considerando que os resultados dos testes utilizando um sistema totalmente simulado foram positivos, um par adicional de experiências integrando placas de comunicações Bosch V2X reais foi planeado: um com a integração destas placas num sistema de simulação já desenvolvido e outro com a integração destas placas nos veículos protótipo da Bosch. Enquanto que esta última experiência não foi possível realizar durante o tempo de desenvolvimento desta dissertação, a primeira foi realizada com sucesso provando que é já é possível desenvolver projetos RD que utilizem placas reais de

comunicações V2X. Assim, os testes destas novas tecnologias em cenários reais mais fáceis, ou, pelo menos, em sistemas controlados que representem melhor ambientes reais.

ACRONYMS

BSM Basic Safety Message

CAM Cooperative Awareness Message

C-V2X Cellular-V2X

CODU Centros de Orientação de Doentes Urgentes

DENM Decentralized Environmental Notification Messages

DSRC Distance Short-Range Communications

ETSI European Telecommunications Standards Institute

IEEE Institute of Electrical and Electronics Engineers

INEM Instituto Nacional de Emergência Médica

ITS Intelligent Transport Systems

LTE Long Term Evolution

MAC Media Access Control

OBU On Board Unit

PHY Physical

RSU Road Side Unit

SPaT Signal Phase and Timing

TOPO Topology

VANET Vehicular Ad Hoc Networks

V2I Vehicle To Infrastructure

V2N Vehicle To Network

V2P Vehicle To Pedestrian

V2V Vehicle To Vehicle

V2X Vehicle-To-Everything

WAVE Wireless Access in Vehicular Environments

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

1.1 CONTEXT

The present work and dissertation were developed under a curricular internship with Bosch Car Multimedia Portugal S.A. The partnership between the University of Minho allowed the combination of knowledge from the university tutors with the knowledge and developed technologies and innovation factor from Bosch, to lead this work to the right path.

1.2 MOTIVATION

According to data from the World Health Organization [6], approximately 1.3 million people die each year on the roads, number that roughly translates to 174 deaths per million inhabitants. In the European Union, the numbers are considerably lower than before with 25.300 fatalities in 2017, translating to 49 road fatalities per million inhabitants. Despite being lower than the rest of the world, the numbers are still too high and should be greatly reduced.

Considering the scenario presented, V2X communications could contribute to an improvement to the numbers. If the vehicles maintained a connection with all entities surrounding them, relevant information could be shared to guarantee road safety. Despite the clear advantage of having knowledge about the road environment, skepticism is raised with the fear of the growing lack of human decision in the driving process, with the general public defending that these advances would not be necessary if people drove safely. However, there are many situations where the driver is not at fault and the accident could be avoided if V2X was implemented.

1.2.1 *Road data*

The statistics of the European Commission regarding the type of roads in which the fatalities occur highlight the need of V2X communications. Statistics such as 8% of the fatalities occurred on motorways, 37% on urban areas, and 55% on rural roads, prove the need for V2X, if we consider the type of actors in each road [6].

Figure 1.1.: Road fatalities in the EU by types of roads [6]

The motorway does not allow pedestrians and cyclists to circulate on it and the number of improbable obstacles is reduced, since the roads are generally long straights, which means the high speeds do not pose a problem as big as anticipated, since there is a low chance that the driver has to do a hard stop.
Regarding urban areas, since all actors can circulate on them, the risk of accidents is much higher, with situations such as a pedestrian crossing the road outside of a walkway, pets spontaneously appearing on the road, and vehicles not being careful on intersections.
About the rural areas, the roads are usually narrow, the visibility may be reduced (with dangerous junctions), wild animals crossing the roads, and pedestrians walking along the curb.

1.2.2 *Communication Protocol*

Most of these concerns can be reduced or solved with V2X communications. Considering the motorways, if an infrastructure alerts all passing vehicles of slippery roads or a stationary vehicle by the side of the road, the driver can act accordingly, reducing the speed and preventing a potential fatal accident.
Regarding urban areas, if all actors are connected, it is possible for a pedestrian to receive an alert from a car he cannot see, so that it will not cross the road; for cars to know when they can enter an intersection safely; or, in a distant (and possible) future, for a pet's collar to send signals to all surrounding vehicles that a lost animal is crossing the road, preventing an accident.
Concerning rural areas, a vehicle can be alerted if a herd animal is close to the road, or if a pedestrian is nearby. In this case, an existing infrastructure can also alert the vehicles of invisible junctions and possible merging vehicles.

1.2.3 *Emergency vehicle data*

Emergency vehicles require a special concern about safety in an emergency response. In order to provide the best medical care (or any other kind of emergency response), it is crucial that the response time is as low as possible, which implies that the emergency vehicle must drive at higher speeds than the rest of the traffic vehicles and obey different traffic laws. These variables represent higher danger for the emergency vehicle and the other entities of the traffic system that may be unaware of the emergency. A study presented by the National Highway Traffic Safety Administration of the United States of America [24], in the years between 1985 and 2015, there were 29 fatal crashes involving ambulances, resulting in an average of 33 fatalities annually. Considering the context of emergency aid, the number of crashes is very high and could be greatly reduced, if V2X communications were implemented, in which all actors of the traffic system were aware of the emergency vehicle beforehand, instead of just hearing or seeing it.
According to data from the CODU (Centros de Orientação de Doentes Urgentes – Orientation Centers of Urgent Patients), the Portuguese National Institute for Medical Emergency (INEM) took an approximate time of 18 seconds to respond to emergency calls, when the optimal value is close to 7 seconds. This added value, when considering urgent situations where time is critical, could impact greatly the patient's health.
In conclusion, this work major goal is to minimize an emergency vehicle trip time and not solving a resource allocation problem. Reducing the emergency vehicle's response time can reduce the impact of the time lost on emergency calls, or possible inconveniences that may arise when giving medical aid at the patient's location.

1.3 MAIN OBJECTIVES

The main objective of defined for this master thesis is to reduce the emergency vehicle's response time, in order to increase the chances of a successful aid, however there are emerging objectives from the main one, such as:

1. develop knowledge of the Cooperative Awareness Message (CAM), Decentralized Environment Notification Messages (DENM), and Basic Safety Messages (BSM);
2. create different algorithms for the different infrastructures (traffic lights, intersections, stop signs);
3. create simulated traffic scenario on SUMO, capable of recreating hazards, such as accidents or stopped cars;
4. implement communication concept between emergency vehicle to surrounding vehicles and roadside units, such as traffic lights and stop signs;

5. implement a simulation on Veins where vehicles do not use V2X and another where vehicles use V2X (with all surrounding vehicles and pedestrians are informed of the emergency vehicle approaching). Compare the emergency vehicle's response time and time stopped at traffic light, with and without V2X, and using Bosch Vehicular Communications interface;

6. create a simulated scenario on SUMO where the communication is guaranteed by the Bosch Vehicular Communications board.

1.4 Thesis Structure

This initial chapter describes the work's main motivation using relevant data, goals, as well as the thesis structure and the main subjects discussed in each section.
In chapter two, the state of the art describes important concepts (like Vehicle-to-Everything (V2X), Distance Short Range Communications (DSRC), Long Term Evolution (LTE), messages, and routing) and related work and European funded projects, such as Drive C2X and Intersafe-2.
In chapter three, the problem and its challenges are discussed. Based on the problem's description, its challenges, a proposed approach and description of the system's entities and a system's architecture, communication protocol with BSM structure (fields and values) and the communication between the system's entities). The simulation platforms, specifically Veins simulator (SUMO and OMNet++) are also introduced
In chapter four, the implementation simulation setup is described, namely issues related to: the roads map, different test roads map, messages and communication, RSUs and their position, the vehicle's behaviour, V2X and Non-V2X decision, routing, the implementation of the use cases, dynamic routing, accidents and traffic, emergency vehicle avoidance, intersection logic with stop signs and traffic lights. The use cases specification follows a specific order, starting with a brief description, a sequence diagram, and a behaviour describing algorithm. It also includes the test preparation and the analysis of all the outcomes .
In chapter five, two experiments are represented: the board integration and the real life scenario. Regarding the former, its goal is to incorporate the boards in the simulation, while the latter is the representation of a traffic light using V2X communications and real vehicles. These descriptions start with a explanation of the problem, its implementation, a sequence diagram, and, lastly, a behaviour describing algorithm. The real life scenario also includes the possible experiment setup.
In chapter six, the conclusions of the project are summarized and possible future work is proposed.

2

STATE OF THE ART

This chapter contains a concise description of the all terms and concepts mentioned throughout the dissertation, subjects such as Vehicular Ad Hoc Networks (VANETs), V2X and all its components, how vehicles communicate with every component of the traffic system, and routing algorithms.
Lastly, on the end of the chapter, two European funded projects are mentioned, as well as their development and results.

2.1 BACKGROUND

The current state of technologies marketed to the general public relies mostly on sensors, such as ultrasonic, radar, and camera technologies. These technologies allow vehicles to check their surroundings and help make safer decisions while driving, however they present the same limitations as humans. For example, the camera may show an obstacle on the road, but it does not guarantee that the driver will be able to react on time to avoid it.
Due to these limitations, the concept of vehicle-to-vehicle communication (V2V) emerged. V2V allows vehicles to communicate with each other through short-range communication. Contrary to the sensors, the V2V range is higher and does not depend on the field of vision. It it is possible to communicate with surrounding vehicles alerting them of a lane change, flat tires, incoming vehicles in an intersection.
Another technology is the vehicle-to-infrastructure (V2I) technology. V2I is used for the vehicles to communicate with infrastructures. In this way, the infrastructure can have a crucial part on creating smart cities with smart signals and smart parking. The smart signals will adapt to the road conditions and traffic modifying the timings of the traffic lights, depending on the current flow, in order to maximize traffic efficiency. The smart parking will allow communication with the vehicle, transmitting the free spaces and the cost.
In order to deliver traffic updates, despite not being close to traffic jams, the vehicle-to-network (V2N) technology was developed, so that the vehicles can communicate with the cellular infrastructure.
Lastly, if all these previous concepts (V2V, V2N, V2I) and V2P (vehicle-to-pedestrian) are

combined, the V2X (vehicle-to-everything) technology emerges, which will combine the powers of distance short-range communication with cellular communications to achieve a total connection between all entities in the road system.

Figure 2.1.: V2X components, courtesy of Qualcomm

2.1.1 *VANETs*

A VANET is an Ad-Hoc network between vehicles and infrastructures, which allows communication between these two entities. This technology took his first big step in 1999, when the United States Federal Communications Commission reserved 75MHz at 5.9GHz band for Vehicle-to-Vehicle communications and Vehicle-to-Infrastructure communications. Three years later, joining the forces of automotive manufactures (such as BMW, Volkswagen, Ford, GM, Nissan, Toyota, and Daimler-Chrysler) and the USA Department of Transports, the Vehicle Safety Communications Consortium project was created, where the Dedicated Short-Range Communications was developed, allowing wireless communications with nodes at high speed at a kilometer range. [23][22]
The VANET architecture contains road side units (RSUs) and on board units (OBUs). A RSU is a device usually fixed to a specific location, such as road side, traffic lights, stop signs, parking spots, or any convenient location. The RSU needs to be equipped with a network device for DSRC, capable of communicating with the OBUs and infrastructures.[3]
OBUs are devices usually attached to a vehicle and are used to exchange information between vehicles and infrastructures. OBUs need a processor (to compute sent and received data) and a network device for DSRC wireless communications.[3]

2.1.2 *V2X*

vehicle-to-Everything (V2X) is a technology that allows vehicles to communicate with all moving parts of the traffic system around them, such as other vehicles, pedestrians, and traffic lights, for example. There are two types of V2X standards, depending on how they

are implemented, a Wi-Fi based one, called DSRC, and a cellular based one, called Cellular-V2X (C-V2X). This technology's main goal is to increase the safety on the roads and it can be achieved considering that with the communication between all parts of the traffic system, obstacles and hazards can be detected before they can be seen. [17] [11] [20]
According to the HIS Markit V2X market snapshot [17], it is estimated that in the European Union, in 2019, there will be DSRC-equipped vehicles on the road, while Japan and the United States of America already have vehicles on the road, with approximately 120000 units sold as of May 2018. The top manufacturers of DSRC-equipped vehicles are Toyota and GM, while Volkswagen aims to enter this market in 2019.
In the same snapshot [17], 2020 is the projected year where the first cellular V2X equipped vehicle will be released, with China being the biggest pioneer, testing this technology in 8 cities, against the EU's 6, the USA's 3, and Japan's 2. The most active companies working on the V2X technology are Qualcolmm (on the chipset); Huawei (on the equipment); and SAIC, Ford, and Audi (on the automobiles).

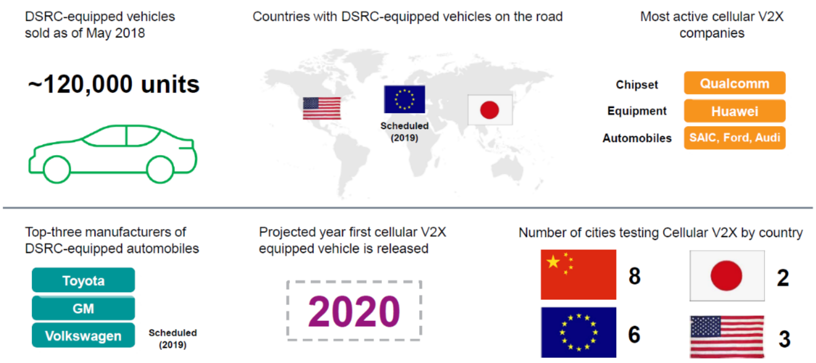


Figure 2.2.: V2X projections [17]

V2X communications will bring numerous benefits to all transportation, such as [1]:

- **safety increase:** with collision avoidance, reducing the number of fatalities and the severity of the injuries;
- **time saving:** through traffic optimization and reduction of the traffic congestion, which can be accomplished by the constant communication between the traffic system's entities;
- **money saving:** with a more efficient and safer transportation system, avoiding traffic and congestion;
- **eco-friendly driving:** through optimal routing and platooning, thus reducing the CO_2 emissions;

- **comfort:** with the possibility of seeing obstacles before they show up on the eye's field of vision, the driver can have a more relaxed and stress free drive.

Despite the numerous advantages, V2X technologies present a major challenge with the security aspect. Considering all the entities present on the traffic system, the attacks may emerge from the infrastructure (with problems with the platform integrity, data analysis, and denial of service against functionality), the V2X communications (with black hole, Sybil attacks, and jamming), and the vehicle (with the tampering or damaging the units, and manipulating the in-vehicle communications). Considering that one of the most important use cases of V2X communications is helping emergency vehicles to improve their response time, under no circumstances an intruder must be able to interfere with the communications, to avoid putting the patient's life at risk [14].
Despite being a step in the right direction, V2X communications need to be very careful and robust against the following networking attacks:

- **denial of service:** this attack prevents users from accessing a service by overwhelming the physical resources or the network connections, flooding the service with traffic or unusable data[10];
- **black hole:** also known as the packet drop attack. It happens when a router is compromised and is discarding packets, instead of relaying them [19];
- **sybil attacks:** this type of attack happens when a reputation system is subverted by identity forgers in peer-to-peer networks [26].

2.1.3 *V2P (vehicle-to-pedestrian)*

V2P incorporates communications among all different kind of road users, such as people walking, children being pushed in strollers, people in wheelchairs (or other mobility devices), passengers entering or exiting buses and trains, and people riding bicycles.

2.1.4 *V2N (vehicle-to-network)*

This type of communication is characterized by its higher latency than V2V, which makes it appropriate to communicate non-emergency messages, such as advertisement, or traffic updates. Considering this, the network could alert an emergency vehicle of unexpected traffic on its route, so that it may choose an alternate route.[11]

2.1.5 *V2V(vehicle-to-vehicle)*

Communication between vehicles includes the exchange of data regarding reporting anomalies in the traffic system (accidents, stopped cars, strong weather conditions), or an emergency vehicle reporting its proximity to all surrounding vehicles.
In order to communicate with each other, the vehicles need to contain an On Board Unit (OBU).

2.1.6 *V2I (vehicle-to-infrastructure)*

In this type of communication, vehicles and infrastructures interact to handle distinct scenarios, such as a traffic signal alerting the vehicles that it is turning red; or an emergency vehicle alerting a traffic light of the emergency, so that it can change its status to allow the emergency vehicle to progress as quickly as possible.

2.1.7 *DSRC*

Distance Short-Range Communications (DSRC) is a term that includes the standardization initiatives based on the IEEE 802.11p standard [16]. These initiatives have different implementations depending on their geographic location, the ARIB in Japan, the WAVE in the USA, and the ETSI ITS-G5 in Europe.[20]
The IEEE 802.11p standard is an amendment to the IEEE 802.11 standard (also known as Wi-Fi), adapting the existing technology, so that it allows communications between two moving vehicles. Contrary to WiFi, where the source's signal is mostly stationary, when two vehicles communicate, we have to consider that they may be moving.[13] This situation poses a problem with the frequency of the signal, due to the Doppler's Effect. As known, the frequency changes as the source and observer of the signal move towards each other, so there is a risk that the signal will arrive at the destination on a frequency not meant for the desired communication. Considering this problem, 802.11p developed a solution where a threshold is considered on the allowed bandwidth, so that the signal can still be received even if the frequency is slightly changed due to the Doppler's Effect, thus, allowing communications between two moving vehicles.
The DSRC is implemented on a PC5 interface and it only allows short-range communications (less than a kilometer long), which means the vehicle can only communicate with nearby entities, i.e, it cannot send a global message alerting an accident. However, since the latency is very low, it makes it capable to send related safety messages. The way that DSRC can achieve this low latency is through an inefficient management of the wireless resources, with the use of wildcards, which make it inadequate for safety applications. [20]

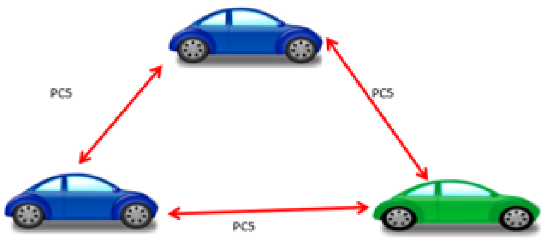


Figure 2.3.: Distance Short-Range Communications

2.1.8 *ETSI vs WAVE*

Muhammad Awais Javed and JY Khan in [15] present a table that compares the differences between the WAVE and ETSI standards. The following table is an abridged version of the mentioned table.

Table 2.1.: Comparison between WAVE and ETSI standards

Parameter	**WAVE**	**ETSI**
Spectrum bandwidth	75MHz	50MHz
Frequency range	[5.855, 5.925] GHz	[5.855, 5.905] GHz
Control channel frequency	5.89GHz	5.9GHz
PHY/MAC layers	IEEE 802.11p	Multiple access technologies
Main safety messages	BSM	CAMs and DENM

2.1.9 *LTE-V*

LTE-V, or as it is commonly known C-V2X, derives from the standard Long Term Evolution (LTE) for high-speed wireless communication. C-V2X combines the capabilities of roadside units (such as traffic light poles, or lamp poles) and the cellular network to support autonomous driving. [20]
C-V2X has two complementary communication modes. The first, the direct mode, implemented over the PC5 interface, operates in the ITS bands (acts on the ITS 5.9GHz spectrum), is independent of cellular network and allows for V2V, V2I, and V2P communications. These communications are short range (highest range is less than one kilometer) and are directed towards safety driven situations, due to their low latency.[20][29]
The second, the network mode, implemented over the UU interface, operates in the mobile broadband licensed spectrum and allows for V2N communications. These communications

are long range (their range is higher than one kilometer) and, due to their high latency, are used to transmit information that is useful to cars connected to the network, such as unexpected traffic or accidents.[20][29]

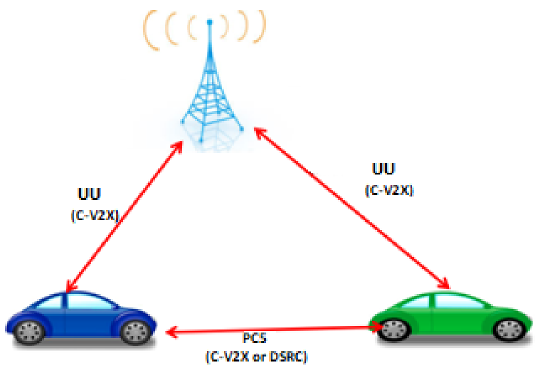


Figure 2.4.: C-V2X and its interfaces

This technology has many benefits, such as a superior range and radio performance compared to 802.11p (two times the range, better performance Non-Line-Of-Sight, enhanced reliability with a lower rate of lost packets, better congestion control in dense environments; it uses the ITS spectrum and there would be an investment reuse (safety applications developed for DSRC will work unchanged); low latency; uses IEEE, ETSI standards to guarantee security[29] [20].

2.1.10 *ITS*

Quoting the European Telecommunications Standards Institute, Intelligent Transport Systems (ITS) are systems to support transportation of goods and humans with information and communication technologies in order to efficiently and safely use the transport infrastructure and transport means[12]. ITS aim to achieve traffic efficiency by minimizing traffic problems, while providing users with prior information about traffic and other traffic related real-time information. This allows the reducing of commuters travel time, while improving their safety. It is used for traffic congestion control and information, road safety, and efficient infrastructure usage.[5][2]
ITS are based on data collection, analysis and usage of the analysis results in the operations, control, and research concepts for traffic management. To achieve the previous operations, sensors, information processors, communication systems, roadside messages, GPS updates, and automated traffic prioritization signals are needed.[5]
Considering this information, an ITS station is a station that can achieve any of the previously mentioned operations.

2.1.11 *CAM*

Cooperative Awareness Message (CAM) is a type of message transmitted within a specific frequency periodically to every single-hop neighbors. Its main objectives are to ensure that all surrounding ITS stations are aware of the sender (with information such as geographic location, movement, direction, speed, and acceleration), and to updating the neighboring tables. [27]

2.1.12 *DENM*

Decentralized Environmental Notification Messages (DENM) are event-triggered asynchronous messages that are broadcasted with the aim of alerting surrounding ITS stations about hazards. These messages require multi-hop communication, meaning they may be forwarded outside the originating ITS station single-hop transmission range. The usual content of these messages contains "information related to an event that has potential impact on a road safety and traffic condition". The event can be described by its type, location, detection time, and duration. Unlike a CAM, a DENM is identified by an event, instead of the ITS station identifier. The operations that can be associated with DENM are the update of the message, the repetition of the message (only the originating ITS station should be able to repeat the message), and the termination of the message. The message can be terminated by the originating ITS station, with a DENM Cancellation message, or by the receiving ITS station if the number of hops or the message's life time surpasses the defined value. [27]

2.1.13 *BSM*

Basic Safety Messages (BSMs) are messages belonging to the WAVE standard that are used to exchange safety information about the vehicle's state. These messages are sent to surrounding vehicles with useful data (such as, for example, position, heading, speed, and information characterizing the vehicle) for safety or other applications. Regarding the transmission rates, these are not generally specified, while a rate 10 times per second is normal. [21] The BSM structure will be mentioned in the Communication Protocol section.

2.1.14 *Dijkstra Algorithm*

The Dijkstra's shortest path algorithm is a routing algorithm, that, starting on an initial node, aims to discover the shortest path in a graph, directed or undirected, through the costs of the graphs' edges. This algorithm has similarities with a Breadth-First Search algorithm with a priority queue, instead of a normal queue. [9] The algorithm functions as follows: [9]

1. initializes source node with zero distance and all other nodes with infinite distance;
2. inserts source node to queue and starts the queue loop;
3. for each neighbor of the current node, calculates a tentative distance between the current node's distance and the distance to its neighbor. If the tentative distance is smaller than the distance to the neighbor, sets the neighbor node's distance to the tentative distance and removes it from the priority queue with that distance as its priority;
4. continues with the priority queue until all node's shortest path to the source node are calculated.

2.1.15 *Routing limitations with emergency vehicles*

Routing needs to be part of the solution concerning enhancing the emergency vehicle's response time, however it should not be considered a final concept. On the traffic system, a lot of factors influence the emergency vehicle's response time, for example, unexpected traffic or stopped cars. These setbacks make it almost impossible that the calculated lowest time and the real time are compatible, because of the dynamic environment.
Thus, the solution will use V2X communications to alert the surrounding cars, change traffic lights, and make the best out of its priority to lower the response time, while adapting its optimal path to the possible setbacks that may appear, such as accidents, or excessive traffic. The emergency vehicle will be able to dodge these obstacles through the V2X messages it receives, calculating the new optimal path each time a setback occurs.

2.2 RELATED WORK

2.2.1 *Drive C2X*

The Drive C2X is a finished and EU funded project, active between 2011 and 2014, where its main objective was to "carry out large-scale field operational tests of cooperative systems, which are characterized by a framework for modeling and controlling the interactions between humans and machines, to evaluate real-world conditions and their impact on user behavior, traffic flow, safety, the environment, and the society. The test sites are located in Finland, France, Germany, Italy, Netherlands, Spain, and Sweden". This project is also aimed at testing the functionality and robustness under adverse conditions and promoting cooperative driving. [8] [15]

Results

According to [18], tests were made in the 7 test sites (Finland, France, Germany, Italy, Netherlands, Spain, and Sweden), with 750 drivers, and 200 vehicles with a total of approximately 1.5 million kilometers and the conclusions were that there were gains to be made with the implementation of the present project.
Assuming 100% penetration rate, in the following table, we can view the percentage of the reduction of fatalities and injuries in the IVS speed limit and weather warning functions.

Table 2.2.: Percentage of the reduction of fatalities and injuries in the IVS speed limit and weather warning functions

	% reduced fatalities	**% reduced injuries**
IVS speed limit	23	13
Weather warning	6	5

In the following table, a prediction of penetration rate and percentage of reduced fatalities are shown for the years 2020 and 2030.

Table 2.3.: Prediction of penetration rate and percentage of reduced fatalities for the years 2020 and 2030

	Penetration rate (%)	**% reduced fatalities**
2020	12	3
2030	76	16

Considering 100% penetration rate one more time, for the percentage of reduced fatalities and reduced injuries, the results show the number of road works warning, emergency brake lights warning, and traffic jam ahead warnings.

Table 2.4.: Percentage of reduced fatalities for road works warning, emergency brake lights warning, and traffic jam ahead warnings

	Road works	Emergency brake lights	Traffic jam ahead
% reduced fatalities	3	2	2
% reduced injuries	2	2	2

All of the values mentioned in tables 2.2, 2.3, and 2.4 are obtained from data regarding the mentioned test sites in [18].

2.3 INTERSAFE-2

The INTERSAFE-2 project is a closed project funded by the EU, which started on the 1st of June 2008 and ended on the 31st of May 2011, whose main goal was to guarantee safety on the intersections through sensors and communication between vehicles, and infrastructures. [7]

The project's main features are object detection, road marking direction, navigation based on natural landmarks, and possessing detailed map of the intersection. Therefore, that all objects and ego-positions (locates an object on a global coordinate system [25]) are known and a dynamic risk assessment is presented. One characteristic of the present project is that it tries to emulate human thinking, through calculations of a risk factor in entering an intersection. It also aims to help the drive through stop sign assistance, traffic light assistance, turning assistance, and right of way assistance. [24]

According to CORDIS, Community Research and Development Information Service, the European Commission's repository to share the results of the EU research projects, the deployment of INTERSAFE-2 could improve the intersection safety on 80% regarding accidents with injuries and fatalities. Therefore, in Europe, these decreases would mean a possible benefit of up to 40% less injury accidents and 20% less fatalities. [7]

2.4 SUMMARY

Apart from the knowledge obtained on V2X communications, this chapter was also important for analyzing the current state of the art on V2X and emergency vehicles, which is very scarce. Since the topic is recent, the relevance of the present dissertation topic is high. The need for the further development of V2X was also corroborated by the European funded projects mentioned, whose results showed clear advantages of using V2X.

Despite only presenting two related studies on the V2X subjects, new ones were created.

However, these are still recent and require monetary funds in order to obtain their knowledge, which was not a possibility in this study.
The next chapter describes the dissertation's problem, the proposed approach, the challenges associated with it, and the tools needed to implement it.

3

PROBLEM AND ITS CHALLENGES

In this chapter the problem needs to be scrutinized, so the focus is on designing a solution to reduce the emergency vehicle's response time. Considering this, the problems needs to be explained, with special attention to pointing out the challenges that may arise, in order to consider all possible scenarios, when implementing the solution.
Regarding the proposed approach and solution, the system's entities are going to be identified and described. A detailed look shall be taken concerning the simulated system architecture and the software/hardware architecture; along with the communication protocol, having a detailed look at the BSM structure and the communication between all the entities. The chapter ends with an explanation of the simulation's chosen software.

3.1 PROBLEM DESCRIPTION

The main problem to target is, considering the initial coordinates of an emergency vehicle and the end coordinates, to reduce the emergency aid's response time. Reducing the response time is extremely important, since time is one of the most crucial aspects on an emergency aid.
However, to accomplish this goal, certain factors must be considered. The road obstructions (such as traffic, construction work, car breakdowns) will always be a constant in the traffic system, possibly blocking the emergency vehicle's way. Another limitation is that the infrastructures are not adapting themselves to the emergencies. Currently, if we consider an intersection with traffic lights on all the junctions, the traffic lights are not capable to coordinate their behavior, so that the emergency vehicle can cross the intersection quickly and safely.
Lastly, the reaction time of the passing cars to the emergency vehicles must be considered. Many factors can influence the driver's attention to the road, which can lead him to be unaware of the emergency vehicle closing in, possibly losing precious seconds to the emergency aid.
In response to this problem, the present thesis proposes to evaluate the gains of implementing V2X technologies in the considered scenario, assuming the following principles:

- the emergency vehicle sends messages to the passing cars to get out of the way;
- the emergency vehicle sends messages to the infrastructures communicating it is going to pass through them. If the infrastructure is a traffic light, the traffic light needs to change its color;
- the infrastructure sends messages with the emergency vehicle's information to passing cars and they must react to the messages;
- the cars send messages to everything in its range alerting that it is obstructing the street, so that the emergency vehicle can avoid the obstruction;
- the infrastructure can stop all traffic in an intersection, so that the emergency vehicle may cross safely.

3.2 CHALLENGES

Vehicular communications are a hot topic nowadays, however the relevance of testing is limited to the number of vehicles. This situation implies that companies with a higher number of resources, for example fleets of vehicles, have an advantage over the rest, due to their higher number of testing results. This will prove to be a challenge on the present dissertation, where the results will be generated in a simulation environment. Regardless of the quality of the results presented in the present thesis, they cannot be compared to the exact same results obtained by one of the market's leaders with a fleet of vehicles.
The chosen simulator will be Veins, which presents a huge advantage that is the ability to implement any situation related to traffic and communications. For example, the original Veins simulator does not contemplate pedestrian crossings, however it is possible to program this facility into it. Despite this advantage, the documentation for the simulator is extremely scarce. Online support is not sufficient, without proper documentation.
Further discussion on the simulation software is provided in section 3.3.4.

3.3 PROPOSED APPROACH AND SOLUTION

3.3.1 *System's entities*

The several entities that constitute the system are the emergency vehicles, non-emergency vehicles, traffic lights, and stop signs. The logic of the latter two entities is controlled by RSUs.
The emergency vehicle, more specifically an ambulance, is an entity that needs to answer to an emergency call and has priority regarding other vehicles. In order to enforce this

priority, it needs to send periodic messages alerting of its passage to the infrastructures and the other vehicles, so that they can help the ambulance pass by, without losing time.
The non-emergency vehicles circulate through the roads with the sole purpose of going from point A to point B. They will communicate periodically their location and have the ability to receive messages from the infrastructures and emergency vehicles, acting in accordance with the received messages.
There are multiple non-emergency vehicles in the system, all of them with different purposes:

- **accident vehicle:** a vehicle that will simulate a stopped car;
- **slow vehicle:** a vehicle that will travel with reduced speed, simulating traffic;
- **non-V2X vehicle:** a vehicle that will simulate a car that does not have the capability to use V2X communications;
- **normal vehicle:** a vehicle that will send and receive messages, without any other particularity.

The aim of traffic lights is to, upon receiving a message alerting the arrival of an ambulance, change its lights, so the ambulance can cross them as fast as possible. This scenario becomes a little more complex, when we consider an intersection. In that scenario, the traffic light needs to change its light to guarantee the safety for every entity trying to cross the intersection.
Regarding the stop signs, they receive messages from the ambulance and try to grant it priority, while maintaining safety in the traffic system. This safety procedure will guarantee that the emergency vehicle crosses the stop sign area without having to slow down due to other vehicles. Simultaneously, the other vehicles will change their behaviour, so that they do not pose as an obstacle to the emergency vehicle.

3.3.2 *System Architecture*

The proposed system will function on the top layer, the application layer, and it will contain all the entities mentioned in the previous subsection. In the following image, the simulated system's architecture is represented, as well as the possible communications among all the components.
The communication regarding traffic lights and stop signs is assured by RSUs and the communication regarding vehicles and emergency vehicles is assured by OBUs. All OBUs communicate with the RSU, while the contrary applies as well, and can communicate with each other. Figure 3.1 shows the architecture of the simulated scenario with RSUs and

OBUs and the type of messages exchanged between them.

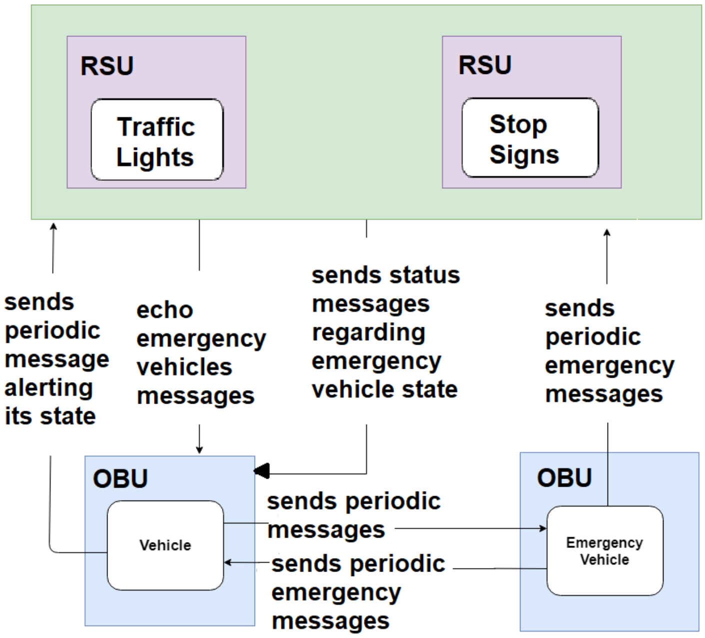


Figure 3.1.: Simulated system architecture

Regarding the system architecture, the Figure 3.2 illustrates all the necessary tools, developed programs, and hardware required to develop the present project.

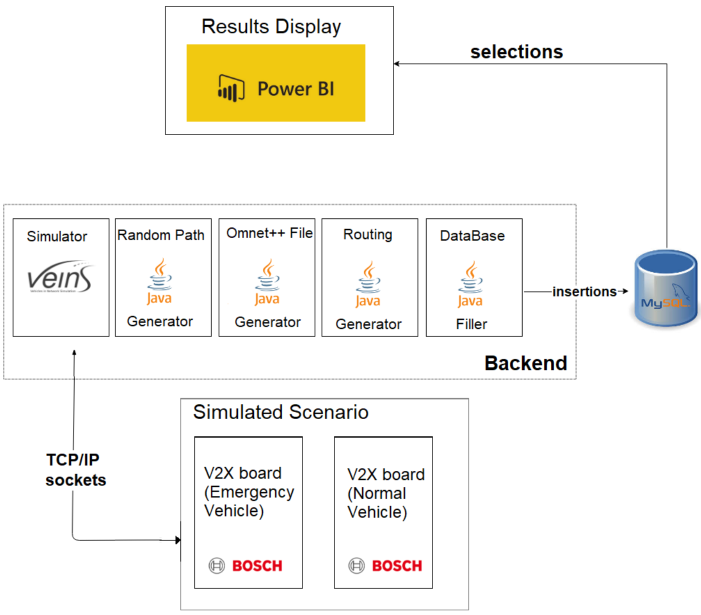


Figure 3.2.: System architecture

3.3.3 *Communication Protocol*

The communication between all of the system's components will be guaranteed by the American standard of DSRC (WAVE), transmitting Basic Safety Messages(BSMs), which, in this case scenario, are going to be the only necessary messages to transmit all of the important data regarding the vehicles state.
The BSM structure considered is based on the Fifth Edition of the Surface Vehicle Standard's (SAE) message set dictionary, an important document that defines the skeleton of all the WAVE messages.
A Basic Safety Message consists of two parts. A mandatory one, known as BSM Core Data, and an accessory one, known as Part II.
The BSM Core Data must be sent in every message and contains the most important content regarding the vehicle state. The following Tables 5, 6, 7, 8, and 9 present all of the Core Data's fields, a brief description, and the range of the values each one can assume.

Table 3.1.: BSM Core Data structure

Field	Brief Description	Range
msgCnt	Message count	[0,127]
id	Device Identifier	String (size(4))
secMark	DSRC second	[0, 65535]
lat	Geographic latitude	[-900000000, 900000001]
long	Geographic Longitude	[-1799999999, 1800000001]
elev	Elevation	[-4096, 61439]
accuracy	Positional Accuracy	Table 3.2
transmission	Current state of transmission	**0:** neutral **1:** park **2:** forward gears **3:** reverse gears **4, 5, 6:** reserved **7:** unavailable
speed	Speed	[0, 8191]
heading	Heading	[0, 28800]
angle	Steering wheel angle	[-126, 127]
accelSet	Acceleration in 3 orthogonal directions	Table 3.3
brakes	Brake System Status	Table 3.4
size	Vehicle Size	Table 3.5

Table 3.2.: Positional Accuracy Sequence

Field	Brief Description	Range
semiMajor	Radius of a semi-major axis representing the accuracy from a GNSS system	[0,255]
semiMinor	Radius of a semi-minorr axis representing the accuracy from a GNSS system	[0, 255]
orientation	Orientation of the semi-major axis	[0, 65535]

Table 3.3.: Acceleration in 3 orthogonal directions

Field	Brief Description	Range
long	Acceleration in longitude	[-2000, 2001]
lat	Acceleration in latitude	[-2000, 2001]
vert	Vertical acceleration	[-127, 127]
yaw	Yaw rate	[-32767, 32767]

Table 3.4.: Brake System Status

Field	Brief Description	Range
wheelBrakes	Brake Applied Statues	**0:** unavailable **1:** left front **2:** left rear **3:** right front **4:** right rear
traction	Traction Control Status	**0:** unavailable **1:** off **2:** on **3:** engaged
abs	Anti lock Brake Status	**0:** unavailable **1:** off **2:** on **3:** engaged
scs	Stability Control Status	**0:** unavailable **1:** off **2:** on **3:** engaged
brakeBoost	Brake Boost Applied	**0:** unavailable **1:** off **2:** on
auxBrakes	Auxiliary Brake Status	**0:** unavailable **1:** off **2:** on **3:** reserved

Table 3.5.: Vehicle Size

Field	Brief Description	Range
width	Vehicle Width	[0, 1023]
length	Vehicle Length	[0, 4095]

Regarding the second part of the BSM, it is formed by Vehicle Safety Extensions, Special Vehicle Extensions, and Supplemental Vehicle Extension. Due to its optional nature, an omission of the majority of the fields is necessary, in order to maintain the focus on the truly relevant fields. Considering the Special Vehicle Extensions, the important information is located on the *Emergency Details* data frame, through the *responseType* field. The response type represents the driving behaviour of the vehicle and can described as follows:

- **0:** not in use nor equipped;
- **1:** emergency;
- **2:** non-emergency;
- **3:** pursuit;
- **4:** stationary;
- **5:** slow moving;
- **6:** stop and go movement.

Examining the Supplemental Vehicle Extensions, the *Vehicle Classification* data frame contains the two necessary fields: the *role* and the *hpmsType*.
The role field represents the role that a DSRC vehicle is playing. Its values are enumerated, with an integer representing a certain type of role. For example, **0** represents a basic vehicle, **6** an emergency vehicle, while an unknown role can be defined by the integer **8**.
hpmsType is a field that characterizes the vehicle through its size, being important to define the type of vehicle that is sending the message. Similarly to the *role* field, it is defined by integers. For example, **2** represents a special vehicle type and **4** represents a car.

Communication between the system's entities

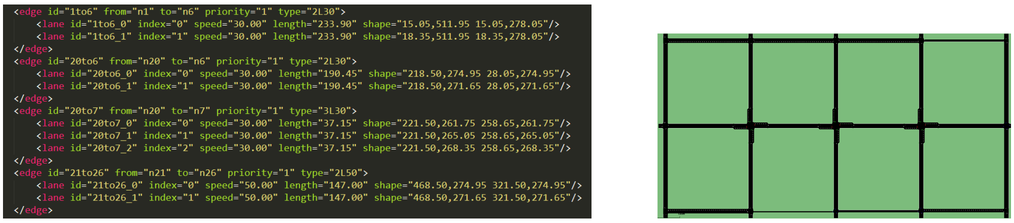
The communication will not be restricted to or by any of the system's entities, which means that a sent message will be broadcasted to everything in range and processed by the receiving entity. This way, the communication occurs between all intervenients on the system and it is not restricted depending on the entity.

3.3.4 *Software*

The Veins simulator framework [28] is the software that is going to be used, which incorporates two simulators, SUMO and OMNet++.

SUMO

SUMO is a traffic simulator that allows the simulation of a real traffic environment, with vehicles, the desired road map, and traffic components. One of its main characteristics is that it presents a deterministic nature, which will be helpful in the future testings comparing V2X usage and non usage. The main advantage is that it is open source, so the user can program an non-existent feature[28].
This simulator works with text files, which are read and transformed into entities and the map. These transformations are reflected behaviourally, but can also be shown through a visual interface.
The necessary files to run a SUMO simulation are **.launchd.xml*, **.net.xml*, **.sumo.cfg*, **.rou.xml*, and **.poly.xml*. The * represents that the file can have any given name, as long as the extension is the same as presented.
The *launch.xml* is the most important file of the ones mentioned previously, as it is the essential file for Veins to run the simulation. In this file, all the simulation's specifications need to be listed.
The *sumo.cfg* is an extension that receives the routes and the roads map and transforms them into a SUMO simulation ready to run.
The *net.xml* file defines the network topology with all the nodes and edges. The nodes are characterized by its coordinates and its type, which can be a traffic light, stop sign, or a node defined by the common right-way priority. Regarding the edges, they are connections between nodes, the number of lanes and the maximum allowed speed, presented in the next figure.



```xml
<edge id="1to6" from="n1" to="n6" priority="1" type="2L30">
    <lane id="1to6_0" index="0" speed="30.00" length="233.90" shape="15.05,511.95 15.05,278.05"/>
    <lane id="1to6_1" index="1" speed="30.00" length="233.90" shape="18.35,511.95 18.35,278.05"/>
</edge>
<edge id="20to6" from="n20" to="n6" priority="1" type="2L30">
    <lane id="20to6_0" index="0" speed="30.00" length="190.45" shape="218.50,274.95 28.05,274.95"/>
    <lane id="20to6_1" index="1" speed="30.00" length="190.45" shape="218.50,271.65 28.05,271.65"/>
</edge>
<edge id="20to7" from="n20" to="n7" priority="1" type="3L30">
    <lane id="20to7_0" index="0" speed="30.00" length="37.15" shape="221.50,261.75 258.65,261.75"/>
    <lane id="20to7_1" index="1" speed="30.00" length="37.15" shape="221.50,265.05 258.65,265.05"/>
    <lane id="20to7_2" index="2" speed="30.00" length="37.15" shape="221.50,268.35 258.65,268.35"/>
</edge>
<edge id="21to26" from="n21" to="n26" priority="1" type="2L50">
    <lane id="21to26_0" index="0" speed="50.00" length="147.00" shape="468.50,274.95 321.50,274.95"/>
    <lane id="21to26_1" index="1" speed="50.00" length="147.00" shape="468.50,271.65 321.50,271.65"/>
</edge>
```

(a) XML (b) Result

Figure 3.3.: Example of XML file and the resulting roads map

Associated with roads map file is the *.poly.xml*, which defines the shapes of the road maps surroundings, such as buildings and other obstacles.

Regarding the vehicles' routes, the *rou.xml* extension is used. This file defines the vehicle's trajectory and the vehicle's specifications adopted, namely:

- **acceleration** : maximum acceleration;
- **deceleration** : maximum deceleration;

- **id** : type identifier;
- **length** : length;
- **maxSpeed** : maximum speed;
- **type** : type.

Secondly, all the possible routes taken by the vehicles must be defined through an identifier and the navigated edges in a chronological order.
Lastly, the routes are associated with the vehicles through the mentioned identifiers, and the vehicles are launched to the simulation through a depart time.

OMNet++

OMNet++ is an event-based network simulator [28], written in C++, that aims to assure communication between the traffic system actors. As SUMO, this simulator is open source, so any changes that the user wants to implement, are possible. This simulator requires an initial file called *omnetpp.ini* that defines all the necessary parameters to run the simulation, such as:

- **RSU scenario specifications:** number of RSUs;
- **simulation parameters and obstacles parameters**;
- **TraCIScenarioManager:** the connector between OMNetpp and SUMO, and where the *launch.xml* is specified;
- **RSU settings:** the RSU coordinates and their type;
- **802.11p specification parameters:** such as the bitrate, for example, and the sensitivity;
- **WAVE application layer specifications:** where the vehicle types are scrutinized;
- **WAVE application layer specifications:** where the vehicle types are scrutinized;
- **accident specifications:** such as the number of accidents and their start time.

Regarding the vehicle's behaviour, its implementation is characterized in C++ files capable of reacting to certain events, in this case, V2X-based events. These files must have the same name as the WAVE application entities types defined above and defined in the SUMO *rou.xml*, in order for the whole simulation to work.[28]

3.4 SUMMARY

In conclusion, this chapter has provided a characterisation of the problem under study, where an architecture is developed after a thorough look is made at the problem description and its challenges. Considering the system entities and their functionalities, two different architectures were designed: one considering all the simulation elements and the communication between the system entities; and the complete system architecture, with all the necessary software and hardware.

The used simulator, Veins, is open-source, so any vehicle, with a specific desired behaviour and using V2X communications, can be created and included on a traffic scenario. The versatility of the simulator will prove to be an important advantage, when developing the solution.

Regarding the V2X aspect of the solution, the usage of the WAVE standard will present the solution with a robust property, since it follows current real communication protocols.

In the next chapter, the implementation details are discussed, including the simulation setup and describing the steps that led to the final solution. Lastly, the results of the simulation will be presented, along with the corresponding discussion.

4

PROTOTYPE DEVELOPMENT

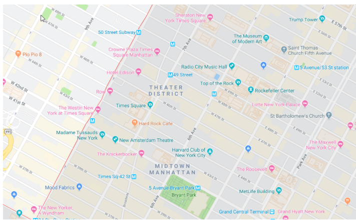
The present chapter describes the development of the solution and is divided into three logical parts: the simulation setup, the explaining of the use cases, and the discussion of the results.
The first part explains the simulation setup and the reasoning behind it, with the choices varying between the roads map, the messages, RSUs and their positions, the results of V2X/non-V2X tests, and the emergency vehicle routing.
On the second part, the implementation of the use cases defined on the previous chapter is explained . This detailing follows an introduction of the use case and the involved entities, a UML sequence diagram, and a behaviour describing algorithm. The mentioned use cases are: BSM message exchange, dynamic routing, accidents, traffic, emergency vehicle avoidance, intersection logic, and traffic lights.
The last section follows a business intelligence approach of dealing and extracting knowledge from the simulation data, which is asking questions to then try to answer them through processed data. This section is important, because the results evaluate the appraisability of the solution.

4.1 SIMULATION SETUP

In this section the simulation setup regarding the prototype implementation and simulation setup are going to be explained and justified. The need for a simulated environment comes from the fact that it is nearly impossible to implement a real scenario, due to resource scarcity.

4.1.1 *Roads Map*

The chosen shape was based on cities that present a certain symmetry between the streets, such as Barcelona and Manhattan, as they, in a real situation, are locations with a high amount of vehicles circulating through their roads. This high volume of traffic will be relevant when testing the distinct benefits between V2X communications and non-V2X communication scenarios. The roads map will be called a grid, henceforth.



(a) Manhattan

(b) Barcelona

Figure 4.1.: Manhattan and Barcelona maps

The outer nodes of the grid all have a small exit and entry point, so it does not seem that the vehicles materialize abruptly, but rather appear from a street that is not important to the simulation.

Since SUMO does not have the capability to represent kerbs, for every single lane, another one must be added to simulate the kerb. Thus, if a street has a kerb, as well as the initial lane, the lane to the right represents the kerb and no vehicle can circulate in it, apart when an emergency vehicle is close.

In order to make the simulation more real, the grid is not entirely symmetric. The number of lanes in the various streets is different, the streets may not have kerbs, and there are one-way roads. This solution will influence the emergency vehicle's route decision and guarantee that the simulation has various scenarios, ensuring that it must be robust enough to consider different circumstances.

Later on, the natural evolution of the project led to the conception of multiple roads map. In a first stage, a smaller grid was used as a roads map and in the latter stages, a larger grid was necessary.

The smaller grid, presented on figure 4.2, had dimensions of [2,4] was used on an initial stage to implement and test all the use cases. The size of this grid brings the advantage of being able to show all the working use cases on a single simulation, that would take less time to execute.

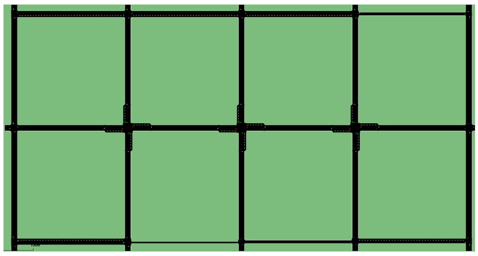


Figure 4.2.: Smaller grid

Despite the initial advantages of testing on a small scenario, in regards to obtaining results of the tests, the small grid was not an adequate solution due to its overly simplified roads map. That is the reason why a second roads map was conceived, to get additional simulation results from scenarios that are more complex and equivalent to real scenarios. The larger grid, figure 4.3, had dimensions of [5,7] and is an adaptation of the first one, with more nodes and edges, obstacles, and different intersections (instead of traffic lights in every intersection, there are intersections where the priority to the right is used). The transformation from the smaller to larger grid is was straightforward, since it is an expansion, which means that the previously defined behaviour will be the same in both scenarios.

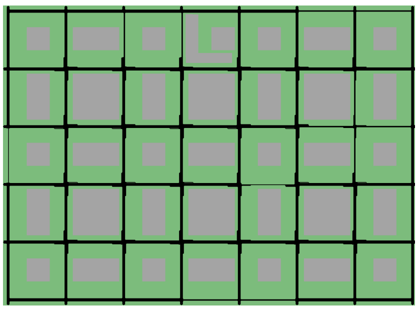


Figure 4.3.: Larger grid

4.1.2 *Messages and communication*

Regarding the vehicular message communications aspect, the chosen standard was the American one, since the simulator had the American standard [21] already partly implemented.

Considering the SAE BSM messages, only certain fields are important to the implementation of this solution, which means the other fields will be filled with null values (as defined by the standard), apart from the elevation field which will be used to indicate the emergency vehicle's estimate time to arrive at the intersection. Regarding the message transmission rate, the standard does not specify a certain value for it, but the transmission rate is higher on the emergency vehicle, since its messages present a higher priority.[21]

4.1.3 *RSUs and their position*

A crucial part of the simulation relies on the RSUs' work. The RSUs will control the traffic lights and the speed around the intersections. They will also echo the received messages from the emergency vehicles, so that their range is higher. Considering the last information, for each intersection, there needs to exist an RSU to control the traffic in that intersection. Whenever there's a stop sign, there needs to exist an RSU, because the stop sign, on itself, could bring problems to the emergency vehicle. Therefore, the RSUs will be located in the inner nodes of every grid and on the outer nodes when there's a stop sign present, as is illustrated in the figures 4.4 and 4.5.

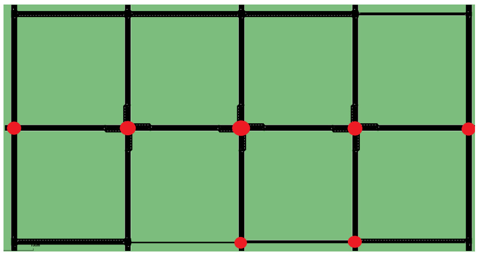


Figure 4.4.: RSU positions marked in red circles in the smaller grid

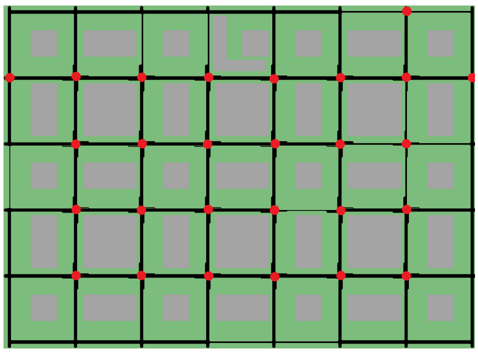


Figure 4.5.: RSU positions marked in red circles in the larger grid

4.1.4 *V2X and Non-V2X*

The vehicles' behaviour is defined so it emulates a real life as close as possible, with the vehicles obeying the traffic and priority rules. This also applies to the emergency vehicle, which is capable of running a stop sign and treat a red light as a stop sign. The emergency

vehicle represented on this simulation is an ambulance, capable of transporting patients from anywhere to the hospital.
The simulation of both V2X and Non-V2X scenarios requires an important decision regarding how the vehicles should behave in both situations and which results should be presented. The vehicle behaviour with V2X was already explained in the 3.3.3 section (Communication Protocol), as well as the RSU behaviour (characterized by the traffic lights, stop signs, and regular intersections).
Regarding the Non-V2X scenario, all of the previously mentioned entities present a different behaviour. The vehicles behave as they did before, except they do not send or receive V2X messages, which means that they will not be able to react to the changes in the environment. Also, the RSU will not be considered on this scenario. In order to create a more realistic model,a warning sign was added to each emergency vehicle, simulating an audible warning bell and a visual warning light mechanism as it is used on present non V2V real-life scenarios emergency vehicles. Since SUMO does not have such a warning sign already implemented, the solution was to use V2X messages as if they were the siren's signals, although the range of the messages had to be reduced comparatively to the V2X scenario. To achieve this, the non-emergency vehicles, upon receiving the message, must verify if the emergency vehicle's distance to the other vehicle is lower than a specified value. In this case, it is assumed that a vehicle can notice the emergency vehicle's siren at less than 100 meters. The only V2X messages are sent by the emergency vehicle to emulate the siren.
Regarding the testing results, a wide variety of variables could be analyzed, however the chosen ones were:

- **total time:** the total time of the emergency vehicle's trip. This parameter is the most important since the main goal is to reduce the emergency vehicle's response time;
- **total stop time:** the amount of time that the emergency vehicle is stopped. This value should be lower for V2X scenarios;
- **total distance:** the amount of distance the emergency vehicle covers throughout its response;
- **CO_2 emission:** the emergency vehicle's CO_2 emission. Despite not being crucial, interesting conclusions can be taken through this parameter.

4.1.5 *Routing*

The dynamic routing allows the emergency vehicle to determine the optimal route whenever necessary. This leads to a decision between two implementation paths: if the optimal route should be determined once in the beginning, or if it could be calculated throughout

the emergency vehicle's trip.
The first solution guarantees that the optimal route is the best possible one, but if an obstacle appears, it cannot adapt to the new situation. As such, the later solution was the chosen one, because it calculates the optimal path at the beginning (like the previous one) and every time an obstruction appears, repeats the process. This could lead to a new optimal path that, technically, would take more time than the original one, but, in reality, will be better, because it avoids an obstacle and is likely, in theory, to reduce the stop time.
The routing calculations will contemplate a file that contains the roads identifiers (edges) and their weight. The Dijkstra's algorithm for shortest path calculation is used to determine the optimal path, since it is a simple algorithm with low complexity.
In order for the routing to make sense, the emergency vehicle must cover the longest possible distance between the grid's nodes, which means that the emergency vehicle will start and end its path in any of the vertices. Analyzing figure 4.6, the emergency vehicle must start and end on the specified nodes and, whichever node it starts it must end on the node that stands obliquely to it. For example, if the emergency vehicle starts on the node 1, it should end on node 4.

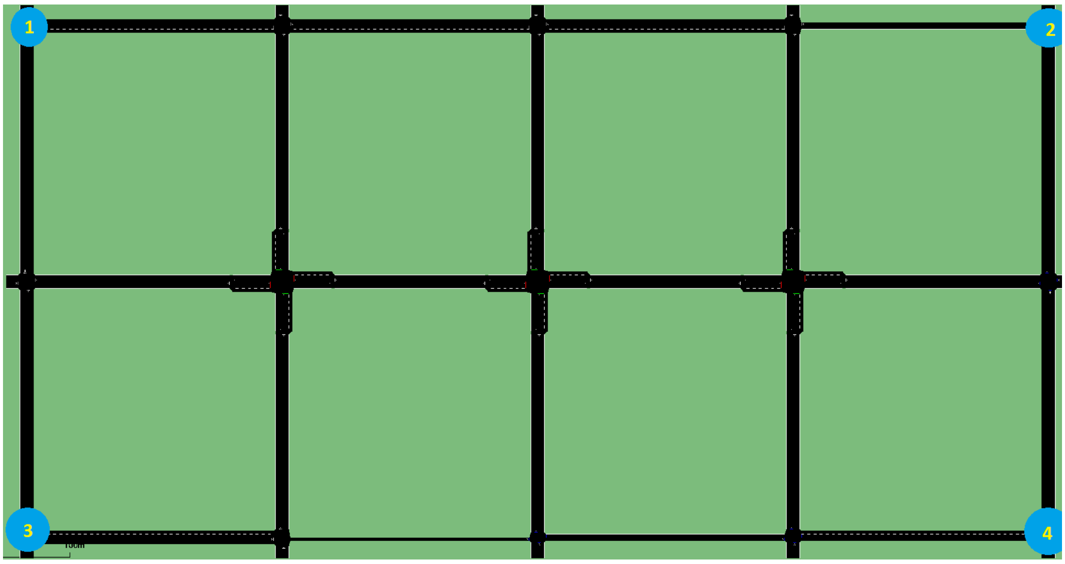


Figure 4.6.: Starting and ending nodes for the emergency vehicle on a grid

The vehicle's trip should not always be the same though, thus a script was created to generate random paths between the vertices of the grid. For the non-emergency vehicles, this rule will not apply, since they can start and end on any of the outer nodes of the grid, with their paths being randomly generated through a script as well.

4.2 Implementation

The developed system is event-based, altering its behaviour through the received messages. Thus, the correct implementation of the messages is crucial. One of the most important goals, regarding the communication, is to place the highest capacity of work on the RSUs.

4.2.1 *BSM message exchange*

Regarding the BSM structure, the core data will have information regarding the vehicle state on a certain moment in time. Since this is a simulation, only few parameters of the original message are necessary for the correct implementation, such as the position coordinates (latitude and longitude), heading, and speed. The other parameters will have a null value defined by the standard.
The second part of the BSM will contain knowledge concerning the vehicle's role in the system. Equally to the core data, only certain parameters are relevant to the simulation, while the other ones must be filled with null values. The BSM pt.II necessary fields to the implementation of the simulation, because depending on the values of these fields, the BSM will have a different meaning and purpose. These specific fields are called *role*, *vehicle type*, and *response type*. These values are numerical and their range is vast, however only some of those values are relevant.
The role's relevant values are:

- **0** : emergency;
- **6** : basic vehicle;
- **8** : none/unknown.

The *vehicle type*'s relevant values are:

- **2** : special;
- **4** : car.

The *response type*'s relevant values are:

- **1** : emergency;
- **2** : non-emergency;
- **4** : stationary.

As mentioned previously, these values will differentiate the way the values of the core data will be interpreted by the receivers. Thus, the different type of messages are:

#1: safety message sent by the emergency vehicle, alerting its presence;
#2: regular message sent by the non-emergency vehicle, informing its state;
#3: message sent by the RSUs informing the emergency vehicle's time to get to the intersection and its own position;
#4: message sent by the RSUs alerting every vehicle of a stopped vehicle/traffic with those vehicle's coordinates.

These messages are related to the different use cases implemented and the vehicles that do not use V2X communications are not mentioned, since they do not have the capability to communicate. These relations are represented on the following table.

Table 4.1.: Types of messages and their values

Type of message	Role	vehicleType	responseType	RSU	EV	NEV
#1	6	4	1		**X**	
#2	8	2	1	**X**		
#3	8	2	4	**X**		
#4	0	4	2			**X**

The Veins simulator has the capability to send BSMs, however, a small modification had to be made by implementing the message in an object, that contains all the fields, soon to be transformed into a string with the *XML* format. With this change, it is possible to send the desired message with the *XML* string as the content.
All the system's entities follow the same behaviour when sending or receiving a message, as defined on the next algorithm:

1. Insert all the necessary parameters in the *XML* formatted string, that following the BSM standard; [21]

2. send the message, through broadcast, to all entities;

3. the entity that received the message parses the *XML* string and obtains all the desired fields, such as the position, speed, heading, and the sender's role in the system. With this information, the entity will determine (through the algorithms mentioned for the several defined use cases) if it needs to alter its behaviour, so that it does not pose as an obstacle to the emergency vehicle.

4.2.2 *Dynamic Routing*

The dynamic routing consists on the ability of the emergency vehicle to alter its route to minimize the response time. In this context, the routing will allow the emergency vehicle to follow the best path and avoid possible road obstructions, such as traffic or accidents.
The routing requires a previous knowledge of the map by the emergency vehicle, so that it can determine the optimal path, to reach the destination in the quickest way possible. In order to achieve this, the vehicle must have access to a file that contains the road identifier, its coordinates (where it starts and where it ends), and the route's cost. Despite sounding redundant, the road identifier and the coordinates are both necessary to the correct routing implementation.
The used algorithm to solve the routing issue is the Dijsktra's shortest path algorithm. It takes a matrix with all possible paths between the nodes. An edge's cost is the value of the cell where, for example, the first column and second row is the path starting the first column and ending on the second row, while the value on it is the cost of the edge. These values can be the edge's actual cost or an infinitely large number, if there is not an edge between the two nodes.
Considering this information, it is logical to conclude that the identifier and coordinates are connected. The road identifier is necessary to identify the road's nodes, since the identifier always begins with the starting node and ends on the closing one, having a delimiter to ensure that the parsing is correct. The coordinates are crucial when the emergency vehicle receives a message indicating an obstruction, because the BSM will only send the coordinates of the obstruction, not the road identifier. Therefore, with the message's and file's coordinates, it is possible to associate them to a road and alter its value.
The algorithm that describes the dynamic routing is defined through:

1. Create a cost matrix with the values read from the routing file and fill with the cost to every possible edge;
2. run the Dijkstra's algorithm to determine the optimal route;
3. the emergency vehicle changes its route to the optimal route;
4. if the ambulance receives a message concerning an accident or traffic:
    a) detect the road where the obstruction is located;
    b) executes Dijkstra's algorithm again, marking the obstruction's road as prohibited (giving the road an infinite value on the cost matrix);
    c) the emergency vehicle changes its route to the new optimal path.

4.2.3 *Accidents*

The simulation of accidents on Veins is possible by altering a flag on the *omnetpp.ini* file (the initialization file) that allows certain types of vehicles to simulate an accident. These vehicles are called *Accident Vehicles*. Whilst stopped, the stopped vehicle continues to send BSMs, which will be interpreted by the RSUs.
In this use case, the two main entities interested in the accidents are the RSUs and the emergency vehicles. The RSUs will receive the stopped vehicle's BSM and, if they interpret that the vehicle is indeed stopped, will broadcast a different BSM, which will be interpreted by the emergency vehicle and will result on a obstructed road avoidance.

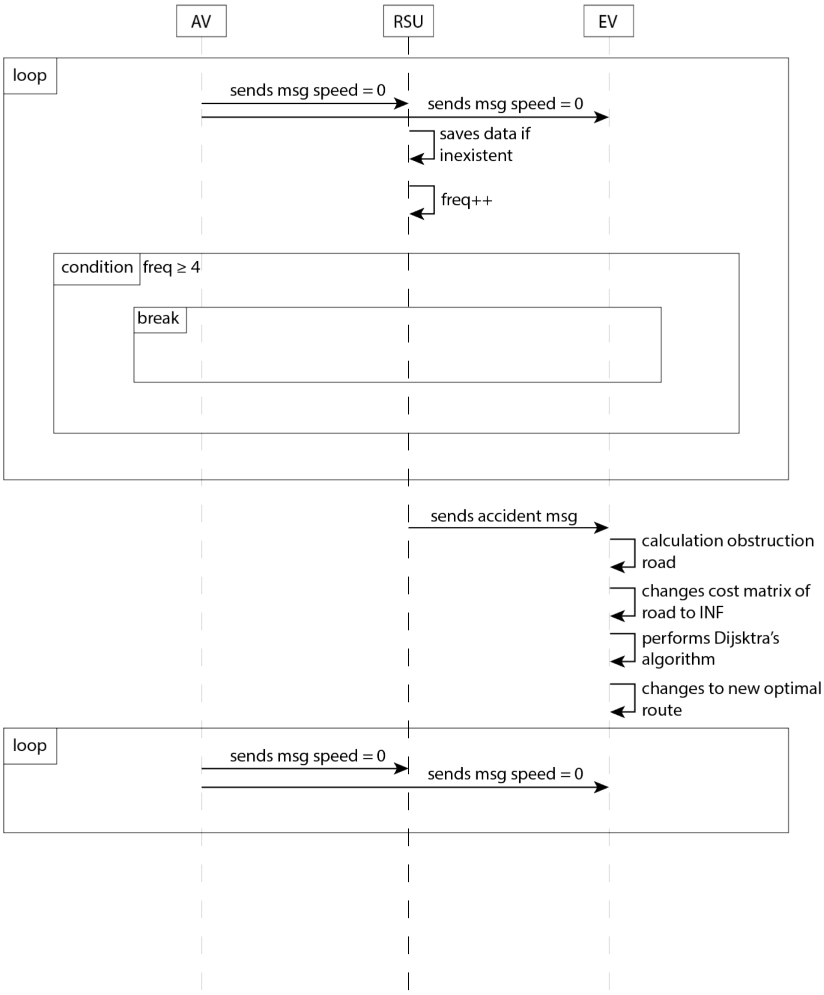


Figure 4.7.: Accidents use case between the accident vehicle, RSUs, and emergency vehicle

The algorithm that defines the RSUs behaviour isilustrated on fig. 4.8 and can be presented:

1. Receives messages with speed equalling zero;
2. saves the vehicle data (coordinates and the frequency of the messages that possess zero speed) to determine if the vehicle is stopped due to an accident, or just at an intersection waiting for a green light;
3. if the frequency of the messages is higher than four messages, there is an accident. So the RSU broadcasts a message alerting the accident, with a specific BSM message;
4. the remaining RSUs that receive the message will relay the same message.

On the other hand, the emergency vehicle's behaviour can be defined as:

1. the emergency vehicle receives the message alerting of the road's obstruction;
2. changes the value of the corresponding cost to the obstructed road to infinity, in order to mark the road as prohibited;
3. performs the routing algorithm and changes its path to a new optimal path one.

Figure 4.8.: Accident example on Veins

4.2.4 *Traffic*

The traffic situation (see Fig. 4.10) is similar to the accidents in its behaviour, except for the entities involved and the RSU's way of determining the existence of traffic.
Instead of being just a single vehicle alerting of its presence, with traffic, there is a need for multiple vehicles to characterize it. Therefore, there was the need for *Slow Vehicle*s, which communicate its state with the same regularity as a normal vehicle.
Considering this information, the way that the RSUs determine if traffic is occurring on a certain road or not can be defined as such (sequence diagram on fig.4.11):

1. RSU saves information if the vehicle's speed is low. The latitude, longitude, and heading are necessary to characterize the vehicles;
2. Saves the slow vehicle on a list;
3. For each slow vehicle added to the list, determine the other slow vehicles that share the same heading and are at a distance lower than 250 meters. When it finds one, the frequency increments;

4. If the frequency of slow vehicles on a certain road is higher than three, there is traffic;

5. Create a set of counted ids, so that the slow vehicles will not be accounted again. Since the ids are based on the coordinates and the heading, there is no risk of disregarding a possible future traffic situation, regarding the same vehicle;

6. Broadcast BSM alerting that there are slow vehicles on the specified coordinates, with a specific BSM message; remaining RSUs that receive the message will relay the same message.

Figure 4.9.: Traffic example on Veins

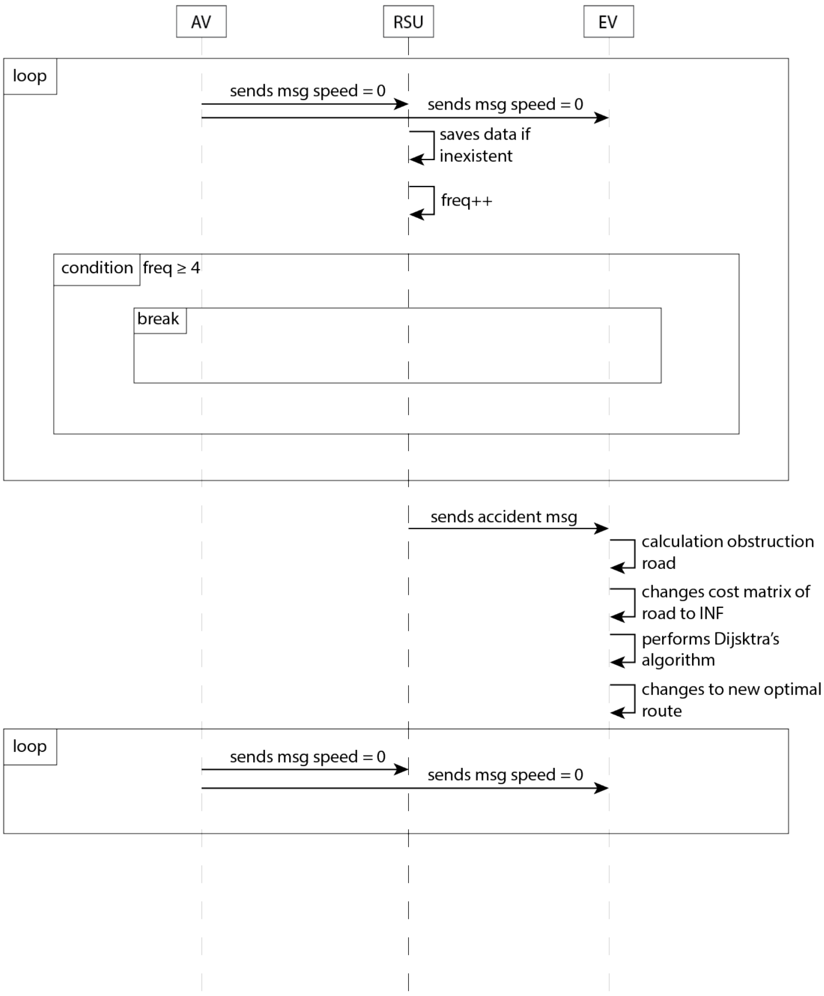


Figure 4.10.: Traffic use case between the traffic vehicle, RSUs, and emergency vehicle

4.2.5 *Emergency vehicle avoidance*

The emergency vehicle avoidance use case is another use case that can be seen nowadays on the roads. The vehicles, after seeing or hearing the emergency vehicle, will divert their path to the kerb so the emergency vehicle loses as little time as possible on its emergency aid. The entities involved are all the vehicles. The emergency vehicle will send emergency messages communicating its presence and the non-emergency vehicles will have to determine if they should move to the kerb to avoid the emergency vehicle. The non-emergency vehicles, upon receiving the emergency message, will compare both their heading and their coordinates with the emergency vehicle's. Of all possible values or scenarios, the non-emergency vehicles will only move if the heading is equal to emergency vehicle, the distance is lower than 25 meters, and if the non-emergency vehicles are after the emergency vehicle. This indicates that they are on the same road, following the same path, and the emergency vehicle will catch up to the other vehicle.

Vehicles' orientation

The vehicle will consider two metrics when deciding if it should move to the kerb, the coordinates and the heading of both vehicles. Regarding the vehicles' heading, the non-emergency vehicle will only move to the kerb if it shares the same heading as the emergency vehicle. Afterwards, it is important to determine if the vehicle is after the emergency vehicle, because if is not, it does not need to move to the kerb. The way this can be calculated is through the position of both vehicles and their heading. Since the vehicles will only travel in four orientations (due to the grid's shape), it is possible to determine situations, where, with a certain orientation and looking at the coordinates of both vehicles, rules can describe when the vehicle should move to the kerb. Considering a non-emergency vehicle V and an emergency vehicle E, the referential presented on figure 4.11, can derive a number of rules in which the non-emergency vehicles need to move away from the emergency vehicle:

$$\begin{cases} heading = 0 \land V_y = E_y \land V_x > E_x \\ heading = \frac{\pi}{2} \land V_x = E_x \land E_y > V_y \\ heading = -\pi \land V_y = E_y \land E_x > V_x \\ heading = -\frac{\pi}{2} \land V_x = E_x \land V_y > E_y \end{cases} \tag{1}$$

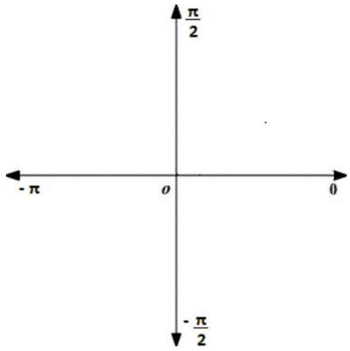
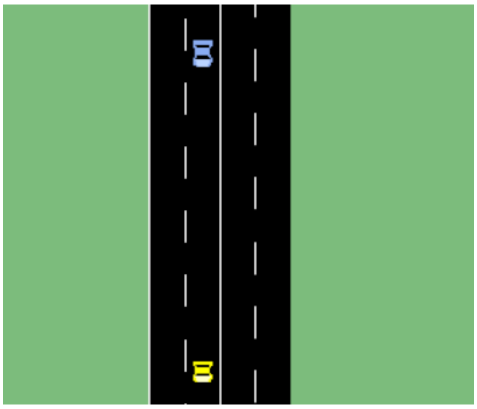
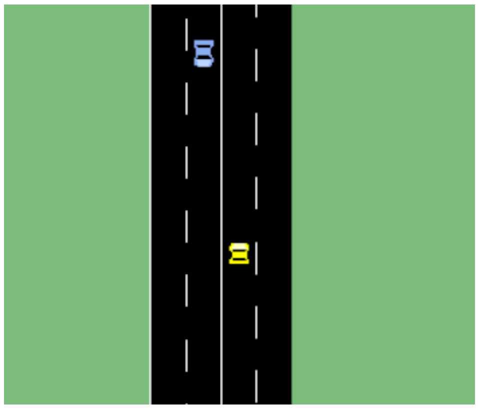


Figure 4.11.: Veins' angles referential



(a) Activates the use case



(b) Does not activate the use case

Figure 4.12.: Examples of the activation of the use case

The algorithm capable of representing this behaviour can be described through the following (illustrations on figures 4.13 and 4.14; associated sequence diagram on figure 4.15):

1. emergency vehicle sends, periodically, messages alerting its presence;
2. the non-emergency vehicles will verify it is on the emergency vehicle's path:
   a) their heading must be the same;
   b) the vehicle must be after the emergency vehicle, or, in other words, the emergency vehicle must point to it;
   c) the distance between the two vehicles must be lower than 25 meters;
3. if the non-emergency vehicle is in the emergency vehicle's path, than it should move to the kerb (represented on the simulation by the lane to the far right) and stays stopped until further messages from the emergency vehicle;
4. the non-emergency vehicle receives another message from the emergency vehicle and verifies if it has gone by:

- if not, stays stopped;
- if yes, returns to the previous state and resumes its trip.

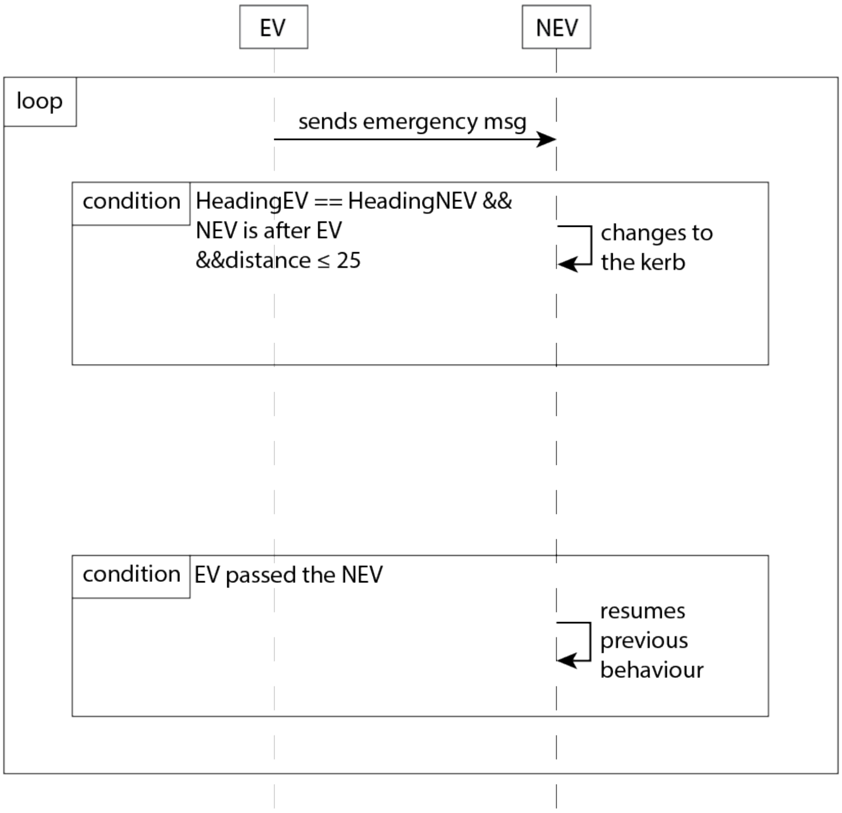
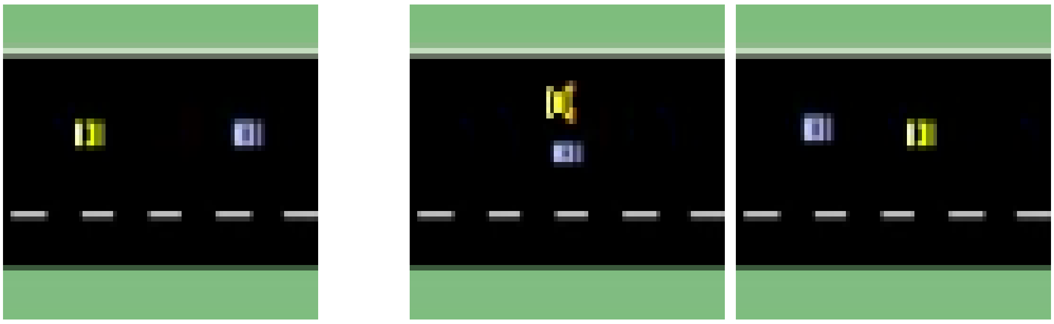


Figure 4.13.: Emergency vehicle avoidance use case between the emergency vehicle and non-emergency vehicles



(a) EV approaches NEV

(b) NEV pulls over and lets EV by

(c) NEV resumes path

Figure 4.14.: Demonstration of the emergency vehicle avoidance use case, where the emergency vehicle (blue) moves from right to left

4.2.6 *Intersections*

The intersections represent a big threat to an emergency vehicle's response. With multiple vehicles going different ways and a common road for them to intersect, they must be treated with the utmost attention, since the risk of collision is very high. In this simulation, the intersections are the foundation to the traffic lights' and the stop signs' use cases, since the non-emergency vehicles behaviour will always depend on the intersection logic.All of the vehicles and the RSUs will play a part in this functionality. While the emergency vehicle continuously sends emergency messages, the RSUs will interpret those messages and determine if the emergency vehicle is in one of the routes that leads to it, directly pointing to it. Only if this happens, will the RSU deal with the intersection logic, otherwise it will ignore the emergency vehicle's messages.

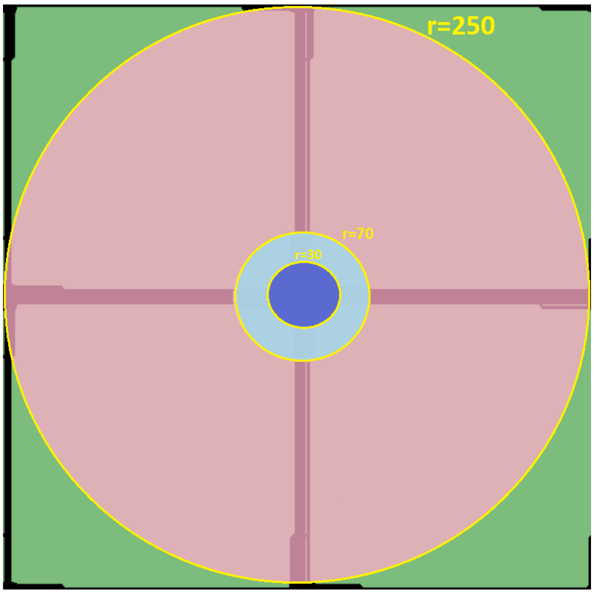


Figure 4.15.: RSU intersection's action area in meters

When an emergency vehicle enters the RSU's intersection area (figure 4.16), the RSU calculates the time that the emergency vehicle will take to arrive at the intersection and sends a BSM specific message with all the RSU's state and the emergency vehicle's arrival time. These messages will be received and interpreted by the non-emergency vehicles so they can calculate which vehicle arrives first at the intersection and change their behaviour. If an non-emergency vehicle arrives first, it needs to reduce its speed to a speed where the emergency vehicle reaches the intersection first. Using the emergency vehicle's arrival time, the other vehicles can calculate an approximate speed in which they must travel, where they do not need to stop and can give way to the emergency vehicle. Let it be known that this is always an approximation where the vehicles will never reach the intersection before the emergency vehicle. Lastly, when the emergency vehicle leaves the RSU defined area, the RSU sends a message informing it and the vehicles that reduced the speed, return to their previous state, changing their speed to the previous value.

Vehicles' orientation to the RSU

In order to determine if any vehicle points toward or away from the intersection, two metrics need to be examined: the vehicle's heading and the RSU's and vehicle's coordinates. Looking at the Veins referential of angles (figure 4.12), it is possible to conclude that the vehicles' heading on a straight road will equal to four values:

$$heading\ \epsilon \{0, \frac{\pi}{2}, -\pi, -\frac{\pi}{2}\} \tag{2}$$

Considering this information, it is possible to determine if the vehicle is pointing toward the intersection by analyzing the heading and the coordinates.

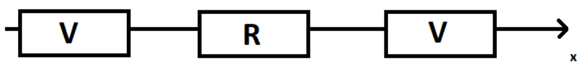


Figure 4.16.: Example of vehicles' and RSU positions in an horizontal context

Looking at the x axis and the figure 4.16, the following rules can be defined:

$$\begin{cases} C_x > V_x \wedge \alpha = 0 \rightarrow Points\ toward\ the\ RSU \\ C_x > V_x \wedge \alpha = -\pi \rightarrow Points\ away\ from\ the\ RSU \\ C_x < V_x \wedge \alpha = 0 \rightarrow Points\ away\ from\ the\ RSU \\ C_x < V_x \wedge \alpha = -\pi \rightarrow Points\ towards\ the\ RSU \end{cases} \tag{3}$$

Looking at the y axis and the figure 4.17, the following rules can be defined:

$$\begin{cases} C_y > V_y \wedge \alpha = \frac{\pi}{2} \rightarrow Points\ away\ from\ the\ RSU \\ C_y > V_y \wedge \alpha = -\frac{\pi}{2} \rightarrow Points\ towards\ the\ RSU \\ C_y < V_y \wedge \alpha = \frac{\pi}{2} \rightarrow Points\ towards\ the\ RSU \\ C_y < V_y \wedge \alpha = -\frac{\pi}{2} \rightarrow Points\ away\ from\ the\ RSU \end{cases} \tag{4}$$

Figure 4.17.: Example of vehicles' and RSU positions in an vertical context

The emergency vehicle's role on this use case is to simply send the emergency messages and follow its path without interruptions, while the other vehicles' and RSUs' behaviour is more complex. The RSU behaviour can be described by the following algorithm:

1. RSU receives an emergency message and calculates if the vehicle is entering the intersection through the distance and the heading. If it is pointing toward the RSU and the distance to the RSU is lower than 250 meters, the emergency vehicle will enter the intersection. If not, the algorithm stops here;
2. calculates and saves the time the emergency vehicle takes to enter the intersection through:
$$t_{EV} = \frac{d_{EV \mapsto RSU}}{v_{EV}} \tag{5}$$
3. sends a specific BSM with the RSU data and the emergency vehicle's arrival time;
4. if the distance is lower than 70 meters and higher than 30 meters (higher than 30 to ensure that it is out of the intersection) and the emergency vehicle is moving away from the intersection:
    a) changes the emergency vehicle's time to a null value, indicating that the it has left the intersection;
    b) sends BSM specific message with the RSU data and the null time, so the vehicles are aware of the emergency vehicle's new position is outside the intersection area;

Regarding the non-emergency vehicles, the algorithm that describes their behaviour can be specified as (complementary sequence diagram on figure 4.19):

1. Receives a BSM from the RSU with all the RSU data and the emergency vehicle's arrival time;

2. calculates the time that it will take to reach the intersection (same method as the RSU behaviour) and if the orientation points towards the RSU;

3. if the distance is lower than 250 meters, points away from the intersection, and the vehicle's orientation is different (if the orientation is the same, the emergency vehicle avoidance use case activates first), the vehicle should reduce the speed;

4. calculates the new speed with the following formula:

$$speed_{NEV} = \frac{d_{NEV \mapsto RSU}}{t_{EV} + b}, \tag{6}$$

   where b represents a safety buffer that needs to be added so to guarantee that the vehicles do not collide (this is of the utmost importance, because without this buffer, the new speed would make the emergency vehicle and non emergency vehicle arrive at the same time, allowing a collision);

5. saves previous speed if the reduction of speed has not started yet (it should only save the initial speed before the maneuver; during the maneuver the vehicle could still alter the speed as it could receive several BSM messages from the RSU);

6. changes the speed to the new reduced speed (in fact, the speed could also be incremented, depending on the relative speed of the emergency vehicle when compared to the vehicle's own speed);

7. receives messages from the RSU that alerts the departure of the emergency vehicle from the RSU area and changes its speed to the previous previous value before the maneuver.

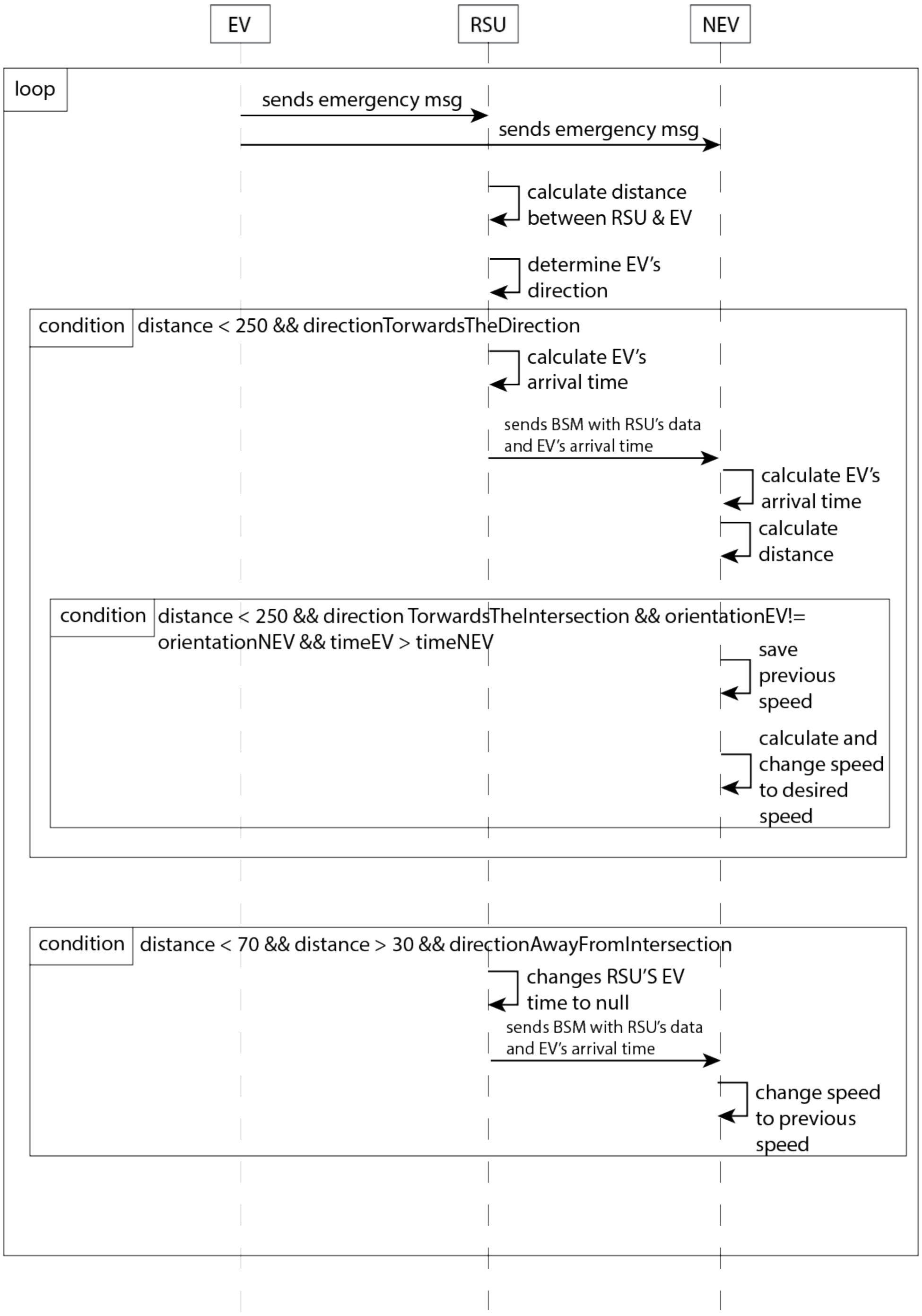
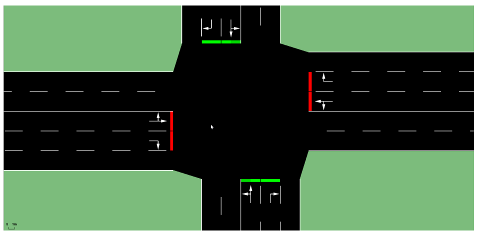


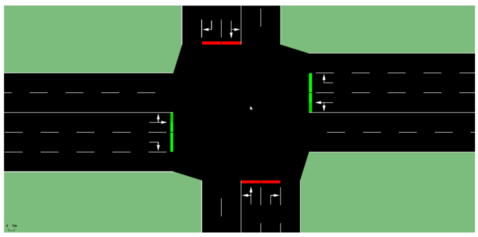
Figure 4.18.: Intersection logic use case between the emergency vehicle, RSUs, and non-emergency vehicles

4.2.7 *Traffic Lights*

The traffic lights use case relies on the same principle as the intersection one, where the vehicles need to slow down when they reach an RSU traffic light delimited area, if an emergency vehicle is also on that area.
The traffic lights will change colour depending on the emergency vehicle's path, which means they must change to the green state, whenever the emergency vehicle enters the traffic light zone. Ideally, the traffic light would change the emergency vehicle's road to green, whilst changing only the ones that cross its path to red. However, there are some setbacks associated with this. Unfortunately, such an outcome is very difficult to obtain in such a complex system where full automation and non-human control of the vehicles is not possible. As such, the solution had to try to guarantee that all normal vehicles were warned and stopped at the traffic lights with a red light while a green light was conceded to the emergency vehicles. An even more secure approach would have been to use an intermittent yellow light for the emergency vehicle or to create a new special green or yellow light only to be used for emergency vehicles, although, at this time, these approaches were not considered. Concluding, the implemented strategy was to change the traffic lights so the emergency vehicle crosses safely and with a very low risk of a vehicle to go through the intersection that could affect the emergency vehicle's response time and safety.



(a) Phase number 0



(b) Phase number 4

Figure 4.19.: The necessary phases of the traffic lights in Veins. The remaining consist of adaptations of the shown ones with yellow state variations and were not relevant

In conclusion, the proposed solution will combine the intersection logic with the traffic light logic. The algorithm that specifies the entities' behaviour can be described as:

1. RSU receives emergency message and calculates the approximate time the emergency vehicle will take to arrive at the RSU area;

2. RSU receives messages from the other vehicles and saves their information (such as identifier), if they are inside the intersection;

3. RSU saves current state of the traffic lights, when the emergency vehicle enters the intersection;
4. RSU prepares the intersection, so the emergency vehicle can cross safely:
   a) Prevent cars closer to the intersection from entering it, so they will not collide with the emergency vehicle;
   b) change traffic light's colours, so the emergency vehicle can cross the intersection;
5. after the emergency vehicle leaves the intersection, check if there are cars inside the intersection and return to the previous state as soon as possible;
6. RSU sends messages for the vehicles to return to their previous speed.

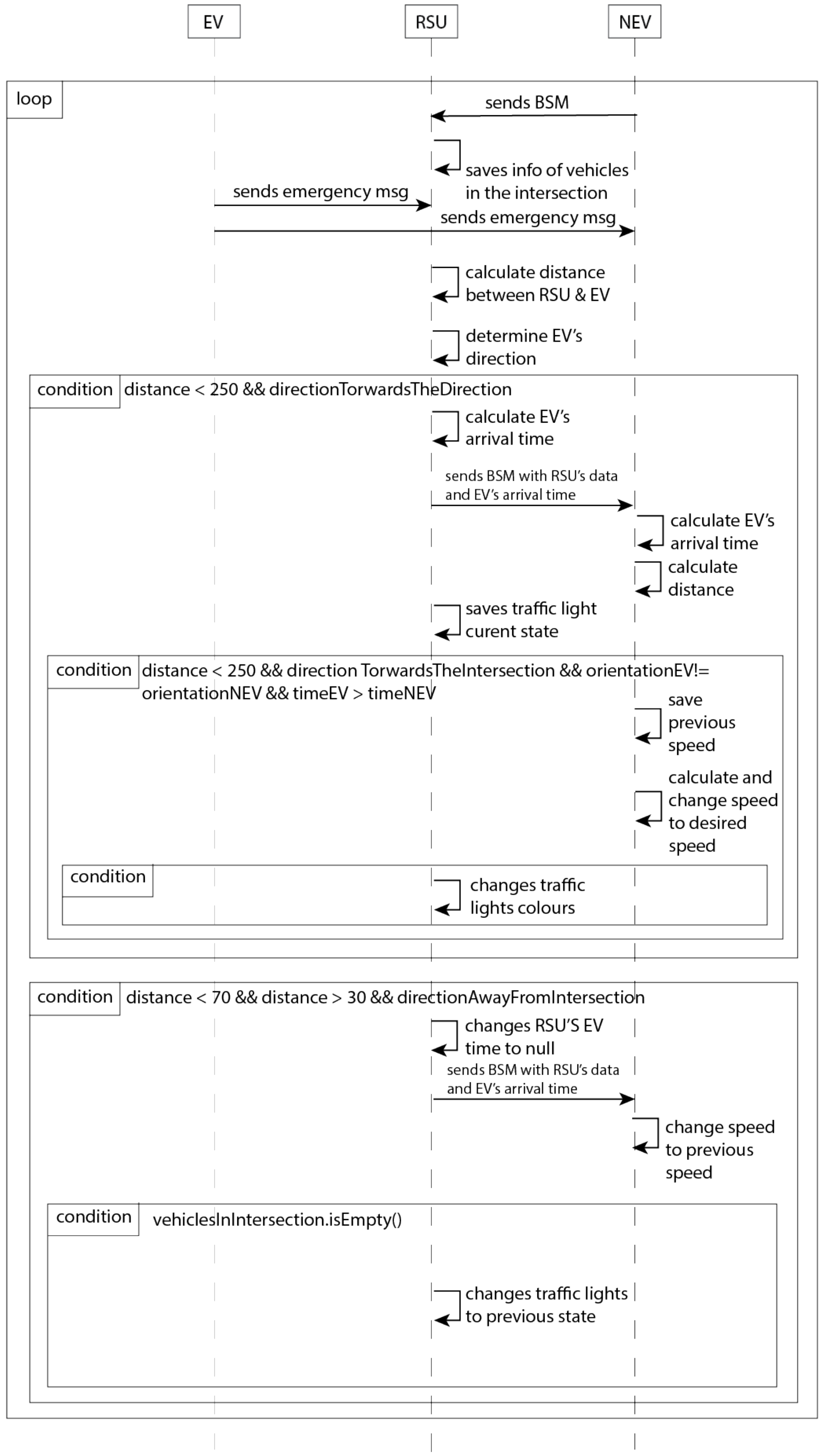


Figure 4.20.: Traffic light logic use case between the emergency vehicle, RSUs, and non-emergency vehicles

4.2.8 *Setups and Scenarios*

In order to properly analyze the potential benefits of V2X communications in an emergency response scenario, the testing must include a comparison between a scenario with V2X communications and one without them.
Since the results of the traffic part of the simulations, which SUMO is in charge of, are deterministic, probabilities do not factor on the end result. Thus, running the same simulation setups and scenarios more than once, will produce the same results. This will be extremely helpful when creating V2X and non-V2X communications scenarios, since their initial behaviour will be the same and only vary through the V2X communications, allowing for a strong comparison between the two cases.
As mentioned previously, the vehicles' behaviour is defined through a specific file, the *rou.xml* file, that needs to be fed to the simulation. In order to guarantee diversified results, a simple JAVA program was developed to generate random versions of this file, with different routes in different simulations, the number of vehicles will fluctuate, the vehicles' types will differ and their departure time in the simulation will be inconstant.

Random Paths and Vehicles Generator

The main aim of this program is to create the files that define the vehicles' behaviour on the simulation, with characteristics such as, their number, their type, their route, and their start time. Considering the need to create two different scenarios, some of the parameters mentioned previously must stay the same, while some need to differ.
As for the number of vehicles sent to the simulation, a random number will be generated between four hundred and five hundred vehicles, a large amount to correctly simulate high traffic. This parameter will be the same regardless of the presence of V2X communications. Considering the depart time, a random number will be generated between zero and two thousand (maximum defined value for the simulation time), meaning the vehicles can start in every value of this interval. This parameter will not present changes in the both scenarios.

Vehicle's routes

The grid in which the vehicles circulate is composed by forty eight nodes, translating into a high combination of possible paths. The initial solution took a matrix with forty eight by forty eight dimensions (representing the nodes), where the cells represent a possible path between each two nodes. In other words, considering the mentioned matrix as *paths*

$$paths[3][7] = 0 \tag{7}$$

$$paths[7][3] = 1 \tag{8}$$

then equation (7) indicates that a path starting on node 3 and ending on node 7 is nonexistent, while in then equation (8) a path starting on node 7 and ending on node 3 exists. Considering this, a breadth-first algorithm was used on every node to determine all possible paths and save them onto a list. Once all the paths were determined, a random number ranging from zero to the list's size was generated to attribute a random path to a vehicle. This solution, although correct, was not directly feasible due to its large execution time. The adopted final and improved solution also considered the *paths* matrix, but, instead of calculating all the possible paths, the program calculates the necessary paths for the number of vehicles determined previously. Knowing the outer nodes, the program starts on one of those and, from all the possible paths, chooses another node. If the node is an outer node, the path is terminated. If not, the process is repeated, until an outer node is found. This strategy reduces the execution time vastly and still allows for a vehicle to start and end on a outer node of the grid.

Non-emergency vehicles

Taking into consideration the pretended behaviour of the setup, four non-emergency vehicles were created. There are indicated on table 4.2. The need for different odds for different vehicles arises from the fact that some vehicles are more likely to appear in a real life scenario. The following values were chosen to try to simulate a real scenario.

Table 4.2.: Probabilities for the generation of the vehicles' types

Type of vehicle	**Probability (%)**
Just Kerbs Vehicle (non-V2X)	10
Accident Vehicle	10
Slow Vehicle	20
Normal Vehicle	60

The non-emergency vehicles routes are defined by the method described on section 4.1.4.

Emergency vehicles

The emergency vehicle's creation does not follow the same principles as the non-emergency vehicles. If a V2X scenario is considered, the used type will be *Emergency Vehicle*, and if not, the type will be *Just Siren Emergency Vehicle*, which means the emergency vehicle will not have access to V2X communications.
Regarding the routes, since the goal is for the emergency vehicle to cross the lowest distance between the vertices of the grid as possible, the routes generated must begin and end on those vertices. Thus, the process will be the same as the mentioned on section 4.1.5, with the slight difference that the route generator will begin and end on the vertices and not on the outer nodes.

Vehicle Route Generator

The algorithm that describes the generator's behaviour is defined as :

1. Create a matrix that conveys all the possibles paths;
2. define an interval [m, n] and generate a random number between that interval representative of the number of vehicles in the simulation;
3. generate a random depart time from the interval [0, maximum], where the maximum is the simulation's maximum execution time;
4. generate a random number that identifies the vehicle;
5. for every non-emergency vehicle:
   a) generate a probability that will identify the type of vehicle;
   b) generate a route for the vehicle starting and ending on an outer node;
6. for the emergency vehicle, generate a route for the vehicle starting and ending on the grid's vertices;
7. create two files, one for V2X communications and one without V2X with the specified parameters.

It is important to refer that the RSU used on the Non-V2X is is a dummy RSU that does not possess any logic for dealing with V2X communications, which means that the non-emergency vehicles do not need to be changed, because the messages they send will be ignored by the RSU. This means that with the use of only dummy RSUs, the scenario equates to a non-V2X setup.

Test running

The tests were performed through a script executable on Linux bash that compiles the simulation and, through a loop, runs the simulation with different parameters and files while writing the results in a text file that will be processed and inserted into a *MySQL* database, for the purpose of data analysis through the business intelligence tool, *Microsoft Power BI*.
For each iteration of the loop, the scripts runs the path generator, which will result in two distinct files, one generated with V2X communications and one without. Then, it changes all the necessary remaining files to consider these new generated scenarios and runs the simulation twice, one for each scenario.
A detailed version of the script is presented on the appendix.

4.3 OUTCOMES

The comparison between the V2X scenario and the non-V2X scenario will be based on the emergency vehicle's elapsed trip time, stop time, covered distance, and the CO_2 emission rate. These values will be printed by the emergency vehicle in the end of its route.
In order to correctly analyze the data, instead of generating graphs and concluding something from them, the idea is to follow a business intelligence approach of writing questions that need answers. Considering this approach the input questions and output graphs will be created on *Microsoft Power BI* to easily visualize the data results.
Even though the most important parameter is the emergency vehicle's response time, other factors can be put into play, to obtain interesting conclusions from the simulations. Thus, the questions considered relevant were:

1. Which scenario presents the best response times?
2. In which scenario does the emergency vehicle stay stopped the longest?
3. In which scenario does the emergency vehicle cross the shortest distance?
4. Which scenario is the least polluting?
5. Which is the maximum and minimum value for the metrics considered? Which scenario are they from?
6. Which is the average value for each of the metrics considered for each scenario?

4.3.1 *Emergency vehicle response times*

As displayed in figure 4.21, the light blue area (concerning the *v2x false*) limits the values obtained on the scenario with no V2X communications, while the darker blue area (concerning the *v2x true*) limits the values obtained on the scenario with the use of V2X communications.

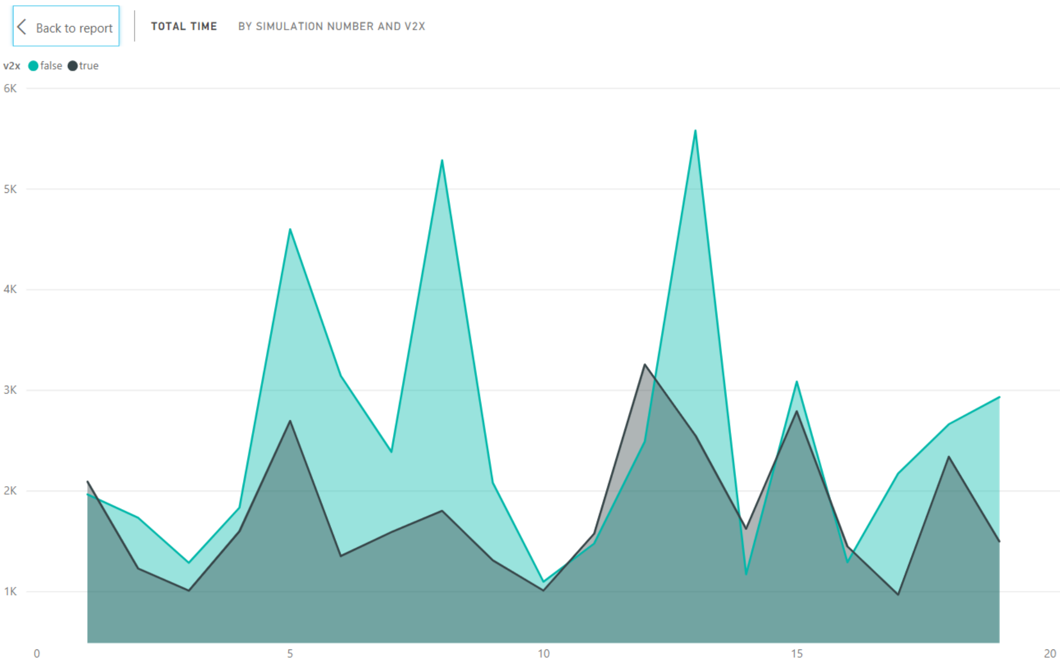


Figure 4.21.: Total time in seconds (y axis) by the simulation number (x axis)

Generally, the use of V2X communications results in lower response times for the emergency vehicles. Although, there are situations where V2X is not effective, this can be explained by the fluctuation on the effectiveness of the routing algorithm. In some cases, the routing algorithm may lead the emergency vehicle to take an alternate path, in order to avoid an obstruction that proves, later on, not to be the best solution. For example, the emergency vehicle may change its route due to a stopped vehicle, despite being close to being moved, freeing the road again. In this scenario, the emergency vehicle chooses to travel freely, instead of stopping by a smaller amount of time. These situations are sporadic and the use of V2X brings an improvement to the total time.

Another conclusion to be taken from the results is that the difference in the two scenarios, for the same simulation, is significant. The V2X results are lower than its V2X free results and by a relevant margin. In one of the experiments the response time for the setup with V2X communications was almost one hour less than the non-V2X counterpart. Considering a critical scenario where a patient must arrive at the hospital as soon as possible, this could

represent **the difference between saving a life and a casualty.**
The gain value of using V2X is 41%, which represents a significant improvement. The average time for the V2X scenario is 1776.84 seconds and without V2X is 2541.74 seconds, which clearly shows that V2X reduces the emergency response time.

4.3.2 *Emergency Vehicle stop times*

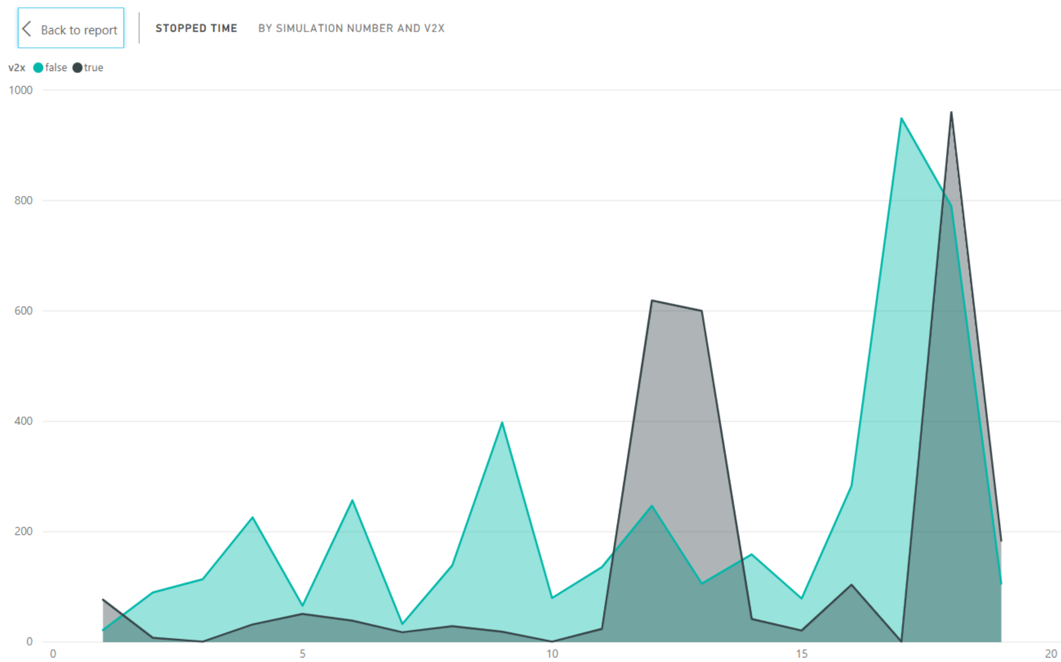


Figure 4.22.: Stop time in seconds (y axis) by the simulation number (x axis)

Analyzing the results as depicted on figure 4.23, we can conclude that, in general, the setup with V2X communications attained substantially lower total stop times. Again, exceptions arise which must be the result of the less effectiveness on a particular routing decision on some special situations already discussed on the previous section. The concept of dynamic routing is interesting and every single situation must be studied extensively in order to implement it correctly. For example, the emergency vehicle changed route to avoid an obstruction, but may have changed to another one where a later obstruction occurred, having no way to avoid it.
The stop time gain value of using V2X communications is 1522%, which shows a massive improvement considering not using V2X. The average time for the V2X scenario is 148.95 seconds and without V2X is 225.26 seconds, which clearly shows that V2X reduces the emergency vehicle stop time.

In conclusion, the stop time shows an improvement, but should be further looked at, to improve the results.

4.3.3 *Total distance*

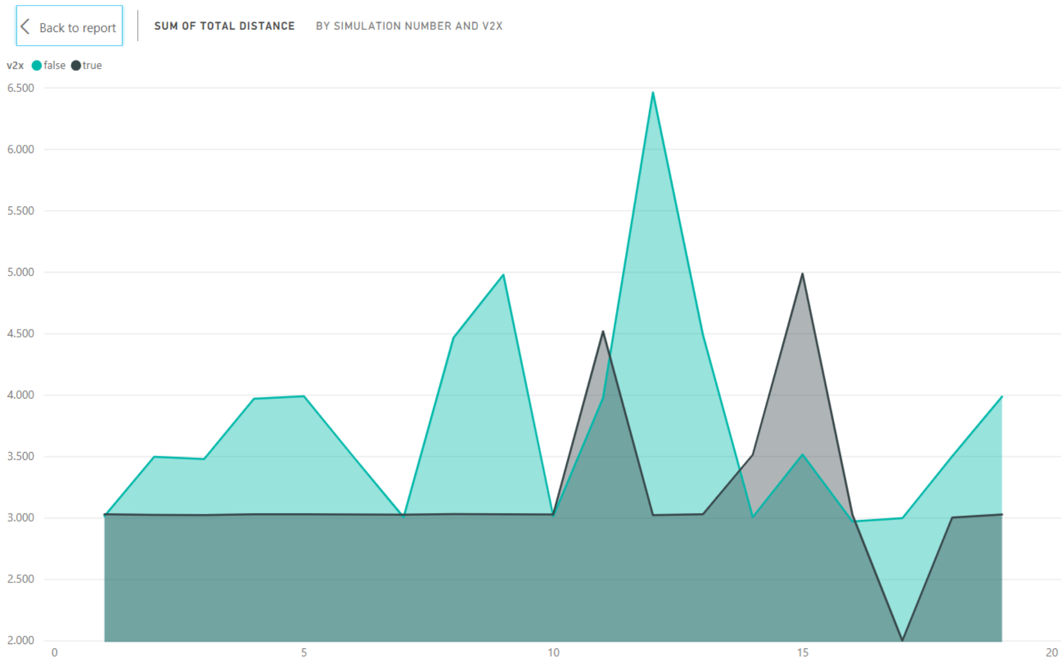


Figure 4.23.: Total distance in meters (y axis) by the simulation number (x axis)

The total distance metric is directly affected by the dynamic routing, that is why it is possible to examine a constant total distance with the V2X results, because, since the board is a grid, the ideal total distance is the same whichever the simulation, that is, the total distance had a minimum value that could not be bettered. This alone shows better results with V2X communications than without, as it can be seeing on figure 4.24.

Again, there are the odd cases where the distance is higher with V2X. As expected, and comparing with the emergency vehicle's response time, there is a correlation that a higher distance normally translates into a higher response time. The total distance covered gain value of using V2X communications is 20%, which shows a massive improvement considering not using V2X. The average time for the V2X scenario is 3180.49 meters and without V2X is 3781.14.

4.3.4 *CO2 Emissions*

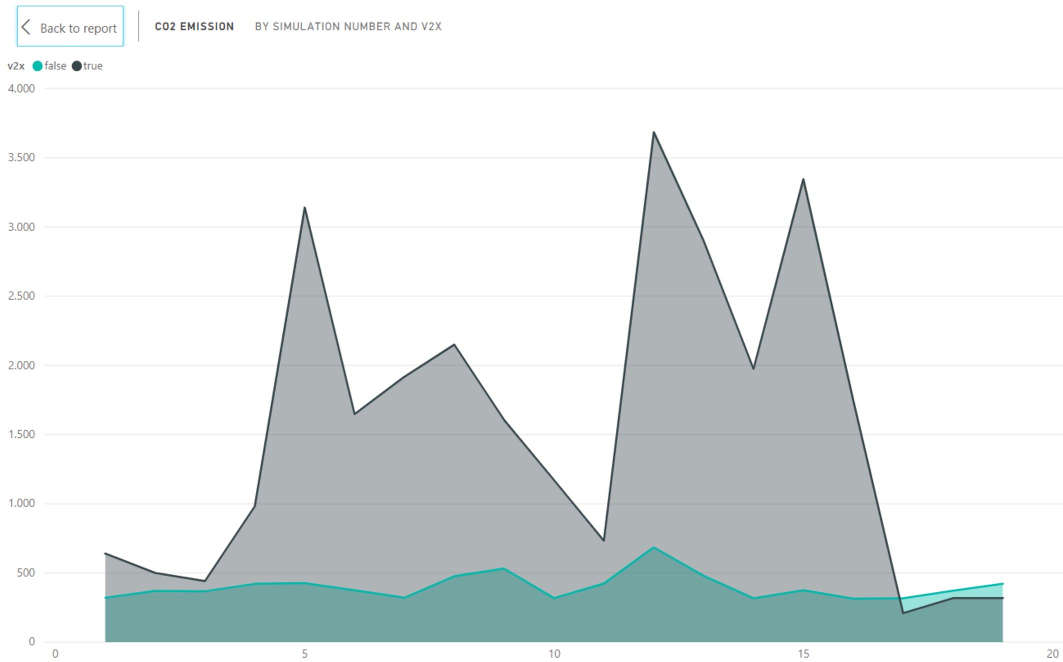


Figure 4.24.: CO2 emissions in grams/second (y axis) by the simulation number (x axis)

It is also interesting to note that when the emergency vehicle uses V2X communications, the CO2 emissions present higher values when comparing with emergency vehicles not using V2X communications. The only logical cause for the higher CO2 emission must be that the emergency vehicle is travelling at higher speeds, thus consuming more fuel. Another possible cause would be the travelled distance. Nevertheless, the smaller response time and the safety of the path are the two most important parameters and, sometimes, will compete against other much less important functional parameters like CO2 emissions and running costs.
The CO2 loss value of using V2X communications is 73%, which shows that using V2X communications proves to be more polluting. The average time for the V2X scenario is 1548.67 grams and without V2X is 401.79 grams, which shows that not using V2X results in a lower CO2 emission rate.

4.3.5 *Statistics summary*

Regarding the remaining questions presented early in section 4.3, they can be answered through table 12, where the best results are marked with green and the worst with red.

Thus, it is possible to conclude which scenario presents the maximum value and which one has the minimum value, while also retrieving the average of each metric.
As expected and concluded before, the scenario with V2X communications has significantly better results than the non-V2X scenario. Moreover, the results are significantly lower on the emergency vehicle's response, which is the most important metric.

Table 4.3.: Statistics of the test results

Metric	V2X	No-V2X
MAX total time (s)	3257	5581
MIN total time (s)	970	1099
AVG total time (s)	1776.84	2541.74
MAX stop time (s)	960	949
MIN stop time (s)	1	22
AVG stop time (s)	148.95	225.26
MAX CO2 emission (g)	3684.19	685.53
MIN CO2 emission (g)	209.67	314.60
AVG CO2 emission (g)	1548.67	401.79
MAX total distance (m)	4989.18	6463.34
MIN total distance (m)	2002.29	2972.95
AVG total distance (m)	3180.49	3781.14

4.4 FURTHER CONSIDERATIONS

Despite the positive results and the implementation being a success, in terms of acquiring knowledge of Veins and transforming the conceptual knowledge into use cases, there are still limitations to the solution.
Considering the roads map, the results will not be as faithful as they could be if a real roads map was used. Since the used map is a grid, the results may not be representative of real-shaped roads maps and thus, less faithful to reality, probably more optimistic.
Due to time limitation, the number of vehicles used is not as large as it could be. Running a single simulation with the number of vehicles ranging from four hundred and five hundred vehicles took at least one day, thus, setting up simulations with substantially larger

numbers of vehicles would be not viable at this stage.
Regarding the dynamic routing, instead of the whole logic being present on the emergency vehicle, ideally, the optimal path should be calculated and defined by the RSUs. In the present solution, the RSU notifies the emergency vehicle of obstructions and, then, the emergency vehicle decides to change route and which route to choose. However, an ideal solution would be for the RSU to inform the emergency vehicle of which route to take. Unfortunately, the BSM protocol does not consider any field in which routes can be sent.
Since the RSUs cover the entire grid, there was no need to implement the vehicles sending messages that they receive, but it should be a feature on another scenarios.
The intersection logic presents a limitation that concerns the use of the vehicles' heading. The heading is used on the simplest way possible, since the roads map is a grid and only contains four possible values of it. This solution is not generic and cannot be applied to a different type of roads map.
Lastly, the major limitation of the present project, the one that took the longest to try to solve and to no avail, was the traffic light's behaviour. The way the traffic light was supposed to work was that it should turn green to the emergency vehicle and red to every other path, to prevent any collision. However, the simulator does not make it possible to change the traffic lights this way, but only through certain phases, which does not support the ideal implementation. This way, the cars that arrive at the intersection need to slow down, since they could not trust the traffic lights completely .

4.5 SUMMARY

Concluding the implementation section of the present project, it can be stated that the results were significantly positive. On the implemented use cases an improvement on the emergency response time was noted, however, and due to time limitations, the results were not as assertive as they should be. Learning to work with the simulator took its toll, since it required many hours to perfect and those were hours that were not spent improving the use cases.
An important and thorough look was made at the simulation's implementation and its results so to understand the limitations and what the next steps should be, in order to obtain a more robust solution with that can yield results that could more faithfully represent equivalent results on the real world.
However, since the results were positive, this means that the steps were taken in the right direction, leading to an additional motivation of improving the current solution and to advance to the integration of real V2X communication boards into the simulation setup as described in the next chapter. That is, two experiments were conceived, both of them using

the Bosch V2X boards. The first integrates the V2X boards in the simulation, while the last considers a real scenario with real vehicles and the V2X boards, as well.

5

ADDITIONAL EXPERIMENTS

This chapter resumes the additional experiments that were designed following the initial prototype development where all components where simulated in software. It starts with an introduction to the Bosch V2X project [4], since the experiments would feature Bosch V2X boards. The first experiment tried to integrate an hardware prototype Bosch V2X board into the simulation setup already developed while the second would setup a totally new live experiment with real prototype vehicles with integrated Bosch V2X boards. It needs to be considered that only the first experiment was implemented and tested. For the second experiment only its planned setup was specified but no real implementation was achieved in the time frame available.
For both experiments, its presentation here includes an introduction, a problem description, an implementation section (with a description, an algorithm, and a sequence diagram) and a section for the the results and conclusions.

5.1 BOSCH V2X PROJECT

The idea of using V2X to improve traffic efficiency and minimize fuel consumption is very common nowadays, with the surfacing platooning technologies, such as the Bosch V2X project [4]. The Bosch V2X project, uses the V2X technology to guarantee the continuous transmission of large volumes of data between the vehicles, infrastructures, and all entities a the traffic system. The communication technology needs to guarantee a high degree of reliability and low latency. This technology can be implemented with DSRC and mobile network technologies, while supporting all the common data transmission standards, making it suitable for worldwide use in the various markets.
The use cases that the Bosch project has already implemented are the following ones:

- **Increase efficiency (platooning):** trucks with V2X communications can form platoons that allows them to be in a perfectly close convoy with a small gap between each truck. This will reduce operating costs, due to the reduced fuel consumption originated by the trucks' slipstream. If a car has to cross the platoon, for example, for getting out of a motorway, it will communicate its intention to the trucks, which will result in an increase of the distance between the trucks, allowing the vehicle to exit freely. Afterwards, the platoon tightens its formation again, guaranteeing safety for everybody.[4]

- **Traffic flow optimization (lane changing):** if a vehicle needs to change lane it alerts all surrounding vehicles, even the ones out of the driver's line of sight.[4]
- **Traffic flow optimization (green wave):** traffic signals can inform approaching traffic of the duration of the green phase, which means the vehicles can adapt their speed accordingly and take advantage of the green phase. [4]

5.2 V2X BOARDS AND THE SIMULATION

One of the goals of the present dissertation was to incorporate the Bosch V2X boards on the Veins simulation. This goal was defined, so that the transition to the vehicles would be easier, since the software responsible for sending messages would be the same on both scenarios.
It should be stated that the V2X boards' software is not entirely designed by Bosch, containing code by external companies. This software is bought by Bosch and the external companies demand that their product is not shared through a dissertation thesis. Considering this, the board's functioning will not be explained due to security reasons, nor will the code be discussed, to prevent disputes on any legal matters.

5.2.1 *Problem description*

The problem consists in recreating the emergency vehicle avoidance use case, in which the communications are not handled by the simulation, but by the boards. The use case's logic is the same and is still embedded in the simulation.
These prototype variations were not possible in the beginning of this dissertation due to no availability of vehicle communications hardware resources. After the analysis of the results of the initial developed prototype using only software simulation it was agreed to push the experiment to a new level of usefulness by incorporate real V2X communications boards into the simulation setup. These new setups present an added element of difficulty, considering that they require resources that are much more expensive than pure software setups. These are costs that many companies may not sustain and, even the ones that can, choose not to, since the payoff may not be profitable.
In this regard, the evolution of vehicular communications may not depend on the expertise of anyone who is interested to develop these solutions, but on companies that have the

capital to do so. Startups will prove harder to create and a monopoly is bound to be held by the car manufacturers on this matter.
Thus, considering the problems mentioned, the integration of the V2X boards to the simulation was considered relevant, since it can add the element of a real scenario to the simulation. That being said, costly resources are not necessary to test complex scenarios, using just the simulation and the boards to guarantee communication between every entity involved in the system.

5.2.2 *Implementation*

The implementation of this solution can be divided in two different parts: the use case's logic and the communication between the vehicles. Since the use case's logic was already explained in a previous section, the only discussion to be had here will be the one regarding the vehicles communication.
Instead of granting the simulator total control of the V2X communications, the idea is to make the boards responsible for the communication. Thus, without using the specific BSMs of the simulator, sockets will be used to ensure communication between the two vehicles.
Since the objective is to approach a real scenario as close as possible, the messages will follow a time based sending system. In other words, once in every 10ms, the emergency vehicle will send a message and, once in every 100ms, the normal vehicle will send its own message. In the WAVE standard [21] these values are not defined (allowing any rate times), however these are standard values on the ETSI standard.

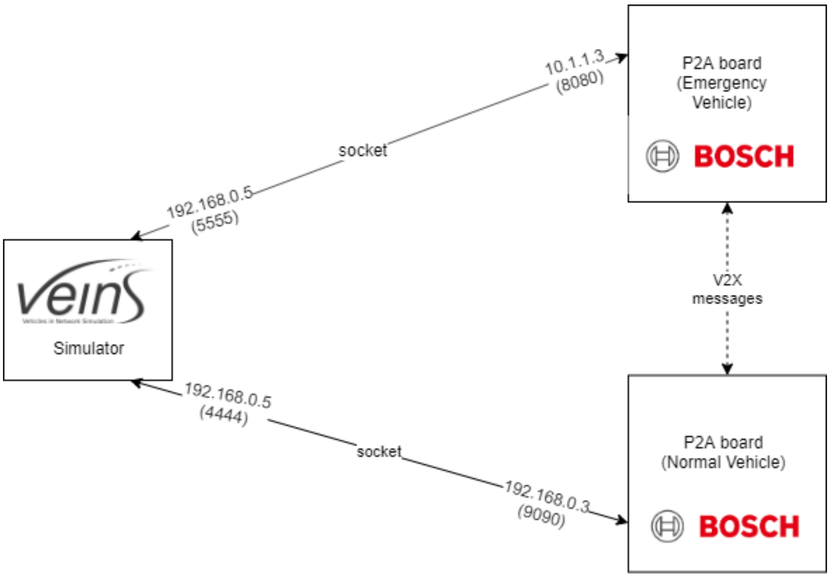


Figure 5.1.: System's architecture with communication protocol

The two boards, one representing the emergency vehicle and the other a normal vehicle, will be connected to the computer running the simulation. Firstly, the boards' program needs to be ran. This program will perform two actions:

- start a new thread that receives messages from the simulation and sends them through V2X messages to the other boards;
- in the initial thread, receive V2X messages and send them through sockets to the simulation. to the specific entity's port.

Afterwards, the simulation starts and runs as described previously. However, when the vehicles need to send messages, these will be sent, through the sockets, to the respective board, which, in turn, will send the message through V2X communications. The other board will receive the message and send it to the respective port in the simulation that corresponds to its vehicle.

Table 5.1 presents all the addresses, ports, and the method of connecting the boards to the computer.

Table 5.1.: Addresses, ports, and methods of connecting the boards to the computer running the simulation

Type of vehicle	Connection mode	Board send address	Board port	Simulation send address	Simulation port
Emergency	RNDIS	10.1.1.3	8080	192.168.0.5	5555
Normal	BroadReach	192.168.0.3	9090	192.168.0.5	4444

The exchange of a message between the two vehicles can be described as such:

1. Emergency vehicle needs to send a message to the normal vehicle, so it sends a message to a socket open on the corresponding board. This message will be a BSM message in a XML format;

2. the board will transform this XML string to a BSM message, ready to be sent wirelessly;

3. the normal vehicle's board will receive this message. Only the normal vehicle will receive this message, because it is the only other board on the system, otherwise, all of the boards would receive it too;

4. the board will transform the receive BSM message and send it to the corresponding port on the simulation's socket;

5. the normal vehicle, upon receiving the message from the socket, will interpret the message and perform the use case's logic to see if it needs to avoid the emergency vehicle.

The previous algorithm, complemented by the sequence diagram of figure 5.2, describes the sending of a message by an emergency vehicle, however, considering the normal vehicle, the algorithm will have the same behaviour.

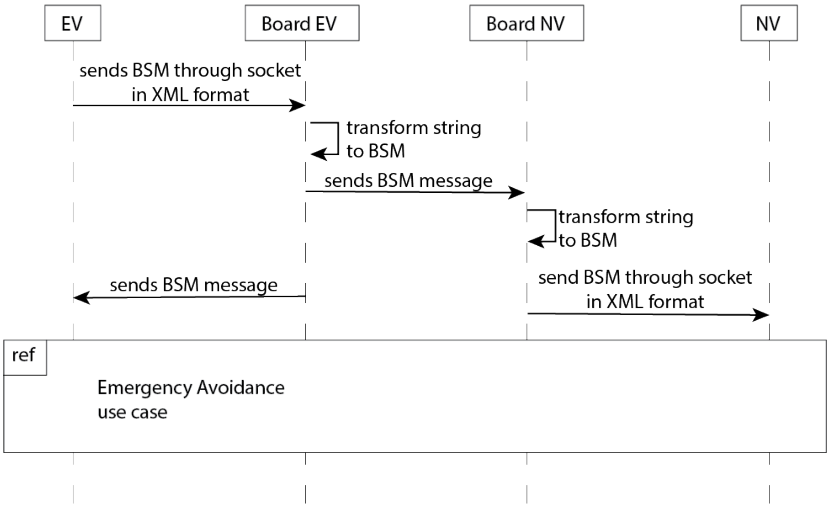


Figure 5.2.: Sequence diagram for the board integration implementation

5.2.3 *Results*

The analysis of the results of the experiment led to the important conclusion that the integration of the Bosch V2X communication boards on the simulation was a success and that it can be used in the future to test on scenarios with a high volume of traffic.

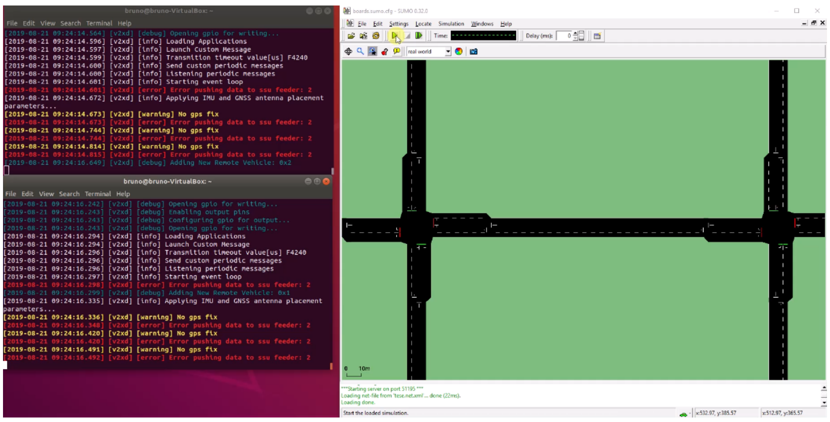


Figure 5.3.: Initial state of the emergency vehicle avoidance use case with the V2X boards

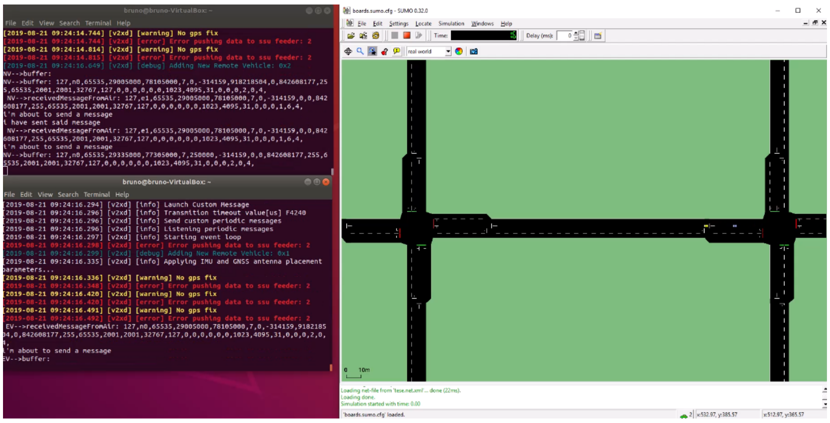


Figure 5.4.: Emergency vehicle approaches the normal vehicle

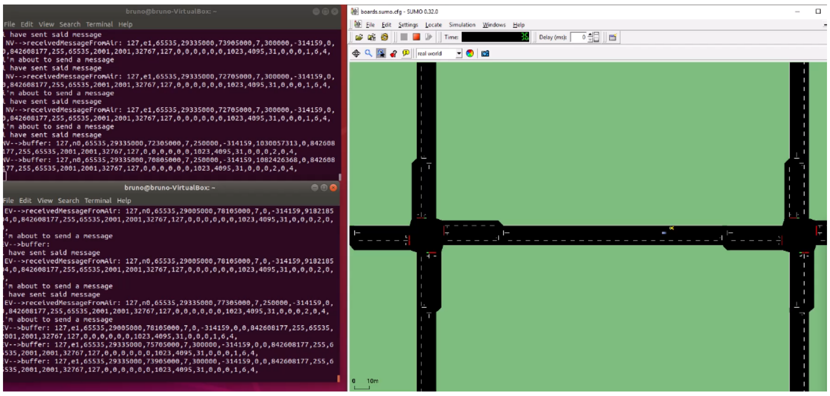


Figure 5.5.: Normal vehicle avoids the emergency vehicle

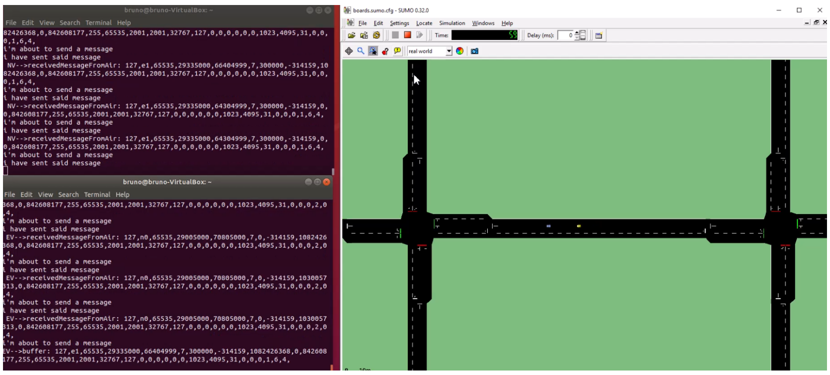


Figure 5.6.: Normal vehicle resumes previous behaviour

Figures 5.3 to 5.6 are included as an illustration of the experiment. In the left side of the images, two terminals appear, which present the debug process on both V2X communication boards. On the right side, the main display for the running simulation is presented. The messages that read "receivedMessageFromAir" are V2X messages from the other boards.

The messages that read "i'm about to send a message" and "i have sent said message" are messages from the boards to the simulation's socket.
The messages that read "EV–>buffer:" and "NV–>buffer:" are messages received from the simulation through sockets.
The images show the simulation's general state through the use case: initial state, emergency vehicle approaches the normal vehicle, the normal vehicle avoids the emergency vehicle, and normal vehicle resumes previous behaviour.

5.3 SUMMARY

The first experiment was clearly a success, since the goal was to integrate the Bosch V2X boards on the simulator. This allows for simple tests to be executed on a simulated environment, albeit with real V2X communications boards, before being implemented on a real scenario. Regarding the implementation of a real scenario, despite not being finished this time, the most relevant setup aspects were covered in appendix B, thus making its deployment easier in a near future.
The following chapter finalizes this document and the final conclusions are presented, including a critical review of the entire research and development work realized.

6

CONCLUSIONS

Nowadays, V2X communications are a trending topic. All the top automotive companies are trying to edge one another by developing their technologies, so that they can support these types of communications in the near future. Analyzing relevant RD projects, it is clear to see that there is a need for this technology to mature and that there is still a lot of topics that need to be studied. These developments can benefit our daily lives, for example, in the case of emergency vehicles.

If we consider the motivation and analyze the results, there is a clear benefit to implement V2X communications along with emergency vehicles. Safety can be enhanced and the emergency response time. However, decreasing the road fatalities of the emergency vehicles is not the present dissertations' purpose. Altogether, it would be a natural consequence of decreasing the response time, since this is going to be achieved by obtaining a natural flow and balance to the traffic system.

The use of V2X communications, on the present project, permitted the implementation of different road use cases: dynamic routing for the emergency vehicle, emergency vehicle avoidance, intersection logic, traffic light logic, and obstruction avoidance. All these use cases were successfully implemented as planned, except for the traffic light logic, which does not change its lights as fast as it should, resulting on the the visual effect of the simulation not to work as it should.

Regarding the results, as was expected, V2X brought a clear improvement comparing to a scenario not using V2X. Through the usage of Veins and the WAVE standard, the most important measure, the emergency response time, was significantly lower with V2X (41% of gain) which proves that the implementation of the use cases was a success and should be adapted to a real life scenario. This can reduce the response time, increase the odds of the patient arriving at the hospital sooner, granting him a better service.

As for the stop time, although the setup with V2X communications presented better results, the use cases need further study and development as it was expected that the stop time could have been close to zero. That is, the emergency vehicle should be able to cross the grid losing as little time as possible on stoppages, ideally, with no stoppages at all.

The last two metrics considered, CO_2 emissions and covered distance are related, but the

CO_2 emission is a more interesting factor to analyze. On average, the CO_2 emission is much higher using V2X, which means higher amounts of fuel are combusted. If more fuel is consumed, more money needs to be spent. This could pose as an obstacle for adoption these technologies as direct costs are always an issue on health care systems around the world.

Additional experiments for integration of real hardware V2X communication devices and real vehicles were planned but only the first one, consisting on the integration of Bosch V2X communication boards into the simulation setup, was implemented and successful tested. Although appearing simple, this setup took weeks to implement because of the difficulty in acquiring knowledge on the electronic circuitry and the software implemented on the board. Despite the setbacks, the implementation was a success and, through the use of simulator and the boards, a larger scenario can now be simulated, that would not normally be simulated, due to the lack of resources.

Analyzing the project, V2X communications are definitely a way forward regarding vehicular safety, fleet management, and every other situation that can benefit by knowing the surrounding environment, thus implementing connectivity functionalities, as proved by the car manufacturers, who are working to make cars as soon as possible.

Regarding plans for future work, they should rely mostly on the implementation for the second additional experiment. Despite all the objectives being achieved, additional studies could be realized and some improvements could be implemented in order to get more precise and significant results. The first step would be to solve all the limitations mentioned in the implementation chapter. The second would be to add other functionalities, such as crosswalks, bicycles, motorbikes, and multiple emergency vehicles, to check how the setup would behave. Instead of DSRC, C-V2X could also be included.

Probably, implementation of the planned second experiment would be the most relevant activity for the near future. Since it presents a scenario that integrates real V2X communication boards on real cars. An obvious improvement to this planned setup would be the implementation of an Android application to be run on a tablet on the normal vehicle, so that it knows exactly what happens, instead of just looking at the lights. Ideally, each vehicle should run Android applications with a graphical interface that, upon receiving messages from the RSU (regarding the traffic light state) would change the colour for the driver, eliminating the need for physical traffic lights, the future of urban mobility.

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A

APPENDIX A - SCRIPT GENERATOR

```
#!/bin/bash
#ciclo for i < 100
cd C://Users//PEB2BRG//src//veins-4.7.1//examples//veins
#alterar o RSUExampleScenario
sed -i 's/6/28/g' RSUExampleScenario.ned
sed -i 's/SocketRSU {/RSU {/g' RSUExampleScenario.ned
#mudar os campos do tese.launchd.xml
sed -i 's/tese.net/tests.net/g' tese.launchd.xml
sed -i 's/tese.rou/withV2X.rou/g' tese.launchd.xml
sed -i 's/boards.rou/withV2X.rou/g' tese.launchd.xml
sed -i 's/tese.sumo/tests.sumo/g' tese.launchd.xml
sed -i 's/boards.sumo/tests.sumo/g' tese.launchd.xml
#correr o script em java que crie o omnetpp.ini adequado aos testes
"C:\Program Files\Java\jre8\bin\javaw.exe" -Dfile.encoding=Cp1252 -classpath
    "C:\Users\PEB2BRG\eclipse-workspace\OmnetGeneratorLotsOfRSUs\bin"
        omnetlots.OmnetppIniGenerator
#mudar o script que mude as cenas do ev, estou cansado
cd "C:\Users\PEB2BRG\src\veins-4.7.1\src\veins\modules\application\traci"
sed -i 's/lotsOfTestsBeingRun = false/lotsOfTestsBeingRun = true/g' EmergencyVehicle.cc
sed -i 's/routingSmall.xml/routingBig.xml/g' EmergencyVehicle.cc
sed -i 's/fewRSUs = true/fewRSUs = false/g' RSU.cc

sed -i 's/fewTests = false/fewTests = true/g' AccidentVehicle.cc
sed -i 's/fewTests = false/fewTests = true/g' JustKerbsVehicle.cc
sed -i 's/fewTests = false/fewTests = true/g' NormalVehicle.cc
sed -i 's/fewTests = false/fewTests = true/g' SlowVehicle.cc
#compilar o projeto
cd "C:\Users\PEB2BRG\src\veins-4.7.1"
./configure
```

```
make

x=1
while [ $x -le 100 ]; do
#mudar para a diretoria onde dá para correr o java
cd "C:\Users\PEB2BRG\eclipse-workspace\PathGenerator"
#correr o java para criar os dois ficheiros aleatórios
"C:\Program Files\Java\jre8\bin\javaw.exe" -Dfile.encoding=Cp1252 -classpath
    "C:\Users\PEB2BRG\eclipse-workspace\PathGenerator\bin"
        randompathgenerator.RandomPathGenerator
#muda para a diretoria do veins
cd C://Users//PEB2BRG//src//veins-4.7.1//examples//veins
#muda a linha do launchd.xml para o caso v2x
sed -i 's/withoutV2X/withV2X/g' tese.launchd.xml
sed -i 's/boards/withV2X/g' tese.launchd.xml
sed -i 's/"tese.rou.xml"/"withV2X.rou.xml"/g' tese.launchd.xml
#muda a linha do sumo.config para o caso v2x
sed -i 's/withoutV2X/withV2X/g' tests.sumo.cfg
#sed -i 's/boards/withV2X/g' tests.sumo.cfg
#sed -i 's/"tese.rou.xml"/"tests.rou.xml"/g' tests.sumo.cfg
#muda a linha do omnetpp.ini para o caso V2X
sed -i 's/\"WithoutVToXRSU\"/\"RSU\"/g' omnetpp.ini
#correr a simulação
../../../omnetpp-5.3/bin/opp_run.exe -m -u Cmdenv
    -n .:../../src/veins --image-path=../../images -l ../../src/veins omnetpp.ini
#muda a linha do launchd.xml para o caso sem v2x
sed -i 's/withV2X/withoutV2X/g' tese.launchd.xml
sed -i 's/boards/withoutV2X/g' tese.launchd.xml
sed -i 's/"tese.rou.xml"/"withoutV2X.rou.xml"/g' tese.launchd.xml
#muda a linha do sumo.config para o caso v2x
sed -i 's/withV2X/withoutV2X/g' tests.sumo.cfg
#sed -i 's/boards/withoutV2X/g' tests.sumo.cfg
#sed -i 's/"tese.rou.xml"/"withoutV2X.rou.xml"/g' tests.sumo.cfg
#muda a linha do omnetpp.ini para o caso sem V2X
sed -i 's/\"RSU\"/\"WithoutVToXRSU\"/g' omnetpp.ini
#correr a simulação novamente
../../../omnetpp-5.3/bin/opp_run.exe -m -u Cmdenv
    -n .:../../src/veins --image-path=../../images -l ../../src/veins omnetpp.ini
```

```
echo $x >> "testResults.txt"
echo "----------------------" >> "testResults.txt"
x=$(( $x + 1 ))
done
```

B

APPENDIX B - REAL LIFE SCENARIO

The last goal of the present project was to implement the proposed solution on a real life scenario. Since the whole implementation of the solution is impossible, due to a obvious lack of resources, since the likeliness that a company can test with hundreds of vehicles is very low. Considering this setback, the proposed solution, just like the previous experiment would only use a specific use case, the traffic light use case.
Since the Bosch V2X communication boards were going to be used, confidentiality is of the utmost importance and details will have to be restricted to only the necessary information, in order not to compromise any of the company's business partners.
The code needed to implement this solution was nearly concluded, but the lack of time, the availability of resources, the testing grounds, and weather conditions made it impossible to conclude and test it, in due time. Nevertheless, the setup specification and some details of the developed software will be presented in the next sections.

B.1 PROBLEM DESCRIPTION

The planned use case to be experimented would be the approach of an emergency vehicle to a traffic light and the necessary actions by every entity involved in the system so to improve all vehicles security and to lower the time response and stop time of the emergency vehicle. In such a use case the entities involved are an emergency vehicle, a normal vehicle, and an RSU, all with V2X communications capabilities. The needed logic equals the logic of the previous traffic light logic use case.
Since this part of the project would require real vehicles, testing would be limited and restricted to Bosch facilities grounds in Braga. Despite being inside the company's private roads, there would be strict speed limits to be observed, which must be lower than 20km per hour. Also, the vehicles on the experiment should not disturb workers or the loading trucks. Considering this, the chosen place for the testing was at a three-way intersection, with a road's structure looking like figure B.1.

Figure B.1.: Scenario's scheme for the traffic light use case in a real scenario

The two vehicles would be Bosch prototype cars both equipped with V2X communications boards, while the RSU would be located near the side of the road in front of the emergency vehicle, implemented on a personal computer with a V2X communications board connected to it.

Considering the entities, the system's architecture would contemplate the vehicles, the boards, and the type of communication between them, as seen on figure B.2.

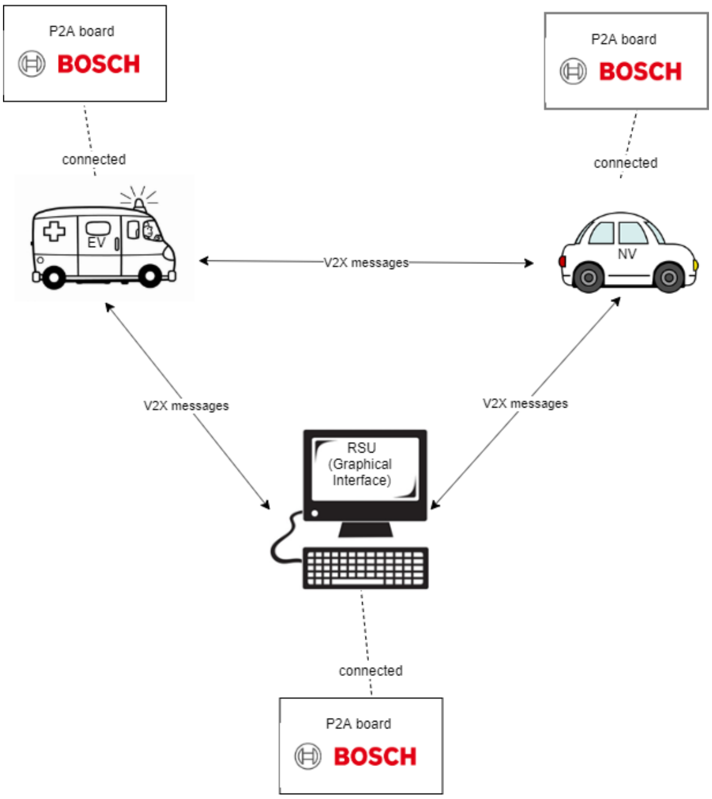

Figure B.2.: System architecture of the traffic light use case in a real scenario

In conclusion, when the emergency vehicle would reach the area close to the intersection, it would need to cross the intersection safely, which means there should not be any obstacles or obstructions, such as the traffic lights being red or yellow, or a normal vehicle crossing the intersection at the same time. This could be controlled by the RSU, by actuating the traffic lights, that is, by turning the lights green to the emergency vehicle and red to the rest of the intersection. As for the normal vehicle, it just needs to follow the traffic light's colours.

B.2 EXPERIMENT SETUP

The setup of this experiment would comprehend two different components: the vehicle setup and the RSU setup. The vehicles used in this experiment would be the Bosch prototype cars, which are vehicles that already integrate a V2X communications board.
As for the RSU, the setup is more complex. The equipment required would include a personal computer, a V2X communications board, and two monitors. The V2X board and the computer are necessary for running the software implementation of the use case's logic,

for processing of the BSM messages and recreating a traffic light. The two monitors are connected to the computer and are necessary due to the lack of a real traffic light, so each monitor would emulate a traffic light pointing to the road where needed.

B.3 IMPLEMENTATION

The traffic light's logic would be similar to the traffic light's use case presented in the previous chapter. It also would incorporate the same updates that went with the integration of the boards, such as the send messages rate.

The major difference, comparing to the pure software simulation, would be the technology used to get data from the vehicles. In the simulation, the data came from the simulator itself, while on the real scenario, the data would be acquired by the board (which is directly connected to the vehicle).

Regarding the RSU, there are three components that would have to be implemented: the traffic light, the visual interface, and the transmission of the traffic light colours to the vehicles. As such, the RSU would be defined by a program with two concurrent threads: one that simulates the behaviour of a traffic light and another whose purpose is to deal with the V2X messages.

B.3.1 *Traffic light thread*

The traffic light thread would include an implementation of a graphical control system and the traffic light's behaviour. The graphical component would be important to follow the experiment in real-time. The computer will show the whole scenario to the viewer, so that, as the emergency vehicle approaches, the viewer can see the lights change. Figure B.3 is an illustration of such a graphical interface.

Figure B.3.: The graphical interface of the control system

The traffic light normal or default behaviour is a simple clocking mechanism, which, depending on the elapsed time since the last change and the current state, changes the lights to another colour. For example, the transition from green to yellow and from red to green would take twenty seconds and ten seconds from yellow to red, as can be seen through figure B.4.

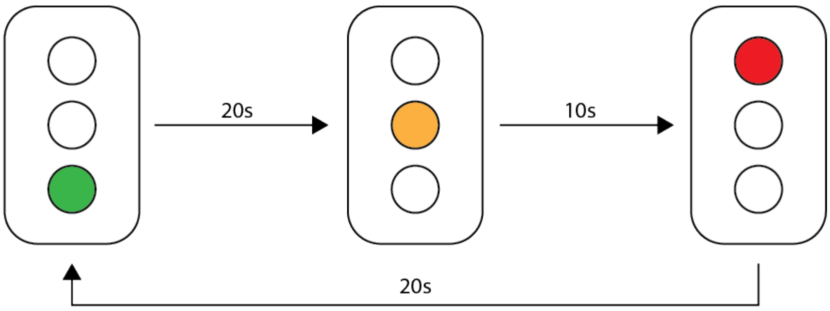

Figure B.4.: Traffic lights' behaviour

The traffic light's state would be represented by a string with the characters $'g'$ for green, $'r'$ for red, and $'y'$ for yellow. The representation for figure 5.9 is $''rgr''$. In order to correctly change the traffic light, the following formula (9) could be used

$$tlColour[(pos+1)\%3] =' g' \tag{9}$$

where *tlColour* represents the colours of the traffic light stored in an array, *pos* the position, and the number three is the number of traffic lights. Thus, even though the string ends, it gets right back to the beginning to repeat the process.
This behaviour would always remain the same if the emergency vehicle is not involved. If an emergency vehicle would enter the intersection, the behaviour would need to save its state and then change green for the emergency vehicle and red for the other ones. After the emergency vehicle has left the intersection, the traffic lights would need to return to the previous state and their default behaviour would be resumed.

B.3.2 *Message receiver thread*

This thread would process the received messages through a socket and, if the traffic light's colours need to be changed, signal the other thread of that necessary action.
A sequence diagram of all specified interactions is presented in figure B.5.

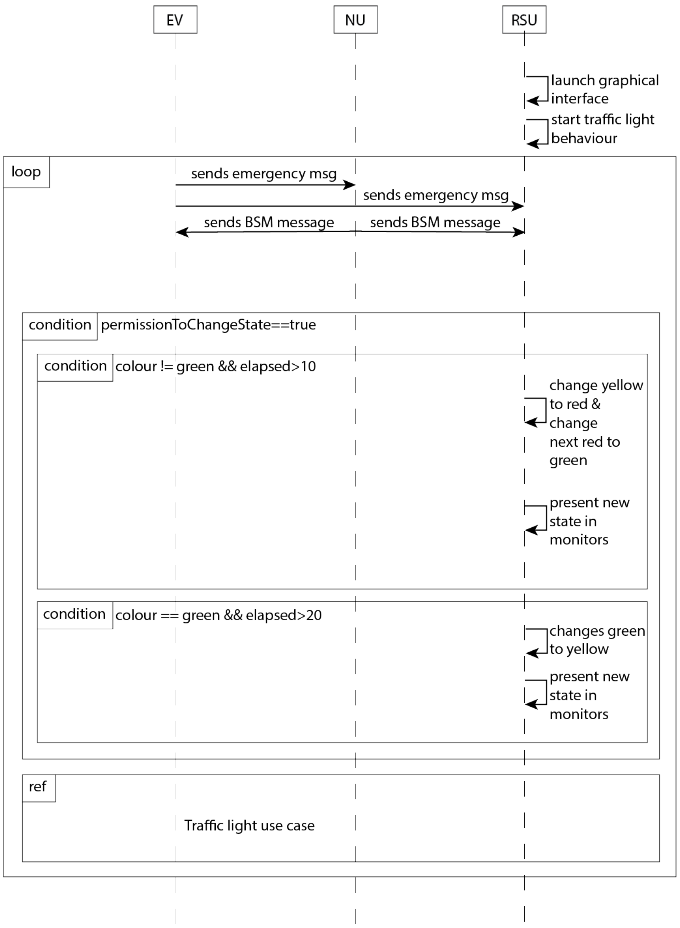

Figure B.5.: Sequence diagram for the real scenario implementation