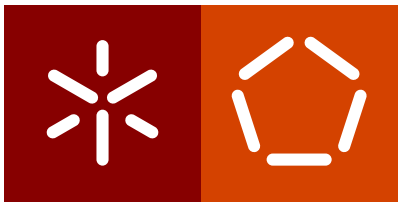
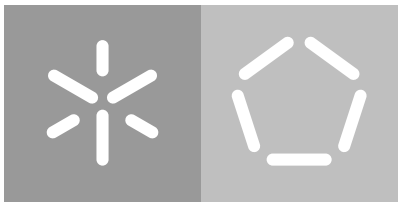


University of Minho
School of Engineering
Department of Informatics

Bruno Daniel Mestre Viana Ribeiro

Platooning Simulation in ITS Communications

October 2016



University of Minho
School of Engineering
Department of Informatics

Bruno Daniel Mestre Viana Ribeiro

Platooning Simulation in ITS Communications

Master dissertation
Engineering of Computer Networks and Telematic Services

Dissertation supervised by
Prof. Alexandre Santos
Prof. Maria João Nicolau

October 2016

Acknowledgments

This research work would not have been possible without the help of many people, for their support and valuable contributions.
I would like to express my appreciation and sincere thanks to my supervisors from *University of Minho*, professors Alexandre Santos and Maria João Nicolau. I am very grateful for their great effort in giving me useful advices and guidance throughout the development of my thesis.
I would also like to thank all my colleagues from *Algoritmi Center* at *University of Minho* for their support, in particular to *Fábio Gonçalves* for his truly valuable input and interesting discussions on *Platooning*.
I must express my gratitude to my parents and family for their inexhaustible support and endless encouragement throughout my life.
And last, but not least, a very special word of appraise goes to my girlfriend Raquel for her patience and for being supportive during the most stressful times.
Part of this research has been sponsored by the Portugal Incentive System for Research and Technological Development. Project in co-promotion nº 002797/2015 (INNOVCAR 2015-2018).

Abstract

Vehicular Ad Hoc Networks (VANETs) is a term used to describe networks of moving vehicles equipped with devices that allow spontaneous communication with other vehicles and infrastructures. Developing collaborative driving applications for VANETs is currently a hot topic and has an increasing popularity in the Intelligent Transportation Systems (ITS) domain. The goal of this thesis is to study the development and testing of advanced ITS applications, using *Platooning* as a use case. It presents a state of the art on typical ITS applications, its evaluation and corresponding implementation and testing methods. The Platooning Management Protocol (PMP) was then implemented and tested by means of simulation, resorting to the V2X Simulation Runtime Infrastructure (VSimRTI) framework, which couples Simulation of Urban MObility (SUMO) and Network Simulator 3 (ns-3). Results show that it is able to work in a smooth and efficient manner: the maneuvers happen during an acceptable interval, the proposed communication requirements are met and the lane capacity is increased.

Resumo

Vehicular Ad Hoc Networks (VANETs) é um termo usado para descrever redes de veículos em movimento, equipados com dispositivos que permitem uma comunicação espontânea com outros veículos e infraestruturas. Desenvolver aplicações de condução colaborativa para VANETs é atualmente um tópico muito estudado e cuja popularidade tem crescido no domínio dos Intelligent Transportation Systems (ITS) - sistemas de transporte inteligentes. O objetivo desta tese é o estudo, desenvolvimento e teste de aplicações de ITS avançadas, utilizando *Platooning* como caso de uso. Neste documento é apresentado o estado da arte relativo às aplicações ITS tipicamente avaliadas e os respetivos métodos de implementação e teste. O Platooning Management Protocol (PMP) foi implementado e testado através de simulação, utilizando a ferramenta V2X Simulation Runtime Infrastructure (VSimRTI), que acopla as ferramentas Simulation of Urban MObility (SUMO) e Network Simulator 3 (ns-3). Os resultados mostram que o protocolo funciona de forma leve e eficiente: as manobras decorrem num intervalo de tempo aceitável, os requisitos de comunicações são cumpridos e a capacidade das faixas é aumentada.

Contents

List of Figures

List of Tables

Acronyms

ACC Adaptive Cruise Control

AES Advanced Encryption Standard

ARC Adaptive Route Change

BSA Basic Set of Applications

C2C TMC to TMC

CACC Cooperative Adaptive Cruise Control

CAM Cooperative Awareness Message

CanuMobiSim CANU Mobility Simulation Environment

CDG Constant Distance Gap

CEN European Committee for Standardization

COLOMBO Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates

COMPANION Cooperative Dynamic Formation of Platoons for Safe and Energy-Optimized Goods Transportation

CTG Constant Time Gap

DCC Decentralized Congestion Control

DENM Decentralized Environmental Notification Message

DSRC Dedicated Short-Range Communications

DynB Dynamic Beaconing

Energy ITS Development of Energy-Saving ITS Technology

ETSI European Telecommunications Standards Institute

EWA Emergency Warning Application

GCDC Grand Cooperative Driving Challenge

GLOSA Green Light Optimized Speed Advisory

GPS Global Positioning System

GTNetS Georgia Tech Network Simulator

GUI Graphical User Interface

HMI Human-Machine Interface

I2C Infrastructure to TMC

I2I Infrastructure to Infrastructure

I2V Infrastructure to Vehicle

iCS iTETRIS Control System

IEEE Institute of Electrical and Electronics Engineers

iGAME Interoperable Grand Cooperative Driving Challenge AutoMation Experience

IP Internet Protocol

ISO International Organization for Standardization

iTETRIS Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions

ITS Intelligent Transportation Systems

JiST Java in Simulation Time

JiST/SWANS Java in Simulation Time/Scalable Wireless Ad-Hoc Network Simulator

MiXiM Mixed Simulator

MOTO Mobile Opportunistic Traffic Offloading

MOVE MObility model generator for VEhicular networks

NHTSA National Highway Traffic Safety Administration

ns-2 Network Simulator 2

ns-3 Network Simulator 3

OBUs On-Board Units

OEM Original Equipment Manufacturer

OMNeT++ Objective Modular Network Testbed in C++

OSM OpenStreetMap

PATH Partners for Advanced Transportation Technology

PER Packet Error Rate

PHEM Passenger Cars and Heavy Duty Emissions Model

PMP Platooning Management Protocol

RSA Rivest-Shamir-Adleman

RSUs Roadside Units

SAE Society of Automotive Engineers

SARTRE Safe Road Trains for the Environment

SHA-256 Secure Hash Algorithm - 256

SUMO Simulation of Urban MObility

SWANS Scalable Wireless Ad-Hoc Network Simulator

TCP Transmission Control Protocol

TMC Traffic Management Center

TraCI Traffic Control Interface

TSIS-CORSIM Traffic Software Integrated System - Corridor Simulation

V2C Vehicle to TMC

V2I Vehicle to Infrastructure

V2V Vehicle to Vehicle

V2X Vehicle to Anything

VANETs Vehicular Ad Hoc Networks

VCS Vehicular Communication Systems

VEINS Vehicles in Network Simulation

VENTOS VEhicular NeTwork Open Simulator

VISSIM Verkehr In Stadten SIMulationsmodell

VSimRTI V2X Simulation Runtime Infrastructure

WAVE Wireless Access in Vehicular Environments

Chapter 1

Introduction

According to some researches [6] [7], it is expected that global Vehicle to Anything (V2X) communication modules in new vehicles will reach 62% and that Original Equipment Manufacturer (OEM) and aftermarket V2X modules will grow to 423 million by 2027. Cadillac recently announced [8] that we should expect Vehicle to Vehicle (V2V) technology in 2017 Cadillac CTS. Toyota has already introduced vehicle-infrastructure communication systems in 2015 car models [9]. These are just some examples of the current state of vehicle communications in the automotive industry.

Vehicles equipped with communication capabilities may be able to exchange important information that can help prevent accidents, save lives, ease traffic flow or even improve the environment. Vehicles that are connected require very efficient and smooth Vehicular Communication Systems (VCS), essentially due to the very short delays that this type of connection depends upon (specially when the communication concerns the safety of the drivers).

Some communication systems that may be adopted are traditional 3G/4G cellular or Wi-Fi, or specially designed systems like Dedicated Short-Range Communications (DSRC) or ITS G5. Cellular networks are typically applied in Vehicle to Infrastructure (V2I) solutions, whereas ad hoc networks are practically the only technology considered in V2V communications [10].

Intelligent Transportation Systems (ITS) are systems consisting of an intricate set of technologies applied to vehicles and infrastructures that ensure an

efficient and smart usage of the roads in general. They allow the control of traffic operations and even influence drivers behavior. These systems have the potential to improve safety, efficiency and productivity or even decrease levels of pollution.
ITS enable the rise of several applications relying on the exchange of information between vehicles themselves and infrastructures, allowing drivers to either manually or automatically make smarter driving choices. These application range from simple applications such as *Emergency Vehicle Warning* to more advanced and complex solutions like *Platooning*.
There are two main approaches when assessing vehicular networks applications (with different benefits and drawbacks): through simulation or field operational trials. Simulation allows the control of scenario parameters and the replication varying conditions, but its development is a challenging task. Field operational trials allow a realistic evaluation of systems but they are very expensive and possess serious safety and also technological constraints.

1.1 Background

This section provides an overview on the background of the project and its context. It contains a description of ITS and how the communication work on these systems, and a complete review on ITS applications and use cases, including advanced applications.

1.1.1 Intelligent Transportation Systems

ITS are defined by the European Parliament [11] as systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, traffic management and mobility management, as well as for interfaces with other modes of transport. There are a wide range of ITS applications, such as road safety applications, traffic efficiency and infotainment.
The ITS standards [12] are defined so that one can establish and enable interoperability, by specifying who communicates with whom (e.g. vehicle,

road-side infrastructure, etc.) and what type of messages must be used, which protocol (e.g. Internet Protocol (IP)) should be used and in which communication media (e.g. wireless frequency band), etc.
Since the regularity constrains differ from region to region (even country to country), there are several ITS standards developing organizations: Institute of Electrical and Electronics Engineers (IEEE) and Society of Automotive Engineers (SAE) in the USA, European Committee for Standardization (CEN), International Organization for Standardization (ISO) and ETSI in Europe, etc.

Vehicle Communications

Luca Delgrossi states [1] that the idea of vehicle communication is that vehicles, roadside infrastructure (roads and highways), and back-end (telecommunications and Internet backbones) work together.
VCS are networks where vehicle's On-Board Units (OBUs) and Roadside Units (RSUs) work as communicating nodes that share information with each other, like traffic information or safety warnings. Since VCS use a cooperative approach, accidents and traffic congestions avoidance can become more effective than by using the traditional way (where vehicles try to solve problems by themselves). Figure 1.1 illustrates how typical vehicle communication modes work. Below are described V2V modes of communication.

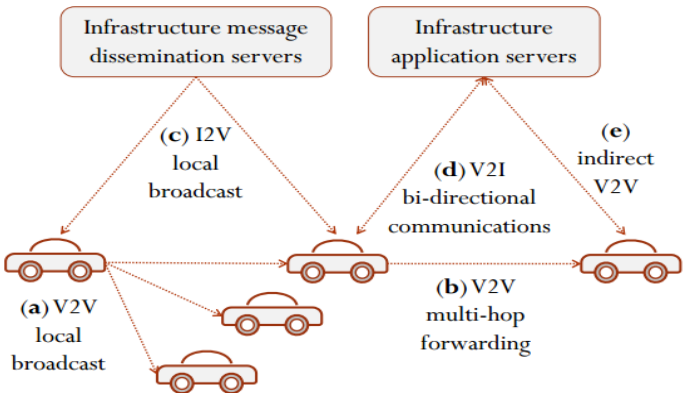


Figure 1.1: Vehicle Communication Modes [1]

V2V Local Broadcast In *V2V Local Broadcast*, a vehicle disseminates messages to all other vehicles that are within the respective communication range. This communication mode is used to support cooperative applications, mostly aimed to prevent collisions. This messages are used to inform nearby cars of current position, speed and such. However, due to the highly dynamic nature of traffic flow, the set of neighbors (vehicles) changes frequently. Thus, short range radios with native broadcasting capabilities are the best way to support this mode.

V2V Multi-Hop Dissemination In *V2V Multi-hop Dissemination*, messages from a given vehicle are relayed by others in order to reach vehicles that are out of the source's communication range. This mode may be used to support hard safety applications, but only if the number of hops is very low.

Infrastructure Communications

The following subsection describes how V2I and Infrastructure to Vehicle (I2V) communications work.

I2V Local Broadcast Vehicles receive local broadcasts from the roadside infrastructure (e.g. Poor road conditions information or traffic controller information). *I2V Local Broadcast* can be implemented through the use of radio transceivers deployed along the roadside. It may also be implemented by using other strategies like cellular or satellite services, etc.

V2I Bidirectional Communications *V2I Bidirectional Communications* are required by a lot of mobility and convenience applications. Some examples are Internet access navigation and media download. *V2I Communications* can also be used to broadcast messages from a vehicle to other vehicles through the applications servers infrastructure. This mode can be supported by either using short range or long range radios.

Additionally, it is possible for infrastructures to communicate with each other (Infrastructure to Infrastructure (I2I)) - this mode is mostly used for relaying

information.

Traffic Management Center Communications

The Traffic Management Center (TMC) is used for monitoring and controlling traffic and the road network. There are three communication modes available for TMC: Vehicle to TMC (V2C), Infrastructure to TMC (I2C) and TMC to TMC (C2C). Through this communications, it is able to monitor the surrounding environmental conditions and manage the transportation resources in order to provide support for a better traffic flow (e.g. keep traffic moving safely after traffic incidents).

1.1.2 ITS Applications

ITS applications are developed to optimize driver safety and comfort. Vehicle communications bring a lot of benefits to users, such as improved safety for the driver (with solutions like *Situation Awareness, Collision Avoidance* or *Post-crash Assistance*), enhanced driving experience (e.g. *Navigation, Routing, Points of Interest*) or extended connectivity (office activity available in the car), etc. Given the wide range of existing (and upcoming) applications, one of the most critical tasks is to standardize the diverse communication requirements for each type of application.
Vehicle Communications Applications are typically divided [2, 13, 14] in two main categories: *safety* and *non-safety*. Figure 1.2 illustrates an example of how ITS applications can be described, according to [2].
The *non-safety* applications can be divided in two subcategories: *Mobility (Efficiency)* and *Comfort (Connectivity and Convenience)*. *Mobility* applications focus mainly in improving and managing the traffic flow. Resorting to live traffic updates, route guidance, navigation and such, traffic behavior can in fact be enhanced. These applications provide updated local information, maps and information of relevance, in order to improve the traffic flow, coordination and assistance. This type of traffic applications is typically used in V2I scenarios. *Connectivity and Convenience* applications are more focused in assuring that the driving experience is more pleasant and

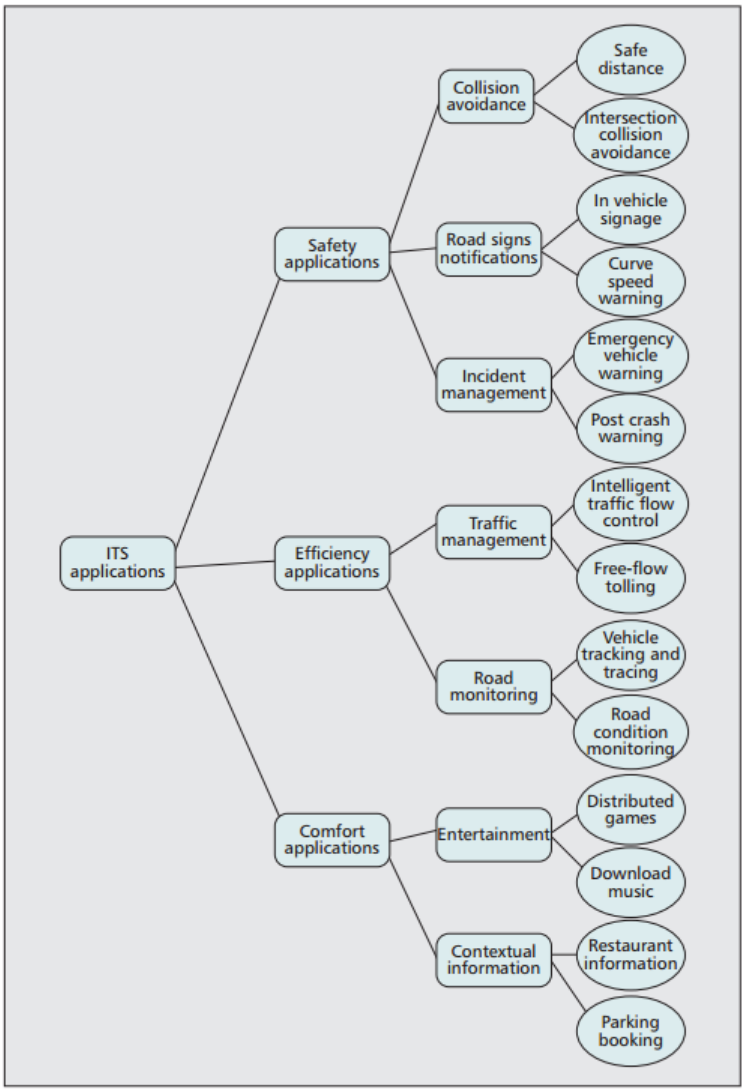


Figure 1.2: A classification of the existing ITS applications [2]

enjoyable to the driver. They provide functionalities needed by passengers and drivers for a convenient travel. They offer a wide range of features like email, media, access to social networks, etc. These applications are often delivered through the use of electronic devices (most of times through the driver's smartphones) or in-vehicle devices. These applications may tolerate some delays but can also occasionally have a high data throughput demand. *Connectivity and Convenience* applications are also referred to as in-car comfort entertainment - they do not use inter-vehicular communications in most

situations.

Safety applications can also be sub-divided [15, 16] in two kinds: *Soft Safety* and *Hard Safety*. *Soft Safety* applications mean to increase drivers safety but, since they do not require immediate attention, they are less time-critical. They notify the driver of not so imminent dangers like icy roads, traffic jams, reduced visibility, etc. Usually, the typical driver reaction to this notifications is to proceed more carefully or to take an alternate route. On other hand, *Hard Safety* applications are used to prevent accidents or, at least, minimize the severity if the crash is unavoidable. Thus, this kind of applications requires a minimum communication *latency* and high *reliability* when delivering messages, so that the driver can react in time. *Forward Collision Warning* and *Emergency Electronic Brake Light* are examples of *Hard Safety* applications. *Safety* applications rely on real-time information and typically resort to V2V communications. They are used to avoid traffic accidents. Vehicles and *RSUs* share information that is used to predict dangerous situations.

1.1.3 Advanced ITS Applications

ITS applications vary from basic management systems (such as car navigation and variable message signs) to more advanced applications that rely on real time live information and feedback from surrounding sources. These kind of advanced solutions aim to provide innovative services, enabling the users to use the network in a more informed and coordinated way. Two very important advanced ITS applications that are heavily researched by the community are vehicle *Platooning* and Cooperative Adaptive Cruise Control (CACC). *Platooning* is defined as a set of vehicles connected via wireless communication that travel in conjunction and in formation, coordinated by a leader vehicle. The lead vehicle is responsible for general cooperative actions such as steering or braking and it is assumed that the leading driver must possess proper training to control a platoon. This solution allows the following drivers to perform tasks that otherwise were not advised to be performed (e.g. use a phone) while their vehicles are being controlled based on

sensor information. Still, these drivers must be able to control the vehicle if, for some reason, the platoon is dissolved or no longer controlled by the lead - deciding if it is safer to remain in the platoon or to drive manually becomes a challenge for every following driver. This way of traveling introduces many benefits such as increased road capacity, fuel efficiency and enhanced safety (fewer traffic collisions). There are several projects focused on the concept of *Platooning*, such as SARTRE [17], COMPANION [18] and i-GAME [19].
The CACC application is an evolution from the Adaptive Cruise Control (ACC) application that resorts to V2V communication to enable the exchange of useful information to and from neighbor vehicles. CACC is a system for vehicles that automatically adjusts the traveling speed to maintain a safe distance from vehicles ahead. Besides allowing a vehicle's cruise control to maintain a proper distance to the following car, it also allows them to communicate between each other and cooperate in an adaptive mode. The neighbor's information on acceleration is typically transmitted using *CAM* messages from the Wireless Access in Vehicular Environments (WAVE) technology. More than providing the driver with a more comfortable experience, CACC has the potential of improving traffic safety and efficiency. The ultimate goal of ITS applications is to reach the point of full automated driving and these applications are the next step towards it. Automated driving is the enabling key to eliminate the potential errors made by humans in transportation systems. Future driver-independent systems will result in fewer accidents, traffic jams and even lower emissions.
These two application have been often mistaken in recent years and assumed to be the same. Although both applications are part of a broader class of automatic vehicle control systems, there are important differences between them. The first difference is that CACC only controls longitudinal distance (the driver is responsible for steering and monitor the vehicle) while *Platooning* is capable of controlling both longitudinal and lateral distances. Also, according to SAE [20] and National Highway Traffic Safety Administration (NHTSA) [21], CACC will fit on a lower level of automation when comparing to *Platooning*.
Another difference between the two is the use of distinct vehicle following

control strategies. *Platooning* solutions typically resort to a Constant Distance Gap (CDG) strategy, coupling vehicles very close to each other with a constant distance, ignoring the vehicles velocity. With this approach, vehicles give the illusion of a chain link. This solution requires a very strict control mechanism and is not very tolerable to disrupt communications due to security issues - if communication fails during an emergency maneuver, following drivers may not be able to react in time in these very short distances. In other hand, CACC typically uses the Constant Time Gap (CTG) strategy, which is similar to human driver behavior. In this approach, the distance between vehicles depends on the vehicles speed - the distance is proportional to the speed.

1.2 Thesis Objectives

The development of advanced applications is currently a hot topic and is becoming more and more popular in the ITS field of work. The primary goal of this thesis is to develop and test advanced ITS applications, using *Platooning* as use case. ITS applications will be tested by means of simulation. The primary goal may be divided in sub-goals, listed as follows:

- Study the ITS applications development state of the art;
- Survey the existent *VANETs* simulation tools;
- Build a taxonomy for ITS applications, including a *Platooning* use case;
- Analyze and test the Platooning Management Protocol (PMP), including descriptions on the application behavior and maneuvers;
- Design and build the simulation environment;
- Obtain and discuss the results from simulations.

1.3 Thesis Outline

The *Introduction* chapter has already presented a summary about the context in which this work has arisen and its objectives. The remaining thesis is structured as follows. Chapter 2 provides an overview on the related work and literature. Chapter 3 introduces the characteristics of simulation tools. Chapter 4 addresses the ITS applications, in particular the *Platooning* use case, presenting the design of the PMP. Chapter 5 presents the process of evaluating the performance of the application. Chapter 6 debates the results obtained from the simulation runs. Finally, Chapter 7 provides the main achievements and future research directions.

Chapter 2

Related Work

This related work review chapter is essentially divided in two parts. The first part intends to provide a brief overview on available publications that cover subjects related to V2X applications, with special attention to advanced applications (e.g. *Platooning* and CACC). Although essentially focused on V2X applications simulation, it presents some important work that describes systems designs, implementations, communication strategies and so on. The second part discusses some important projects/consortium that have similar goals and aims regarding advanced applications in Vehicular Ad Hoc Networks (VANETs). Not being practicable to introduce all the related projects existent, the main focus has been directed into funded projects, looking into their main objectives and results.

2.1 Related Literature

Milanés et al. [22] present the design, development, implementation and testing of a CACC system. The design of the system is based on controllers that determinate the maneuvers in the platoon: the leader vehicle approaching maneuver and the car-following regulation maneuver. The solution aims to reduce significantly the gaps between the vehicles, taking advantage from information exchanged using DSRC wireless communication. In order to experiment its performance against the commercially available ACC, the system

was implemented and tested on four Infiniti M56s vehicles, in three different scenarios: The first evaluated the behavior of the following cars when the gap settings are changed, the second tested cut-in and cut-out situations and the third compared the CACC performance of the vehicles following a speed change profile with the performance of the traditional ACC system. The authors conclude that the system performed well and was able to reduce the gap variability and handle the cut-in and cut-out situations. Additionally, the CACC improved the response time and platoon stability, when in comparison to the ACC system, proving that the system may be able to improve traffic flow and capacity.

Katsaros et al. [23] propose an implementation of a Green Light Optimized Speed Advisory (GLOSA) application, and evaluates its performance using the V2X Simulation Runtime Infrastructure (VSimRTI) simulation tool. Their goal was to measure the GLOSA effect on fuel and traffic efficiency, resorting to average fuel consumption and average stop time behind a traffic light metrics. The GLOSA application consists in providing the vehicles accurate traffic lights information (using I2V communication), and giving them speed advice, in order to assure a more fluid speed with less stopping time. To test the application, an urban area traffic scenario with a single route and two traffic lights was defined, using the SUMO tool. The simulations had different penetration rates of equipped vehicles and traffic density. The authors conclude that the system could in fact improve the fuel consumption and traffic congestion levels and that the higher the penetration rate is, the more benefits the application can provide, specially in high density scenarios.

Bergenhem et al. [24] survey the state of the art and present an overview of projects related to vehicle *Platooning* that took place at the time the article was written - Safe Road Trains for the Environment (SARTRE), Partners for Advanced Transportation Technology (PATH), Grand Cooperative Driving Challenge (GCDC), Development of Energy-Saving ITS Technology (Energy ITS) and SCANIA platooning project. They conclude their work with a summary and comparison between the different projects using the following parameters: vehicle type, automatic control direction, requirements/potential changes to infrastructure, integration, mainly used primary onboard sensors

and the main goals of the project regarding *Platooning*.

Guvenc et al. [25] present the *Team Mekar's* CACC implementation at the GCDC. They show both experimental and simulation results, discussing the challenges found. Their CACC implementation was based on V2V communication - exchanging information about the Global Positioning System (GPS) position and velocity, and preceding vehicle acceleration data, resorting to IEEE 802.11p WAVE protocol. The scenarios included both a traffic light and an urban environment.

Katsaros et al. [26] evaluate the impacts of a GLOSA application implementation on efficiency of traffic in urban areas and present its performance resorting to the VSimRTI tool, with Java in Simulation Time/Scalable Wireless Ad-Hoc Network Simulator (JiST/SWANS) and SUMO simulators. Additionally, they also study the behavior of the Adaptive Route Change (ARC) application (route alternation through V2I/V2V communication). The metrics used to analyze the applications were average fuel consumption, average stop time behind a traffic light and average trip time. The authors defined different urban scenarios that included traffic lights, using different penetration rates of vehicles running the applications, vehicles that complied to the recommended speed and traffic density. Their results show that this systems could in fact improve fuel consumption levels and also reduce traffic jams and trip time.

Segata et al. [27] analyze the interference of non-automated vehicles, when a given vehicle is joining a platoon. They define a protocol that supports the join maneuver, and validate it using the *Platooning* extension (Plexe [28]) from Vehicles in Network Simulation (VEINS), showing if a maneuver can be performed with success or safely aborted. Furthermore, they analyze the impact of the Packet Error Rate (PER) on the maneuver's rate of success. The results show that their protocol can support complex joining maneuvers and that the dangerous maneuvers can be safely aborted. Additionally, they conclude that platoons remain stable even with high loss rates and that maneuvers are aborted only when networking conditions are bad (PER larger than 10%).

Amoozadeh et al. [29] developed a CACC management protocol based on

IEEE 802.11p communication, including three basic maneuvers (along with commands to accomplish them). These maneuvers enable several operations such as joining and leaving the platoon. The protocol was implemented in the VEhicular NeTwork Open Simulator (VENTOS) simulation platform (which couples SUMO and Objective Modular Network Testbed in C++ (OMNeT++) simulators) and tested in different scenarios and settings (including platoon communication structure, inter-platoon spacing, time-gap and size). To build a better model, they also implemented a more complex longitudinal control system in SUMO. They conclude that the protocol is able to ensure a stable traffic flow and theoretical throughput. The protocol is also able to react to loss in communication, either by using retransmissions or downgrading to ACC mode.

Aissaoui et al. [30] propose a real-time traffic monitoring system that aims to enhance typical reliability, accuracy, and granularity levels, providing information to vehicles with the lowest overhead possible. To accomplished that, they propose a cluster solution, where only the cluster head (the one responsible for providing RSUs the data about all vehicles in the cluster) updates the information. To evaluate the system, they used the Network Simulator 3 (ns-3) version made available by the Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions (iTETRIS) platform (which combines ns-3 and SUMO simulators). They conclude that by using this mechanism it is possible to reduce overhead to one quarter when in comparison to typical approaches, while gathering more than 99% of the existent data.

Bellavista et al. [31] work focus on the implementation and evaluation of protocols that arisen from the COLOMBO project, developed on the iTETRIS platform. In particular, the COLOMBO project aimed to develop local-based cooperative protocols that determine traffic characteristics without the need to communicate with global data centers. COLOMBO aspired to achieve accurate traffic estimations with low penetrations rates of V2X technology equipped vehicles. In this paper, they describe how they implemented the protocols on the platform, together with the learned lessons. The results from the simulations (based on real traffic traces and a real topology) prove

the feasibility of the proposed approach (even with low penetration rates).
Segata et al. [32] investigate communication strategies for *Platooning* and compare the proposed approaches to two beaconing protocols that have been designed for cooperative awareness applications: Decentralized Congestion Control (DCC) and Dynamic Beaconing (DynB). The simulation models were validated and parameterized based on real world experiments. To establish the comparison between the approaches they resorted to PLEXE, which is based on the VEINS tool. Their goal was to evaluate the performance and behavior of the protocols under "stressful" configurations, regarding the networking and application perspectives. The obtained results show the protocols can greatly improve the performance, both in the application and network layers.
Goebel et al. [33] introduce a trace-based simulation tool chain for V2X applications resorting to cellular networks and real world traces as a basis, assuring that some unpredictability present in other simulation approaches is minimized. To prove their concept, they used the VSimRTI framework (coupling SUMO and OMNeT++ simulators) to compare the performance of the ETSI defined Emergency Warning Application (EWA) against their optimized version. The results show that the developed version is superior in its performance.
Fazio et al. [34] propose an application that aims to advise danger on emergency situations on VANETs resorting to V2V and V2I message exchanges working on top of the IEEE 802.11p standard. To perform an evaluation on the application, the authors executed simulations on various scenarios, in order to retrieve general information that is independent form the scenario. The selected framework was VSimRTI, which permitted the coupling of the SUMO and JiST/SWANS simulators. From the obtained results, they proved that the proposed emergency management application is able to improve the reaction for general vehicles and emergency ones. The designed solution allows vehicles (communicating with the WAVE protocol) to update their path in order to avoid traffic jams near accidents, saving time for reaching their destinations. It allows for emergency vehicles to intervene in less time, managing the accident in a better and safer way, since it also brings

benefits to the injured people, which can be treated faster (the emergency vehicle average speed is higher when running the application). Additionally, the normal traffic flow can also be restored in less time. The application benefits are proportional to the number of vehicles running the application. The application tends to achieve better results in the suburbs, since the roads are more sparse than the central ones.
Krajzewicz et al. [35] evaluates the simulation of the GLOSA application (included in BSA), measuring its effects on traffic efficiency and predicting the results on real-world environments. The GLOSA system suggests vehicles a speed that will allow them to pass the traffic lights when they are green. To evaluate the system, the simulations were performed using SUMO together with a communication model coupled via Traffic Control Interface (TraCI). The main goal of the work was to validate the developed simulation models capabilities. The authors conclude that GLOSA helps in fact vehicles to go through the network, although some vehicles do not need to halt at all and some have to stop (which is assumed to happen due to receiving the traffic lights states too late). The evaluations shown that increasing the number of vehicles reduces the application benefits (even with all vehicles equipped).

2.2 Related Projects

Cooperative Dynamic Formation of Platoons for Safe and Energy-Optimized Goods Transportation (COMPANION) [18] is an ongoing European project that aims to develop co-operative mobility solutions for *Platooning*, in order to enhance fuel efficiency and safety [36]. They intend to develop and validate a system that is able to form, create and manage platoons. In particular, they expect to create both off-board and on-board coordination and interface solutions and analyze the legislative conditions of *Platooning*. Finally, the last objective is to demonstrate the validity of the system in proper tracks and through simulation.
Interoperable Grand Cooperative Driving Challenge AutoMation Experience (iGAME) [**?**] is an ongoing European project that aims to speed real-life implementation and interoperability of automated driving via wireless com-

munication. Its goals is to design a functional architecture and requirements for automated driving, and demonstrating its validity in a multi-vendor challenge. Additionally, they aim to create a control system, an interaction protocol for cooperative applications, tools used for validation and verification, and to standardize interaction messages. The project also specifies scenarios and the needed requirements (functional, communication, etc.).

SARTRE [17] is a project funded by the European Commission that aimed to develop *Platooning* solutions, with significant environmental, safety and comfort benefits. SARTRE defines *Platooning* as a set of vehicles driving together with a lead vehicle (driven by a professional) and several followers fully automatically, with short gaps between them. The project investigated the human and safety factors of *Platooning*. To prove the concept, they developed a system with a lead truck, a following truck, and 3 following cars. Additionally they developed a solution to help vehicles find and join a suitable platoon, but this solution was not integrated in the system. The system was tested on specific tracks in order to measure the fuel consumption benefits. Finally, they studied the commercial viability of the product, infrastructure and environmental concerns, and defined recommended policies to achieve a wider impact.

Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates (COLOMBO) project [37] aimed to overcome the problem of most cooperative systems requiring high penetration rates of equipped vehicles for their functionality to be assured. The project's main goal was to design traffic management components that enable the correct functioning of the system with penetration rates below 10%. The key objectives were to decrease costs and vehicular emissions. The researchers focused on two topics: traffic surveillance (determine the traffic state by collecting data from V2X messages) and traffic light control algorithms (making traffic lights adjust according to the traffic state). As part of the results, the project concludes that the self-organizing traffic control algorithm performs well even with very low penetration rates (1%), based on the metrics of waiting time, number of stops per vehicle in intersections and the emission levels. Additionally, they made available and public a series of open source software and simulation

scenarios. In particular, they developed extension for commonly used tools such as iTETRIS, SUMO, ns-3 and the Passenger Cars and Heavy Duty Emissions Model (PHEM).
There are also other relatively relevant projects that deserve a mention, such as KONVOI [38], CHAUFFEUR II [39], Energy ITS [40], Mobile Opportunistic Traffic Offloading (MOTO) [41] or Partners for Advanced Transportation Technology (PATH) [42], but detailed descriptions have been omitted here.

2.3 Summary

This chapter presented an overview on related work regarding ITS applications (including advanced applications) and on important projects/consortium relative to the same field of study.
Most related literature that aims to analyze the behavior of a given application or solution (e.g. GLOSA, CACC, *Platooning*, etc.) tends to resort to simulation using frameworks such as VSimRTI and VEINS to evaluate their performance. However, there are several works that test the solutions in experimental environments, which potentially present more accurate results. Related work focus mostly on information and solutions related to CACC and *Platooning*, including full-system designs, communication performance analysis or even state of the art surveys.
The related projects focus on advanced applications, giving special emphasis to *Platooning*, which is currently a very hot topic in the research community.

Chapter 3

ITS Simulation

The development of efficient VANETs advanced systems or applications requires the determination of the main system properties and consequent evaluation of its performance. Performing field tests in vehicular environments is a tough challenge for a series of reasons. The large number of existent vehicles and traffic scenarios makes it very difficult to collect data in the experiments. Moreover, the development of real prototypes is usually very expensive and they take too much time to be prepared and processed. In other hand, resorting to simulations is a popular solution when it comes to evaluate the performance of transportation and communication systems. When using simulation tools, researchers are able to control parameters, configurations, conditions and input data, which are major advantages. Furthermore, tests can be easily accomplished and repeated, and using widely known tools does not require researchers to validate individual models, allowing them to focus only on developing solutions. Although both solutions (testbed and simulation) allow the study of the system, simulation is able to perform assessments in a larger scale. However, the simulation method normally assumes the use of simpler models, which may reduce the system realism - the accuracy of their implementation may affect the results veracity. In summary, simulating VANETs brings benefits in terms of cost, repeatability, scale and practical requirements. For this reason, researches tend to resort to simulation rather than field testing.

3.1 Simulation Tools

To perform a proper simulation of VANETs, both a traffic and a network simulator are required, although they may work independently. The aim of this section is to identify and describe the most widely used tools and frameworks when performing VANETs simulations. First, some important networks simulators are presented, followed by traffic simulators and finally also some important platforms/tools that integrate both traffic and networks simulators.

3.1.1 Network Simulation

Network simulation is one of the most prominent evaluation methods in computer networks. This method is commonly used for developing new communication protocols and architectures.
Network Simulator 3 (ns-3) [43] is a well-known discrete event simulator for communication networks that evolved from Network Simulator 2 (ns-2) [44]. This evolution brought several improvements such as scalability and memory usage - ns-3's design incorporated architectural concepts from Georgia Tech Network Simulator (GTNetS) [45], known for being a simulator with good scalability. ns-3 supports realistic models of wireless communications for cooperative ITS applications - it provides models to emulate radio propagation effects and functionalities and protocols for all layers of the *ITS-G5* stack.
The Objective Modular Network Testbed in C++ (OMNeT++) [46] open source tool is an extensible, component-based C++ discrete event network simulator, known for scaling well for large networks. Although not providing any specific components for computer network simulations, these models are developed independently - its user community has provided support mainly for standard wired and wireless IP networks. OMNet++ has two main frameworks that benefit from a specially designed propagation model for V2X: Mixed Simulator (MiXiM) [47] and *INET Framework* [48].
Java in Simulation Time (JiST) [49] is a discrete event simulation engine written in Java, that allows the simulation of real Java applications. Although allowing general purpose network simulation, it is commonly used

together with Scalable Wireless Ad-Hoc Network Simulator (SWANS) [49] - a highly scalable mobile ad hoc networks simulator, that is able to simulate scenarios of more than ten thousand nodes. Unfortunately, the official development of JiST is no longer mantained, and the latest version does not include neither mobility nor propagation models for VANETs.

3.1.2 Traffic Simulation

Traffic simulation tools emulate the traffic flow in transportation networks. Traditionally, traffic simulators can be classified as microscopic, macroscopic, and mesoscopic, depending on the granularity: microscopic simulators model traffic at a large scale, treating each entity (e.g. cars, trains) individually; macroscopic tools are used to model traffic at a large scale, treating traffic like a fluid; mesoscopic simulation combines the properties of both microscopic and macroscopic simulation models, describing the reality in terms of aggregated traffic platoons of vehicles characteristics, avoiding the time and complexity issues of implementing microscopic scenarios. However, VANETs scenarios required accurate models of communication between nodes and their exact position, which make both macroscopic and mesoscopic not so reliable solutions since they offer less detail when in comparison to microscopic simulations.
Simulation of Urban MObility (SUMO) [50] is an open source and highly portable microscopic simulator widely used for VANETs research and typically used to simulate automatic driving or traffic management strategies [51]. It possesses several features such as large road networks, collision free vehicle movement, different vehicle types, single-vehicle routing, multi-lane streets with lane changing, etc. Additionally, SUMO includes a visualizer that shows the road topology and nodes movement during the simulation runtime. It is possible to combine SUMO with OpenStreetMap (OSM) [52] and simulate traffic in any location in the world. Unfortunately, SUMO is a pure traffic generator, which means that the traces generated by the tool cannot be easily used by network simulators (in a direct way). The TraCI API existent in SUMO allows it to act as a server and connecting to an ex-

ternal application using a Transmission Control Protocol (TCP) socket.

MObility model generator for VEhicular networks (MOVE) [53] is a realistic mobility models generator that is built on top of SUMO. MOVE generates mobility traces with data from realistic vehicles movements that can later be used in other network simulators (e.g. ns-2). Additionally, MOVE provides a Graphical User Interface (GUI) that allows an easy way to generate scenarios.

Verkehr In Stadten SIMulationsmodell (VISSIM) [54] is a multi-modal microscopic, time-step and behavior-based traffic simulation tool. VISSIM is considered a leader in the field of micro-simulation software. It is a framework that provides a powerful GUI that allows users to define maps and scenarios, and the traffic conditions can be visualized in a very high level of detail. This tool implements a car-following traffic model that takes into consideration psychological aspects of drivers. Additionally, it also provides a pedestrian mobility model, which sometimes is useful in urban scenarios. It is able to analyze traffic under constraints such as lane configuration, speed limits, traffic signals, and so on. VISSIM allows the following types of traffic to be simulate: vehicles (cars and trucks), trams, buses, bicycles, motorcycles, pedestrians and even rickshaws.

VanetMobiSim [55] is an extension for the CANU Mobility Simulation Environment (CanuMobiSim) [56], a flexible framework that is used for modeling mobility. CanuMobiSim is able to generate trace files in different formats, supporting different mobility simulation software. *VanetMobiSim* provides vehicular mobility, with both microscopic and macroscopic realistic vehicular movement models. At macroscopic level, it supports multi-lanes, bidirectional flows, differentiated speed constraints and traffic signs. At microscopic level, *VanetMobiSim* implements V2V and V2I models that enable vehicles to regulate speed, overtake maneuvers and respecting traffic signs in intersections. *VanetMobiSim* mobility models have been validated by the well known Traffic Software Integrated System - Corridor Simulation (TSIS-CORSIM) [57] traffic generator.

3.1.3 Coupled Simulation

Although mobility and network simulators work in an independent way, there are some tools that allow their interconnection, which enables them to interact with each other. These systems are usually of type: i) isolated, ii) federated or iii) integrated. In i) isolated solutions, the mobility tool generates a trace file which is later processed by the network simulator. In ii) federated mode, the simulators communicate through a two-way interface: the network simulator controls the traffic simulator through commands and the traffic tool reports back information about the vehicles (e.g. position). In the iii) integrated mode, a single simulator handles both traffic and network simulation simultaneously.

Vehicles in Network Simulation (VEINS) [58] is an open source framework that provides a control interface between SUMO and OMNeT++ via TCP sockets. VEINS framework development was based on MiXiM. The communication between the simulators (network and mobility) is accomplished though the use of SUMO's TraCI. Both simulators are bidirectionally coupled and run in parallel, which means traffic has direct impact on network performance and vice versa. In this framework, the OMNeT++ simulator is directly extended - it is able to control and send commands to vehicles directly (e.g. orders to change speed or path). VEINS contains modules that implement the IEEE 802.11p standard and the higher layer of the DSRC stack.

Integrated Wireless and Traffic Platform for Real-Time Road Traffic Management Solutions (iTETRIS) [59] is an open source simulation platform developed under the European FP7 Program and it is characterized by a modular architecture that allows the integration of two widely used traffic and wireless simulators (SUMO and ns-3), and supports the implementation of cooperative ITS applications in various programming languages. iTETRIS implements a new central block called iTETRIS Control System (iCS). The iCS handles the SUMO and ns-3 interaction, in addition to preparing, triggering, coordinating and controlling the execution of simulations. The modularity of iTETRIS source code allows the coupled use of other open source

simulators, without having to modify their internal modules.
V2X Simulation Runtime Infrastructure (VSimRTI) [60] is a general framework for the evaluation of VANETs solutions that is able to couple different simulators each for a particular domain (networking and mobility). The VSimRTI modules are responsible for handling all the management tasks - time synchronization, interaction, communication, data exchange and so on. The integration of simulators is enabled by the implementation of generic VSimRTI interfaces. This framework provides also a simple network and a cellular communication simulator, a Java-based application simulator, and a battery simulator. Additionally, it provides visualizer and analysis tools. Furthermore, VSimRTI is being extended to enable the simulation of electric mobility environments.

3.2 Summary

The increasing popularity of VANETs lead the research community to develop accurate and realistic simulation tools for these environments. Given the fact that test fielding in VANETs is a tough challenge, researches resort to the use of simulation tools to evaluate the performance of applications, communication systems and so on.
This chapter reviewed some basic general aspects of *ITS* simulation and surveyed the most prominent tools available to perform network, traffic and coupled simulations. Regarding networking, the ns-3 and OMNeT++ are tools widely used and validated by the research community, while JiST development is no longer maintained. In traffic and mobility simulation, SUMO is a very popular solution that has proved its reliability and performance within the ITS community. Although not as strong as SUMO, *VanetMobiSim* is also often used for modeling mobility in VANETs. For these reasons, it is quite natural that most coupled frameworks tend to resort to the use of these powerful simulators, in order to render the simulation results as accurate as possible when comparing to real life.

Chapter 4

ITS Applications Taxonomy

Considering the availability of a wide range of applications (with their corresponding requirements), it is important for the research community to establish reference values for the requirements of each type of existing applications and use cases. This chapter presents an overview of the related work and a summary of the main aspects that build a taxonomy of applications. Furthermore, this chapter introduces a detailed description of the *Platooning* use case and presents the proposed Platooning Management Protocol (PMP).

4.1 Application Taxonomy

Regarding the related work of characterizing applications, Lèbre et al. [61] introduce concepts and specific vocabulary in order to classify current innovations or ideas on the emerging topic of smart cars. They organized the solutions according to their societal and scalable evolution.
Dar et al. [2] summarize the communication characteristics and features of typical applications from the three main types (*Safety*, *Efficiency* and *Comfort*). Additionally, they provide a mapping methodology that allows to select for each class of applications a suitable communication media.
Papadimitratos et al. [62] summarize the state-of-the-art solutions (available at the time) from a broad range of projects, and present a representative list of vehicle applications and their requirements. The applications

names are closely compatible with those used by projects such as *Car2Car Communication Consortium (C2C-CC)* [63], *SAFESPOT* [64] or *Cooperative Vehicle-Infrastructure Systems (CVIS)* [65]. Although their work illustrates requirements for different kinds of applications, the values are not proposed, but rather based on several technical reports, such as [66] or [4].

Sepulcre and Gozalvez [67] illustrate the importance of considering the requirements of cooperative applications when designing congestion control protocols. They demonstrate the application requirements impact on the communication settings of each vehicle and on the overall channel load.

Nekovee [68] specifies bounds for the maximum message delivery latency and reliability requirements of the V2V communication protocols for rear-end collision avoidance applications.

Karagiannis et al. [69] compile the safety use cases and their respective communication performance requirements from the main existent initiatives in US, Europe and Japan. Additionally, they establish relations between applications and the possible carriers based on their requirements.

Mahmod et al. [3] establish communication requirements for applications suggested for the *CVIS* and *SAFESPOT* projects, as well as general safety applications that are related to the applications from the *PReVENT* project (not existing anymore). To quantify the communication requirements the authors assigned values within a certain range: latency is classified as *very short* (VS - less than 100 ms), *short* (S - ms to one second), *medium* (M - seconds to one minute), and *long* (L - minutes); A *small* bandwidth (S) is often used for short safety messages, *medium* (M) for other traffic related information, and *high* (H) for multimedia services; Communication range can be *short* (S - up to 1000m), *medium* (M - few km) or *long* (L - several km); Reliability can assume the values of *high* (H - critical data), *medium* (M - non-critical data), and *low* (L - media data download); Priority is usually *high* (H) for information that requires immediate attention from the driver, *medium* (M - if it requires special attention but does not pose imminent danger) or *low* (L - e.g., commercial or entertainment information). Table 4.1 illustrates the summary of their work - in short, the characterization of the requirements for the applications introduced by the related projects.

Application	Information Transmission Control	Com. Mode	Addressing	Direction	Latency	Bandwidth	Range	Reliability	Priority
CVIS CURB: Flexible Lane Allocation	Event	V2I I2I I2C	P2P	Two-Way	M-L	M	M	M	M
CVIS CURB: Network Management	Time	V2I I2I I2C	P2P	Two-Way	M-L	M	M	M	M
CVIS CURB: Area Routing and Control	Event	V2I I2I	P2P	Two-Way	M	M	S-M	M	M
CVIS CURB: Local Traffic Control	Event	V2I I2I	P2P	Two-Way	S-M	M	S	M	M
CVIS CINT: Enhanced Driver Awareness	Event Time	V2V V2I I2I	P2MultiP	One-Way	M	M	S-M	M-H	M-H
CVIS CINT: Travelers Assistance	Event Time	V2I I2I I2C	P2P P2MultiP	One-Way Two-Way	M	M	M-L	M	M
CVIS CFF: Monitoring and Guidance of Dangerous Goods	Time	V2C	P2P	Two-Way	L	M	L	M	M
CVIS CFF: Parking Zone Management	Event	V2I I2C	P2P	Two-Way	L	M	S-L	M	M
CVIS CFF: Access Control to Sensitive Infrastructures	Event Time	V2I I2C	P2P	Two-Way	L	M	S-L	M	M
SAFESPOT - General Active Safety Applications	Event	V2V V2I	P2MultiP	One-Way	VS-S	S	S	H	H

Table 4.1: ITS applications and their communication requirements [3]

The **ETSI TR 102 638** standard [4] describes a Basic Set of Applications (BSA), focusing on V2V, V2I and I2V communications in the V2X dedicated frequency band (although it does not exclude the use of alternative technologies, such as cellular networks). The BSA was developed in conjunction with other European research projects such as *Car2Car* [63] and *EU PRE-DRIVE C2X* (information on the project now available on [70]). The document serves as a reference for developing standards for applications in the BSA and other ITS services. Each application/use case specification has taken into consideration several criteria, such as strategic requirements, system capabilities

requirements, legal requirements and so on. These specifications are the first step taken in order to deploy these standardized applications. ETSI defines four classes of applications: *Active road safety* (equivalent to *Safety* applications), *cooperative traffic efficiency* (identical to *Mobility* and *Efficiency* applications), *co-operative local services* and *global internet services* (correspondent to *Connectivity* and *Convenience* applications). *Co-operative local services* are provided from within the ITS network, while *global internet services* are obtained from providers in the wider internet. The BSA is illustrated in Table 4.2.
Annex C from the standard contains a catalog of V2X use cases on which the BSA was based. The catalog of applications and use cases represents only part of the nowadays existing solutions/proposals, since it was based on the state of the art at the time of publication. It provides knowledge on *latency*, *minimum frequency*, *messaging type*, *communication mode* and some other requirements for every use case. Table 4.3 sums up the information on the requirements for a few typical use cases from each class type. The table does not address all applications from the BSA to ease its reading and comprehension. Nonetheless, is contains all crucial information and the reference values for application classes.

The *CAR 2 CAR Communication Consortium Manifesto* document [5] introduces an overview of the *CAR 2 X Communication System*. It was designed based on a vast collection of use cases and their requirements. In addition to the description of these use cases (giving emphasis to its potential regarding safety, traffic efficiency, and comfort, and the benefits of V2V communication), this work also aggregates them into six types of applications, based on their security requirements and types of information exchange (e.g. the *Emergency Electronic Brake Lights* and *Approaching Emergency Vehicle Warning* use cases are part of *Vehicle 2 Vehicle Cooperative Awareness* applications). Table 4.4 states the general requirements for each existing type of application.

Application Class	Application	Use Case
Active road safety	Driving assistance - Co-operative awareness	Emergency vehicle warning
		Slow vehicle indication
		Intersection collision warning
		Motorcycle approaching indication
	Driving assistance - Road hazard warning	Emergency electronic brake lights
		Wrong way driving warning
		Stationary vehicle - accident
		Stationary vehicle - vehicle problem
		Traffic condition warning
		Signal violation warning
		Roadwork warning
		Collision risk warning
		Decentralized floating car data - Hazardous Location
		Decentralized floating car data - Precipitations
		Decentralized floating car data - Road adhesion
		Decentralized floating car data - Visibility
		Decentralized floating car data - Wind
Cooperative traffic efficiency	Speed management	Regulatory/contextual speed limits notification
		Traffic light optimal speed advisory
	Co-operative navigation	Traffic information and recommended itenerary
		Enhanced route guidance and navigation
		Limited access warning and detour notification
		In-vehicle signage
Co-operative local services	Location based services	Point of interest notification
		Automatic access control and parking management
		ITS local electronic commerce
		Media downloading
Global internet services	Communities services	Insurance and financial services
		Fleet management
	ITS station life cycle management	Vehicle software/data provisioning and update
		Vehicle and RSU data calibration

Table 4.2: BSA Definition [4]

Application Class	Application	Maximum Latency	Minimum Frequency	Messaging Type	Com. Mode	Other Requirements
Active Safety	Emergency Vehicle Warning	100 ms	10 Hz	Periodic Triggered	V2V	
	Slow Vehicle Warning	100 ms	2 Hz	Periodic Triggered	V2V	
	Emergency Electronic Break Lights	100 ms	10 Hz	Time-limited Broadcast	V2V	
	Stationary Vehicle Warning	100 ms	10 Hz	Time-limited Broadcast	V2V	
	Traffic Condition Warning		1 Hz	Time-limited Broadcast	V2V	
	Roadwork Warning	100 ms	2 Hz	Time-limited Broadcast	I2V	
	Collision Risk Warning from RSU	100 ms	10 Hz	Time-limited Broadcast Event	I2V	
	Decentralized Floating Car Data		1 to 10 Hz	Time-limited Broadcast Event	V2V	
Traffic	Regulatory Speed Limits	100 ms	1 to 10 Hz	Periodic Broadcast	I2V	
	Traffic Light Optimal Speed Advisory	100 ms	2 Hz	Periodic Broadcast	I2V	Minimum positioning accuracy: better than 5m
	Traffic Information and Recommended Itinerary	500 ms	1 to 10 Hz	Periodic Broadcast	I2V	
	Enhanced Route Guidance and Navigation	500 ms	1 Hz	On-Demand	I2V	Internet access: IPv6 is required
	Limited Access Warning, Detour Notification	500 ms	1 to 10 Hz	Periodic Broadcast	I2V	
Comfort	Point of Interest Notification	500 ms	1 Hz	Periodic Broadcast	I2V	Internet access: IPv6 is required
	Media Downloading	500 ms	1 Hz	On-Demand	I2V	Internet access: IPv6 is required
	Insurance and Financial Services	500 ms	1 Hz	On-Demand	I2V	Internet access: IPv6 is required
	Vehicle Software Data Provisioning and Update	500 ms	1 Hz	On-Demand	I2V	Internet access: IPv6 is required

Table 4.3: Requirements of ITS use cases [4]

Typical *active road safety* applications coverage distances go from 300 meters to 20 kilometers. *Traffic efficiency and management applications* vary from 300 meters to 5 kilometers if they manage speed, or between 0 meters and 1000 meters if they are of co-operative navigation type. *Comfort* applications have a coverage distance from 0 m to full communication range, depending on the use case.

Application	Communication Type	Communication Range	Roadside Units	Security
V2V Cooperative Awareness	Broadcast Geocast	300 m to 1 km	N/A	V2V Trust
V2V Unicast Exchange	Unicast	0 m to 5 km	N/A	V2V Trust
V2V Decentralized Environmental Notification	Broadcast Geocast	300 m to 20 km	Not required but can aid applications	Originator Trust
I2V (One-way)	Broadcast Geocast	300 m to 5 km	Required	Vehicle must trust RSU
Local RSU Connection	Unicast	0 m to 1 km	Required	RSU/OBU must trust each other
Internet Protocol RSU Connection	Unicast	0 m to full radio range. Can be extended by Multihop	Required	Internet Security (IPsec, application layer security)

Table 4.4: General requirements for applications [5]

The match between the BSA and the types defined by [5] is illustrated in Table 4.5. Although the applications from the *V2V unicast exchange* type do not belong to the BSA, they are represented for illustrative purposes. *Collision Risk Warning* can be either of type *V2V Cooperative Awareness* or *V2V Decentralized Environmental Notification*, depending on the use case. Table 4.6 summarizes the minimum requisites for the application types defined before. The most strict applications in terms of *safety* have a maximum *latency* of 100 ms and a minimum *frequency* range between 2 and 10 Hz, with *ranges* between 300m and 1km. Despite being slightly more relaxed and flexible in terms of *latency* and *range*, *soft safety* applications have similar requirements to *hard safety* applications and their differences are not very significant. *Traffic efficiency* applications can tolerate higher *latencies* (usually 500 ms, with some exceptions) and have higher *ranges* - can go up to tens of kilometers, depending on the access technology being used. Finally, *comfort* applications are typically characterized for having a maximum *latency* of 500 ms, minimum *frequencies* of 1 Hz and covering full radio range.

Type	Applications
V2V Cooperative Awareness	Emergency vehicle warning Intersection collision warning Motorcycle approaching indication Emergency electronic brake lights Wrong way driving warning Collision risk warning
V2V Unicast Exchange	Pre-Crash Sensing/Warning V2V Merging Assistance Cooperative Vehicle-Highway Automation System (Platoon) Instant Messaging
V2V Decentralized Environmental Notification	Slow vehicle indication Stationary vehicle Traffic condition warning Collision risk warning Decentralized floating car data
I2V (One-way)	Regulatory / contextual speed limits notification Traffic light optimal speed advisory Limited access warning and detour notification In-vehicle signage Signal violation warning Roadwork warning
Local RSU Connection	Traffic information and recommended itinerary Point of Interest notification Automatic access control and parking management ITS local electronic commerce Loading zone management Vehicle software / data provisioning and update
Internet Protocol RSU Connection	Enhanced route guidance and navigation Media downloading Insurance and financial services Fleet management Vehicle and RSU data calibration

Table 4.5: ETSI applications according to CAR2CAR classification

Applications		Maximum Latency	Minimum Frequency	Range
Safety	Hard-Safety	100 ms	2 Hz to 10 Hz	300 m to 1 km
	Soft-Safety	100 ms	1 Hz to 10 Hz	300 m to 20 km
Traffic Efficiency		100 ms to 500 ms	1 Hz to 10 Hz	Full radio range
Comfort		500 ms	1 Hz	Full radio range

Table 4.6: Applications Requirements Summary

Communication technologies for ITS applications

Dar et al. [2] present a mapping between ITS applications categories and potential communication technologies. DSRC (sometimes it is also referred as WAVE also) is a typical communication technology that is used by *safety* and *efficiency* applications - particularly when applications demand V2V and/or V2I direct communication with a range within 1 km. *Cellular* and *WiMAX (Worldwide Interoperability for Microwave Access)* technologies can be considered in V2I or I2I cases, where a long range communication is required. *Cellular* technologies (e.g. *3G* or *4G*) are a good fit for *Internet* access (if medium data rates are acceptable) and they have the advantage of already possessing infrastructures that are provided by network operators. On the other hand, *WiMAX* can also provide users with high speed *Internet* access - however, it requires the installations of *WiMAX* base stations. The *DVB/DAB (Digital Video Broadcasting/Digital Audio Broadcasting)* technologies have potential to be used within specific ITS applications for broadcasting purposes (such as *traffic management* and *road condition monitoring* applications). *DVB-H (Digital Video Broadcasting - Handheld)* can also be considered to be used in broadcasting audio/video programs for infotainment. *MMWAVE (millimeter wave)* can be employed as a high speed air interface for devices that are within vehicles. Table 4.7 complements the mapping between applications and recommended carriers.

Applications	ITS Application Category	Recommended Carriers
Safety	Collision Avoidance	DSRC/WAVE
	Road Sign Notifications	DSRC/WAVE, CALM, Li-Fi
	Incident Management	DSRC/WAVE, Cellular Networks
Efficiency	Traffic Management	DSRC, WiMax, Cellular Networks
	Road Monitoring	DSRC/WAVE, Cellular Networks, Li-Fi, ZigBee
Comfort	Entertainment	DSRC/WAVE, Cellular Networks, Li-Fi, ZigBee, WiMax, Bluetooth
	Contextual Information	DSRC/WAVE, Cellular Networks, Li-Fi

Table 4.7: Potential Wireless Communication Technologies for ITS Applications

4.2 Platooning Use Case

The *Platooning* application, introduced before on advanced ITS applications section 1.1.3, is a solution that allows vehicles to travel very close to each other in groups (*platoon*) with automated velocity and steering control. Driving in *platoon* with automatic control enables the enhancement of safety, traffic flow and highway capacities, while also providing drivers with a more convenient and comfortable driving experience. Furthermore, it helps to save energy and fuel, while reducing emissions [71–74]. Figure 4.1 illustrates an example platoon of vehicles in an highway, identified in between the red frames.

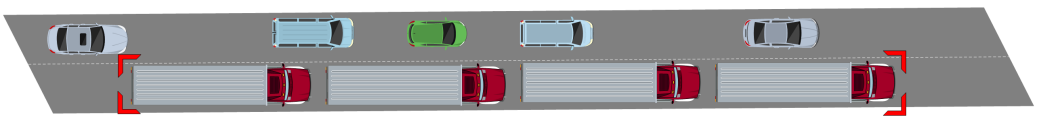


Figure 4.1: Platoon of vehicles

The simplest way of implementing *Platooning* is through the use of V2V communication, where vehicles only share information with their immediate predecessor. In these systems, vehicles receive notifications from the preceding vehicles (about acceleration changes, breaking values, etc.) within constant intervals (typically, with an update frequency of 10Hz), allowing them to respond accordingly - adjusting their speed and position, and so on. However, there is a major issue regarding communication delay since the delay values accumulate from vehicle to vehicle until the last group follower receives the message. More advanced solutions disseminate information not only about the preceding vehicles but also from vehicles that are not in line of sight, providing the driver with situational awareness feedback to understand the status of his vehicle and the whole group. When vehicles possess group information in advance (sent by the group leader), they can predict the behavior of vehicles in front, which helps to stabilize the platoon - similarly to real world defensive drivers paying close attention to road to predict what might happen. Another way of overcoming the lack of visibility from the drivers is by providing a video stream from the front group leader view, but this solution is not as strong as the cooperative exchange of information. The implementation of *Platooning* systems can either be resorting to infrastructures (V2I communication) or not. Although V2V communication is often the choice for highway environments, V2I communication seems to bring more benefits on urban areas, where RSUs and TMCs provide information such as recommended speeds to vehicles.

Despite *Platooning* being a different application from CACC, there are a lot of improvements and results from previous research that are useful and can easily be moved and applied on *Platooning* as well. Since CACC and *Platooning* share the same concerns on distance gaps, one should take into account the results from several works such as Nowakowski et al. [75], which state that drivers are generally comfortable with short following time gaps (about 0.6 seconds) when using CACC, which results an increased highway capacity. The work from Shladover et al. [76] also shows that by using short following gaps in CACC systems, the lane capacity can be increased from around 2000 vehicles per hour to about 4000 vehicles, when moving from zero to one hun-

dred percent market penetration. Ploeg et al. [77] analyzed the properties of string-stability in CACC and concluded that time gaps below one second are possible. The ideal time gap value was of 0.7 seconds, although it is possible to reduce the gaps down to 0.3 seconds (when minimizing the latency of the communication).
Another main concern in *Platooning* is the size of the chain (usually named as *string* in CACC systems), for reasons such as security or performance. Although being possible to establish the maximum length of the chain as the distance between the first and last vehicle, it is typically defined as the maximum number of vehicles. The first studies [78] claimed the ideal size to be around 20 vehicles but, a more recent study [79] from the SARTRE project advises the maximum platoon size to be 15.

4.3 Platooning Management Protocol

Platooning is an application that has the potential to bring several benefits, but it requires a very efficient Platooning Management Protocol (PMP) that specifies all the required maneuvers and proper communication behaviors, so that a good vehicle's cooperation performance is achieved. The following section describes the proposed PMP, including a full description of the maneuvers and also the specification of the requirements based on European standards.

4.3.1 Maneuvers

This subsection presents the main assumptions regarding the PMP maneuvers as well as their complete description.

Create

The *Create* maneuver starts when a given vehicles tries to join a platoon but there are no available strings around him (may be non-existent or already have the maximum number of vehicles permitted). Hence, the *Create* maneuver results from a previous failed *Join* maneuver (described in detail

ahead). A vehicle may create a new platoon if it possess a special license that allows him to do so. The process of creating a platoon is listed below:

1. *Leader* vehicle starts a new *Platoon* (*ID=CarName_PlatoonNumber*).
2. *Leader* vehicle propagates the *Platoon* existence, broadcasting the ID every second.

Figure 4.2 illustrates this use case.

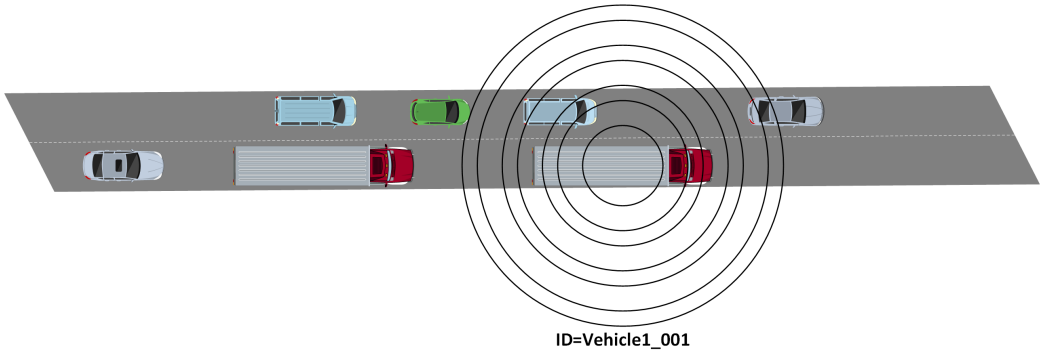


Figure 4.2: *Create* maneuver

Join

The *Join* maneuver is triggered when a vehicle wants to join a *platoon*. In this solution, the platoon choice is automatic, although the driver may be able to choose one of its preference in a real world application. An important aspect of the *Join* maneuver is the string ordering. The simplest solution of all is to make vehicles join the *platoon* tail. In contrast, joining the *platoon* at the front of the string is harder, since it assumes a change of rolls in the string (a new *Leader* is chosen). Allowing vehicles to join the platoon in any position, enables the vehicle's string to be ordered by one of several parameters: engine, weight or braking performance, aerodynamics, distance to be traveled, and so on. In this cases, vehicles open a gap that allows the joining vehicle to merge to the correct lane. This solution is more challenging, since it requires more coordination between several vehicles. Joining the string becomes even more difficult when traffic is dense and there are vehicles

traveling close to the *platoon*. If the maneuver cannot be completed safely, it is aborted. A vehicles is able to join a *platoon* if the string does not exceed its maximum length and if no other maneuver is occurring. Additionally, there may exist several other requirements that the vehicles must fulfill (e.g. vehicles must meet the platoon velocity).
The process of joining a *platoon* is listed below:

1. *Joiner* sends a *Join Request* (broadcasted every second) until it finds an available *Platoon* or *Time Out* is exceed.

2. *Leader* responds with a *Join Acknowledgment* if it's possible for the vehicle to join. Otherwise, it responds with a *Join Reject* and the maneuver is aborted.

3. *Joiner* moves to the correct position in order to merge to correct lane and informs the *Leader* with a *Distance Achieved* message.

4. *Leader* notifies the *Followers* to open up a gap, with a *Adjust Gap* message, unless the *Joiner* is joining in the rear of the *platoon*.

5. *Followers* notify the *Leader* when the adjusting process is completed with *Adjust Gap Acknowledgment*s.

6. *Leader* sends a *Start Maneuver* message, informing the *Join Follower* that the maneuver can be accomplished.

7. *Joiner* merges to the correct lane and enters automatic mode, notifying the *Leader* with a *Maneuver Completed* message.

8. *Leader* sends a *Platoon Update* message for all *Followers* with updated information.

Figures 4.3 to 4.6 illustrate the *Join* maneuver.

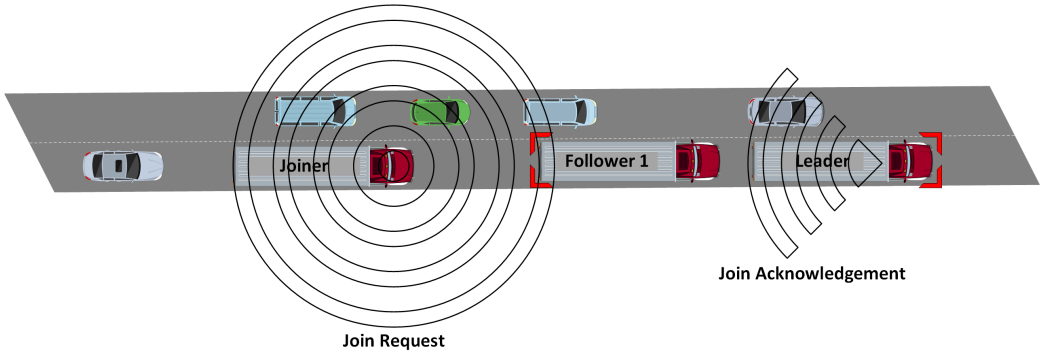


Figure 4.3: *Join* maneuver - Steps 1 and 2

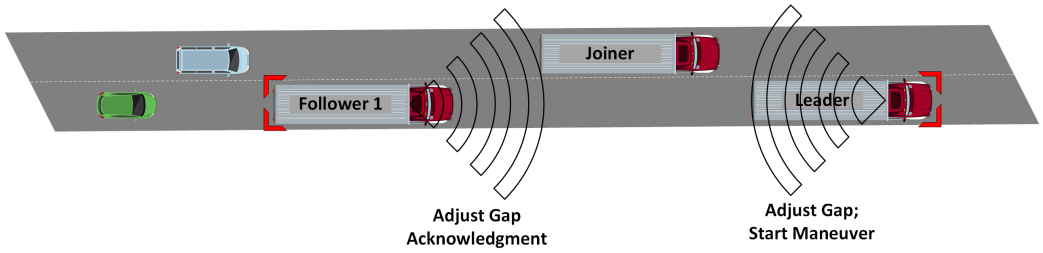


Figure 4.4: *Join* maneuver - Step 3 to 6

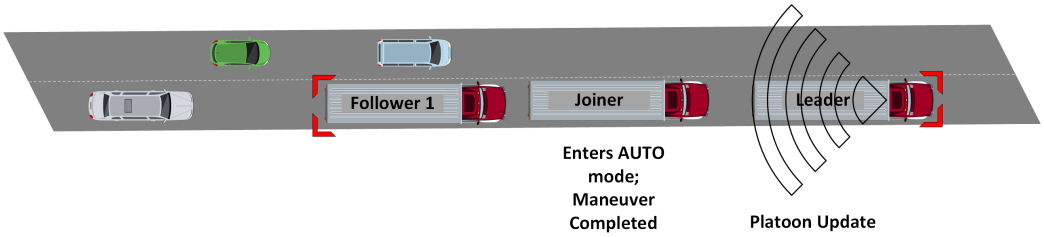


Figure 4.5: *Join* maneuver - Step 7 and 8

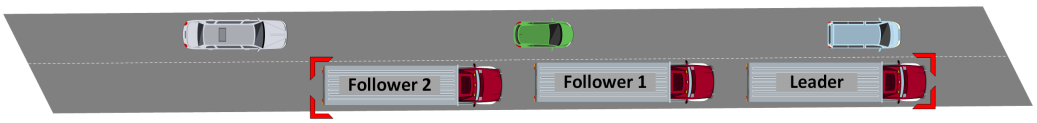


Figure 4.6: *Join* maneuver - Final state

Dissolve

The *Dissolve* maneuver happens when the *Leader* decides to disassemble the string. This may happen for several reasons: For example, the *Leader* may leave the *platoon*, there are obstacles on the road ahead or all vehicles left the

platoon. The *Leader* may only follow manual driving mode after all *Followers* acknowledge the command to leave the string. The steps of the use case are described below and illustrated on Figures 4.7 to 4.10:

1. *Leader* sends a *Dissolve Request*.
2. *Followers* enter manual driving mode and send back a *Dissolve Acknowledgment* to the *Leader*.
3. When all *Followers* respond (if any), the *Leader* enters manual driving mode and dissolves the *platoon*. Additionally, it stops broadcasting its existence.

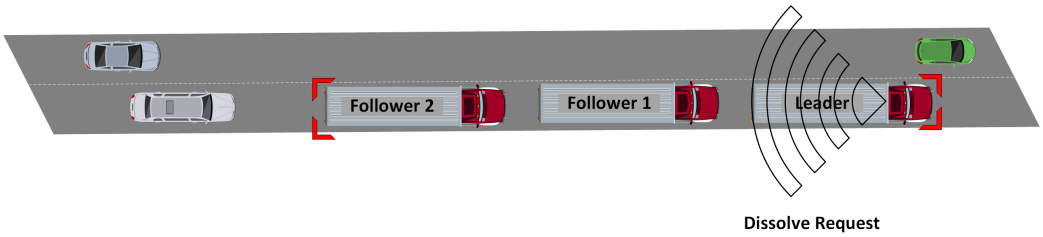


Figure 4.7: *Dissolve* maneuver - Step 1

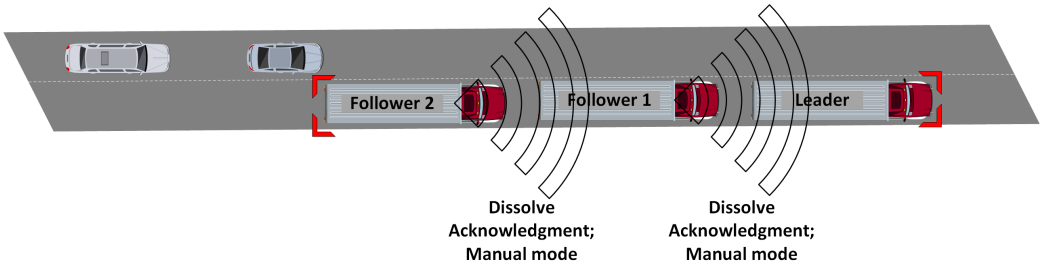


Figure 4.8: *Dissolve* maneuver - Step 2

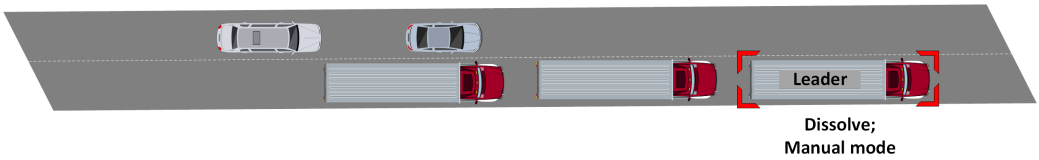


Figure 4.9: *Dissolve* maneuver - Step 3

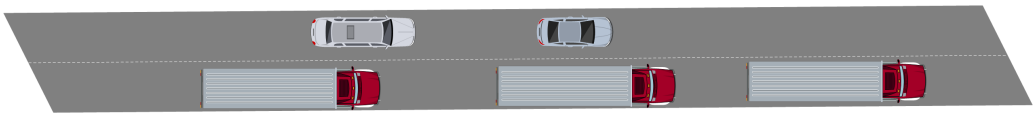


Figure 4.10: *Dissolve* maneuver - Final State

Leave

The *Leave* maneuver is initiated when a given *Follower* needs to exit the platoon (e.g. reaching its destination). It informs the *Leader* about its decision and then awaits for its response, in order to assume manual control and change lane. Due to complexity of the maneuver, only one vehicle may leave the platoon at a time. The maneuver steps are detailed below and in Figures 4.11 to 4.15.

1. *Follower* sends a *Leave Request*.
2. *Leader* computes the new gap distances for *Followers*, informing them with *Adjust Gap* message.
3. *Followers* acknowledge new distances, resorting to *Adjust Gap Acknowledgment* messages.
4. *Leader* returns a *Start Maneuver* message for the *Leaver*.
5. *Leaver* shifts to manual driving and changes lane.
6. *Leaver* notifies the *platoon Leader* with a *Maneuver Completed* message.
7. *Leader* notifies *Followers* with a *Platoon Update* message.

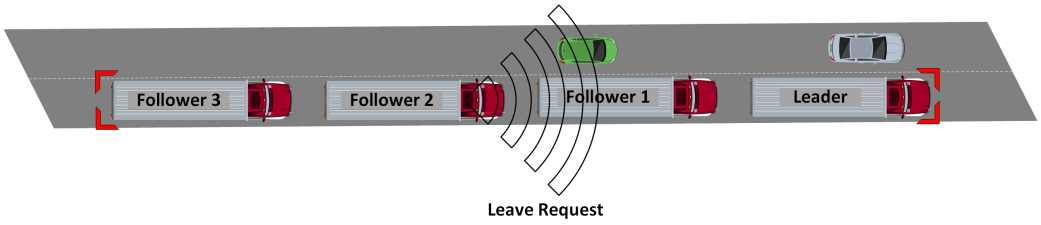


Figure 4.11: *Leave* maneuver - Step 1

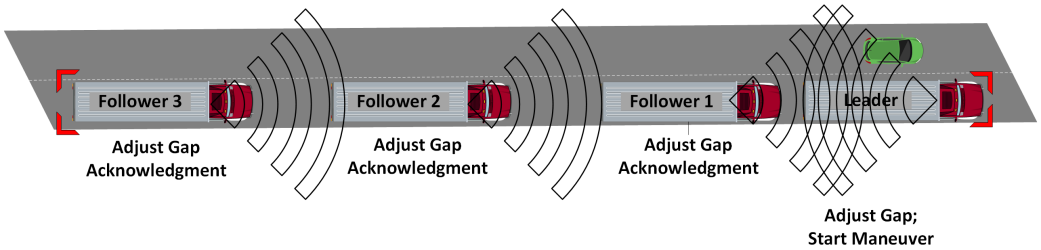


Figure 4.12: *Leave* maneuver - Steps 2 to 4

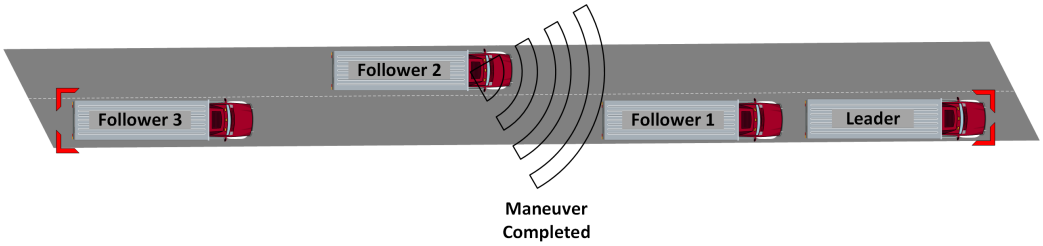


Figure 4.13: *Leave* maneuver - Step 5 and 6

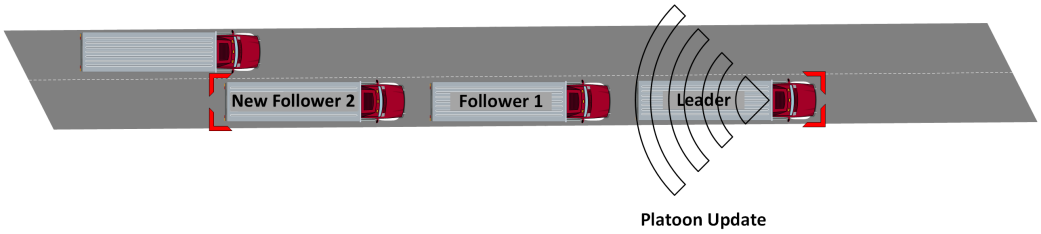


Figure 4.14: *Leave* maneuver - Step 7

Merge

The *Merge* maneuver consists on the process of joining two *platoons* that are traveling on the same lane. This maneuver is only possible if the size of the two *platoons* combined is less that the maximum length allowed. Typically,

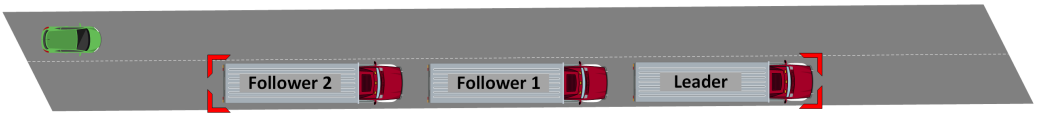


Figure 4.15: *Leave* maneuver - Final State

the process is initiated by the *Leader* of the rear *platoon* and the front *platoon* leader decides whether to accept or reject the request (in case of exceeding the maximum length or if the front *platoon* is performing another maneuver, which makes the *Merge* process not possible). The following steps and Figures 4.16 to 4.20 show how the *Merge* maneuver is performed. To ease the reading, the front *Leader* and *platoon* are refered as *Leader A* and *platoon A*, while the rear *Leader* and *platoon* are referred as *Leader B* and *platoon B*.

1. *Leaders* (both A and B) send *Merge Requests* through broadcast every 10 seconds.

2. *Leader A* receives the request and responds with a *Merge Acknowledgment*.

3. *Leaders* exchange *Platoon Info* messages with information to determine the new *platoon*.

4. *Leader B* sends a *Adjust Gap* message to *Leader A*.

5. *Leader B* moves *platoon B* to the rear of *platoon A*.

6. *Leader A* acknowledges the notification with a *Adjust Gap Acknowledgment* message.

7. *Leader B* sends a *New Leader* message to its *Followers*.

8. *Leader B* assumes a *Follower* role.

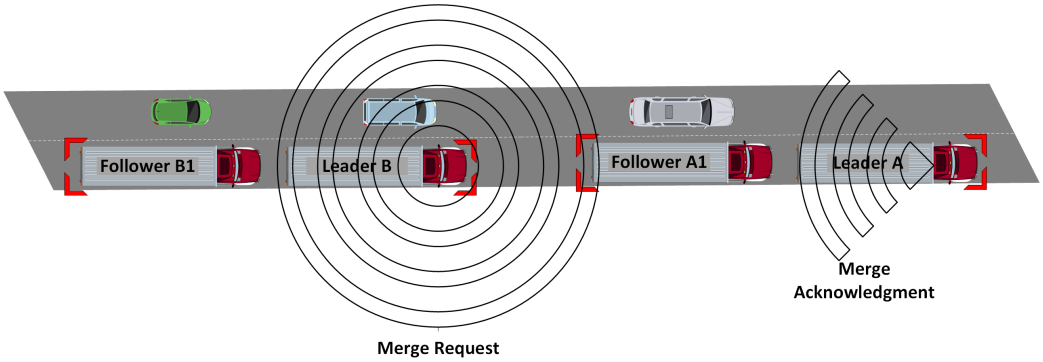


Figure 4.16: *Merge* maneuver - Steps 1 and 2

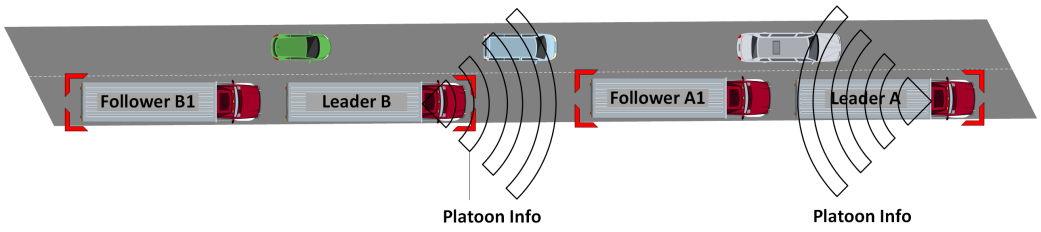


Figure 4.17: *Merge* maneuver - Step 3

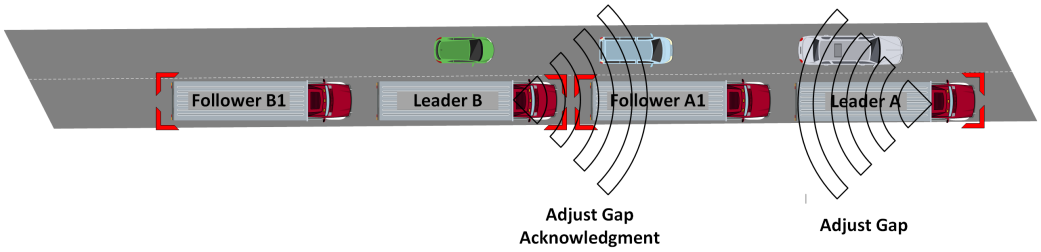


Figure 4.18: *Merge* maneuver - Steps 4 to 6

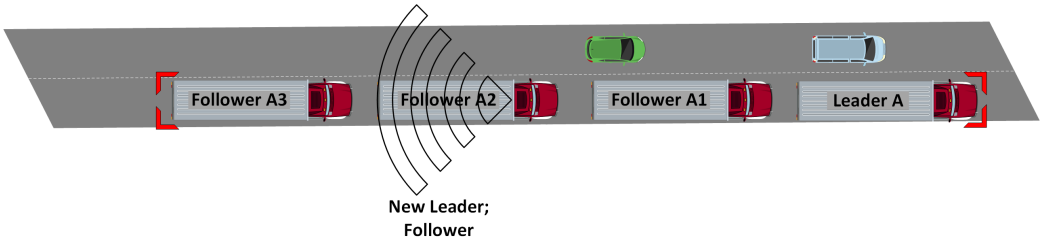


Figure 4.19: *Merge* maneuver - Steps 7 and 8

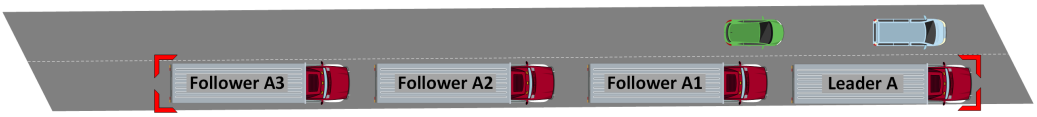


Figure 4.20: *Merge* maneuver - Final State

4.3.2 Platooning Requirements

This subsection defines the most important functional and communication requirements for the *platooning* application. The requirements are split for each maneuver existent. The requirements were essentially based on the ETSI **TR 102 638** standard [4], which provides the main requirements for a *Co-operative vehicle-highway automation system (Platoon)* use case. This standard defines that vehicles should be able to *broadcast* V2X Cooperative Awareness Message (CAM) messages and to establish *unicast* connections with other vehicles. The maximum *latency* should be of *100 ms*, the minimum *frequency* of messages should have at least a value of *2 Hz* and the vehicles relative *positioning accuracy* should be better than *2 m*. Hence, as general requirements, the *latency* was defined to have a maximum value of *100 ms*, the *communication range* should able to reach 1 km and the relative *position accuracy* should be equal or better than *1 m*. Additionally, it is defined that the *authenticity* of the V2X messages should be verified. Some of the parameters were slightly adjusted depending on the maneuver and the information exchanged, since the events in the *platoon* don't have all the same level of demand. The requirements are presented on Table 4.8.

Requirements					
Use Case	**Create**	**Join**	**Dissolve**	**Leave**	**Merge**
Communication Type	V2V	V2V	V2V	V2V	V2V
Messaging Type	Periodic Broadcast over short period	Periodic Broadcast over short period; Event-Triggered	Event-Triggered	Event-triggered	Periodic Broadcast; Event-Triggered
Message Period	Every second	Every second	-	-	Every ten seconds
Direction	One-Way; Point to Multi-Point	Two-Way; Point to Point; Point to Multi-Point	Two-Way; Point to Point; Point to Multi-Point	Two-Way; Point to Point; Point to Multi-Point	One-Way; Two-Way; Point to Point; Point to Multi-Point
Transmission Mode	Broadcast	Broadcast; Unicast; Geocast	Geocast; Unicast	Geocast; Unicast	Broadcast; Unicast; Geocast;
Frequency	1 Hz	10 Hz	10 Hz	10 Hz	0.1 Hz; 10 Hz
Other Requirements	Driver is required to have a special license.	String size must not exceed its maximum length; No other maneuvers occuring.	Leader may only dissolve the string after all vehicles acknowledge they have moved.	Only one vehicle may leave the platoon at a time.	Size of the two Platoons is less than the maximum allowed.
General Requirements	See above				

Table 4.8: *Platoon* Maneuvers Requirements

The ETSI **TS 102 637-1** [80] introduces functional requirements for the BSA, also including requirements for communication scenarios and messages contents. Although not providing direct requirements for *Platooning* (since it is not part of the **BSA**), some of the requirements from the *driving assistance - co-operative awareness* application are perfectly applicable in the *platooning* scenario, since the environments share similar characteristics, namely the type of information exchanged and the fact that they do not resort to *RSU*s to communicate. This application includes the *Emergency Vehicle Warning*, *Slow Vehicle Indication*, *Intersection Collision Warning* and *Motorcycle Approaching Indication* use cases. Below is provided a functional requirements list for this application (extracted from the standard):

- An ITS station shall announce its presence to its vicinity;
- An ITS station shall broadcasts its position, speed and moving direction to its vicinity;
- A vehicle ITS station shall broadcast its basic dynamics and status information to its vicinity;

- CAM shall provide the position information with a confidence level that is sufficient for the all use cases of the BSA;
- Vehicle ITS station shall have access to the in vehicle system to obtain the required information for the CAM construction. A receiving ITS station should update the position of the sending ITS station;
- Information included in CAM shall allow receiving ITS station to estimate the relevance of the information and the risk level;
- An ITS station shall be able to modify the sending interval of two consecutive CAMs;
- CAM shall be set with high priority for transmission;
- ITS station shall provide one hop broadcasting functionality for CAM.

The standard defines that *driving assistance co-operative awareness* should use broadcasted CAMs (transmission process defined in [81]) and resort to Decentralized Environmental Notification Message (DENM)s if the use case requires so, in order to provide more information on the situation. When receiving messages, the ITS *station* evaluates the relevance of the situation and should provide the information to the driver via Human-Machine Interface (HMI). [82] defines specifications for the *Cooperative Awareness* basic service, including the definition of the syntax and semantics for CAM messages (including message handling). [83] defines similar specifications for DENM messages.

Chapter 5

Simulation Deployment

This chapter details the process of deploying the Platooning Management Protocol (PMP) in a simulation environment. First, the deployment decisions are discussed, regarding the simulation tools and the application implementation choices. Finally, the simulation scenario is presented and discussed.

5.1 Deployment Decisions

The first step towards deployment is the choice of the simulation tool(s). Among all solutions to simulate VANETs, the most complete and realistic way is through the use of coupled simulators, since they integrate both mobility and network simulation tools in a transparent way to the user. According to [84], iTETRIS, VEINS and VSimRTI are strong solutions and there is no clear winner, since they all cover the required aspects for VANETs simulation.

Despite iTETRIS potential, there are some drawbacks to the use of this framework for developing ITS applications. Since iTETRIS project finished on 2011, there is not available any community or technical support, with exception to a brief and incomplete document with installation and application development guidelines. The lack of documentation, together with the language-agnostic design makes it very difficult to understand how the applications should be build and implemented. Furthermore, the project's

virtual machine was built to communicate with an old *ns-3.7* version, which now contains deprecated IEEE 802.11p code (fundamental for a proper study of any ITS system), according to the *CHANGES.html* file available with the *ns-3.18* version - this release started to implement new IEEE 802.11p code introduced in [85]. Since the iTetris code is not in the ns-3 main branch, the evolution of other models is not included in it, causing issues. This problem is also mentioned in MOTO project [86]. Additionally, some users [87] state that they have issues installing iTETRIS on recent versions of *Linux Ubuntu*. The use of older operating systems is often not advised, since they usually lack support, have problems with recent hardware and so on.

For the reasons presented before, VEINS and VSimRTI seem to be more reliable solutions in comparison to iTETRIS. VEINS simulator already includes a platooning module denominated as *PLEXE: A Platooning Extension for Veins* [28]. However, due to the uncertainty about the flexibility and adaptability of the implemented *PLEXE* protocols in VEINS and the fact that VSimRTI resorts to the Java programming language (which on a personal level eases the development of applications, due to previous background and expertise), the choice falls for the latter. To simulate transportation, including mobility, transit policies, vehicles emissions and even fuel consumption, the choice is SUMO tool, since it is able to support detailed representations of large scale traffic scenarios. To support accurate and realistic simulation of communication for cooperative ITS systems, the choice is ns-3, since it includes all models to reproduce functionalities and protocols for the ITS communications stack.

According to [88], a very suitable wireless technology available today to interconnect vehicles is *IEEE 802.11p*. It was specifically built for vehicular environments and it is able to support applications which are very strict in terms of requirements - such is the case of *platooning*. For this reasons, it was the technology chosen to allow communication between vehicles in the simulation scenario.

Although the advised size of the string is of 15 vehicles, as discussed before in section 4.2, two different sizes were defined for the two different *platoon* strings created in the simulation. *Platoon A* has a maximum string size of

15 and *platoon B* has a size of 3. This happens so that it is easier to test the cases where the string is already full: e.g. vehicles joining a fulfilled *platoon* and merge maneuvers cannot be performed (i.e. *Platoon A* cannot merge into *Platoon B*).

Platooning solutions tend to resort to constant time gap to determine the distance one vehicle should keep to its preceding vehicle in the *platoon*. However, the distance was decided to be constant and equal to 2 meters. This choice was based on the work of [29], which states that for homogeneous vehicles case (same acceleration and deceleration capabilities), the minimum gap was set to be 2 meters.

Vehicles running in the simulation can assume three roles: *Non-platoon*, *Leader* and *Follower*. To achieved this in the simulation, each vehicle reads a configuration file, in order to know which role it should assume. If a vehicle is of type *Leader*, it creates a new *platoon* and starts broadcasting its existence. If it is of type *Follower*, it starts searching for *platoons* in order to join one. Additionally, a given *Leader* may also assume a *Follower* role after a *Merge* operation is finished. If a vehicle leaves the *platoon*, it becomes a *Non-platoon* vehicle. When in a platoon, *Follower* vehicles are fully automatic, always following the instructions coming from the *Leader*. The "manual" driving behavior had to be forced in *SUMO* simulator, with constant commands to change speed, position and driving lane on the vehicles. The *Leader* is responsible for all communications within the *platoon* (centralized solution), and he is the only vehicle in the string that manages information on the *platoon* configuration and vehicles parameters.

This implementation follows a sufficient and simple approach where the *platoon ID* is fixed, which simplifies the data propagation. However, it has the drawback of not being able to adapt to a more dynamic environment in the real world, unlike solutions such as [89, 90] which resort to multicast-based communication.

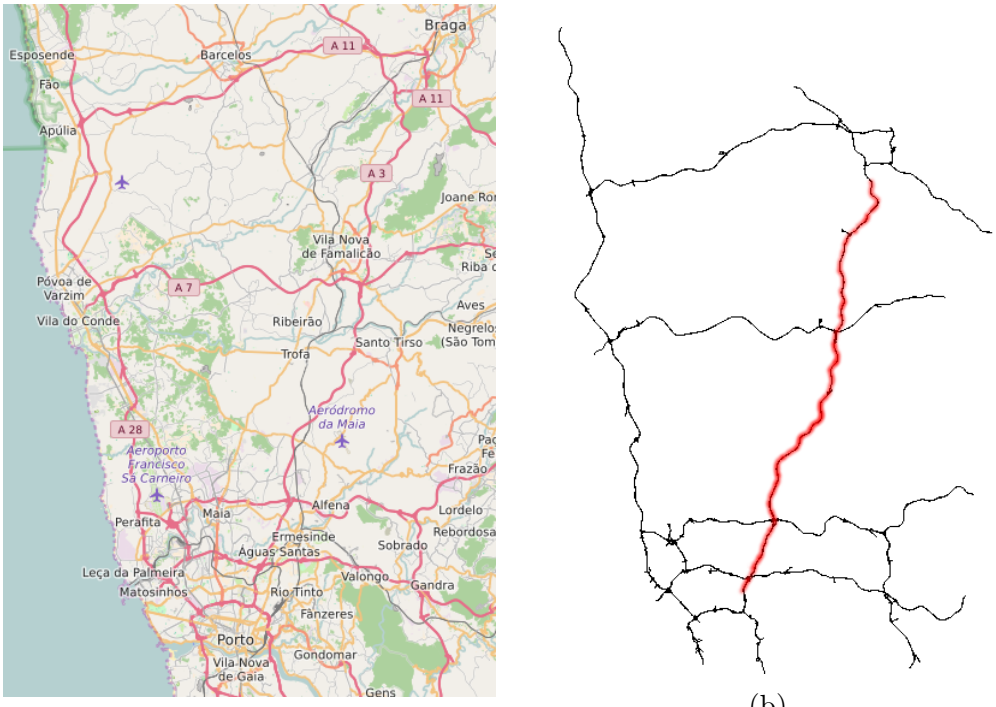
Another important aspect of this PMP is that maneuvers can happen at any point but only one maneuver is allowed at a time. Allowing more than one maneuver would make the management task extremely complex. Additionally, the right lane (*lane 0* in sumo) is only used for platooning, meaning that

non-platoon vehicles are not allowed to merge to the *platoon lane*. When vehicles leave the platoon, they move from *lane 0* to the left lane (*lane 1*).
Regarding the vehicle parameters (acceleration and deceleration values, vehicle length, etc.), it was hard to find evidence of any reliable example values on related work that was useful for this simulation. For this reason, the defined parameters were obtained from the SUMO proposal [91].
Finally, and regarding security concerns, a basic and simple security mechanism for messaging exchanging was implemented for testing purposes. Although the [92] standard advises ITS messages (CAMs and DENMs) not to be encrypted, the non-standard application defined messages used in the simulation are all signed and encrypted, since it is considered that the information contained on the payload is sensitive. In this scenario, the vehicles are statically assigned one public key pair and one symmetric key and all public keys are pre-shared between the vehicles. The symmetric cipher algorithm used was Advanced Encryption Standard (AES) with a 128 bits key and for public key scheme it was used a Rivest-Shamir-Adleman (RSA) key with 1024 bits. First, a hash is generated from the message payload, resorting to the Secure Hash Algorithm - 256 (SHA-256) algorithm. The hash is then signed using RSA. The final message consists of the signature and the AES encrypted message payload. This way, a receiver is able to check if the signature is valid, and if so, decrypt the rest of the message.

5.2 Simulation Scenario

This section presents the general steps taken in order to create the simulation scenario. At first, the chosen simulation scenario was the scenario provided in the *Tiergarten* to get in acquaintance with the VSimRTI framework. But since the map was from a city center, the path was short and did not allow to fully simulate the platooning application. Hence, a new map creation process was started.
The selected simulation area comprises the main highways that connect the Portuguese cities of *Braga* and *Porto*, obtained from a OSM map file [93]. The remaining roads (secondary, rural, etc.) were cropped out of the map

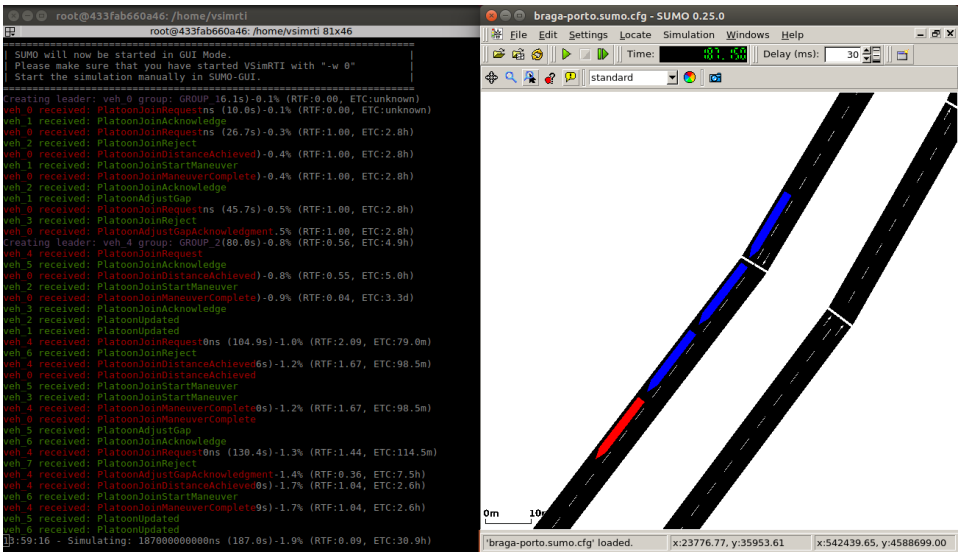
using the *osmosis* [94] tool (also made available by OSM). The data was then processed by VSimRTI's *scenario-convert* tool, which generates a navigation database and the appropriate SUMO files. This tool allows the generation of random routes, but since random routes do not meet the application needs, the routes were defined manually, by providing the tool with two geographic points. The obtained scenario map is illustrated on Figure 5.1 below. Figure 5.1a shows the real map from the scenario and Figure 5.1b the network of roads (highways) used in SUMO. The route used in the simulation is highlighted in red.



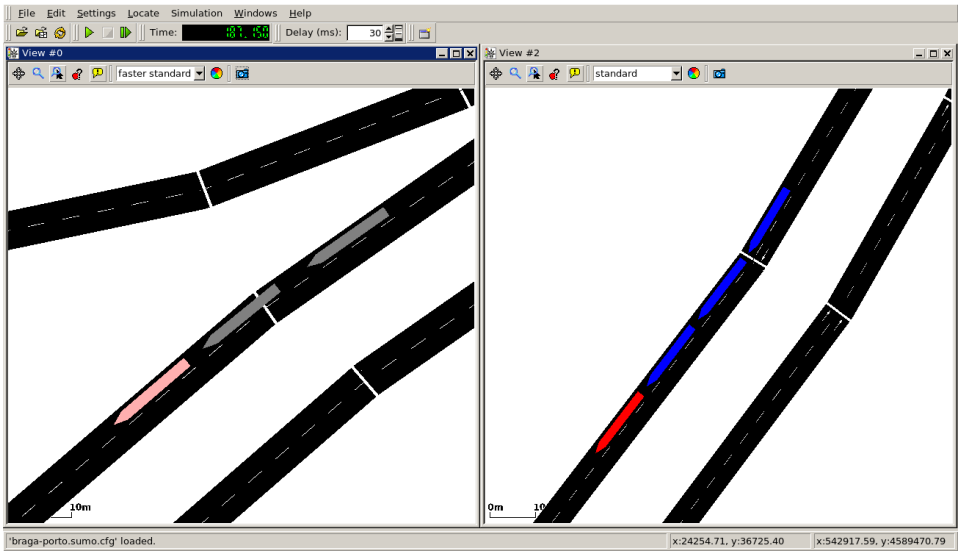
(a) (b)

Figure 5.1: Scenario Maps

Figure 5.2 below shows the working environment when running the simulations - the combined view of the log in the terminal with the SUMO simulator and the SUMO visualizer in detail.



(a) *Terminal log* and *SUMO* environment



(b) SUMO environment

Figure 5.2: Working Environment

Regarding the configuration files, the *vsimrti_config.xml* file was not modified in this scenario. This file provided in the framework contains general configurations for the VSimRTI platform itself. The SUMO configuration files were all generated automatically using the tools described before. The mapping configuration file (*mapping_config.json*) is used to define the number of vehicles of each type running in the simulation. In this case, the mapping is deterministic, which means that the mapped vehicles are the same in each simulation run. In this file, it is possible to define the values for the parameters illustrated below (configuration extracted from the file).

```
{
  "prototypes":[
  {
    "applications":["com.uminho.invovcar.platoon.apps.
       VehiclePlatoonApp"],
    "name":"PLATOON_VEHICLE",
    "accel":1.1,
    "decel":4.0,
    "length":16.50,
    "maxSpeed":36.11,
    "width=":2.55,
    "minGap":0,
    "sigma":0.1,
    "tau":0.05
  },
  {
    "applications":["com.uminho.invovcar.platoon.apps.
       VehiclePlatoonApp"],
    "name":"PLATOON_VEHICLE_2",
    "accel":1.1,
    "decel":4.0,
    "length":16.50,
    "maxSpeed":36.11,
    "width=":2.55,
    "minGap":0,
    "sigma":0.1,
    "tau":0.05
  },
  {
```

```
    "applications":["com.uminho.invovcar.platoon.apps.
       VehiclePlatoonApp"],
    "name":"PLATOON_VEHICLE_3",
    "accel":1.1,
    "decel":4.0,
    "length":16.50,
    "maxSpeed":36.11,
    "width=":2.55,
    "minGap":0,
    "sigma":0.1,
    "tau":0.05
  }],
  "vehicles":[
  {
    "startingTime":0,
    "route":0,
    "maxNumberVehicles":4,
    "types":[{"name":"PLATOON_VEHICLE"}]
  },
  {
    "startingTime":70,
    "route":0,
    "maxNumberVehicles":4,
    "types":[{"name":"PLATOON_VEHICLE_2"}]
  },
  {
    "startingTime":115,
    "route":0,
    "maxNumberVehicles":1,
    "types":[{"name":"PLATOON_VEHICLE_3"}]
  },
  {
    "startingTime":0,
    "route":0,
    "maxNumberVehicles":0,
    "types":[{"name":"NON_PLATOON"}]
  }
  ]
}
```

Additionally, some *helper configuration files* were written to define properties for each vehicle. This way, the vehicles read their information from the files, which prevents the rebuild of the entire project code every time a simple change is done to any of the parameters. The *platoon vehicle properties* files (shown below) possess information about the maneuver timings, parameters to compute distances and speeds, etc.

```
# Vehicle parameters
is_platoon=1

# Group params
group_name=GROUP_1
leader=veh_0

# Speed adjustments
adjust_weight=2.5
adjust_weight_dec=3.5

# Maneuvers
maneuver_distance=15
max_distance_value=5.0
min_distance_value=-2.0

# Leaving
leaving_v=veh_2
left_color=YELLOW
leaving_time=200

# Dissolve
dissolve=550

# Velocity variation
variation_init=450
variation_end=530
```

The *group properties* files possess information about the *platoon* group - namely the speed, minimum gap, maximum size and colors to be used in SUMO's visualizer. The file containing the *platoon A* information is presented below:

```
# Group parameters
platoon_speed=20
platoon_distance=2
string_size=15

# Colors
leader_color=RED
slave_color=BLUE
maneuver_color=GREEN
left_color=YELLOW
```

Additionally, a *non-platoon* configuration file was created, which contains only one parameter that states that a vehicle with this properties does not have *platoon* capabilities:

```
is_platoon=0
```

To perform an evaluation on all the maneuvers and to obtain results from their behavior, the following set of events was defined to occur during the simulation:

1. *Leader A (Vehicle_0)* creates a *platoon* and starts broadcasting its existence.
2. *Followers A1, A2* and *A3 (Vehicle_1, Vehicle_2 and Vehicle_3)* join *Platoon A*.
3. *Leader B (Vehicle_4)* creates a *platoon* and starts broadcasting its existence.
4. *Followers B1* and *B2 (Vehicle_5 and Vehicle_6)* join *Platoon B*.
5. *Vehicle_7* attempts to join *Platoon B* but the request is rejected (*platoon* is already full).
6. *Followers A2* and *B1* (*Vehicle_2* and *Vehicle_5*) leave their respective *platoons*.
7. *Vehicle_8* joins *Platoon B*, becoming *Follower B2*.
8. *Platoons B* merges into *Platoon A*.

9. *Follower A5* (*Vehicle_8*, former *Follower B2*), leaves *Platoon A*.

10. *Leader A* dissolves *Platoon A*.

The course of events is now described in detail, accompanied by screenshots from the actual simulation and some example extracts of the application code. Due to space constrains, some breaklines were forced on the code samples. Lines starting with *.method()* should be understand as the continuation of the previous line. Table 5.1 presents the colors for each state of the vehicles, to ease the understanding of the application and vehicles behavior.

Colors		
State	**Platoon A**	**Platoon B**
Leader	Red	Pink
Follower	Blue	Gray
Waiting	Orange	Orange
During Maneuver	Green	Magenta
Non-Platoon	Yellow	

Table 5.1: Vehicle colors in SUMO

The simulation begins with *Vehicle_0* creating *Platoon A* and broadcasting its existence (Figure 5.3).

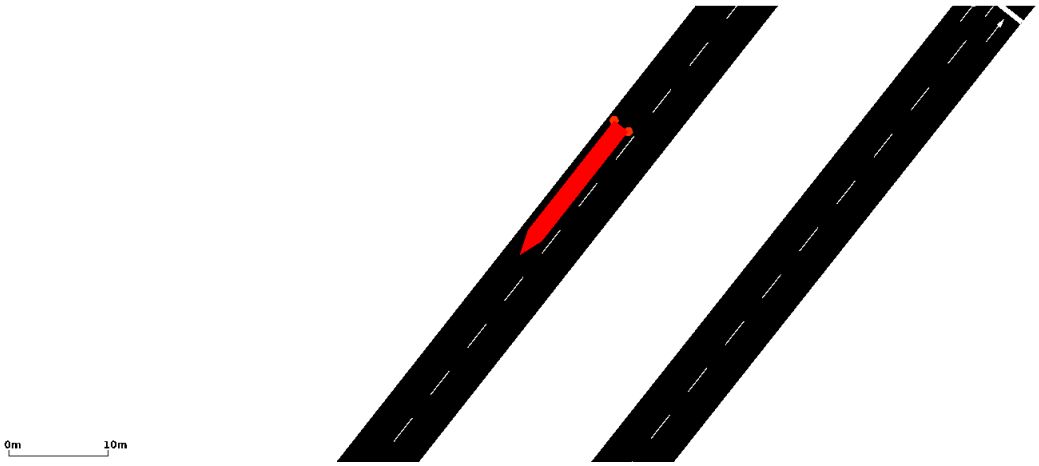


Figure 5.3: *Leader Vehicle_0* creates *platoon A*

To broadcast the information on the *platoon*, the *Leader* uses *Geocast* messages. The code used to send a broadcast message is listed below. First, the *Leader* calculates the destination addresses within a given radius range. Then, the destination addresses are wrapped in a container created via *createGeocastDestinationAddressAdHoc()* and creates the routing for that message, giving as argument the destination address and the default source address. Finally, the message goes through the process of signing and ciphering (described before in this document before) being sent using the *SendV2XMessage()* method provided by the operating system.

```
public class SendMessageGeocast implements SendMessage{
  private GeocastDestinationAddress gda;
  private DestinationAddressContainer dac;
  private MessageRouting routing;
  private OperatingSystem operatingSystem;
  private GeoCircle dest;

public SendMessageGeocast(OperatingSystem operatingSystem,
   double radius){
  this.operatingSystem = operatingSystem;
  dest = new GeoCircle(operatingSystem.getPosition(),
     radius);
  this.gda = GeocastDestinationAddress.createBroadcast(dest);
  this.dac = DestinationAddressContainer
     .createGeocastDestinationAddressAdHoc(gda,
     AdHocChannel.CCH);
  this.routing = new MessageRouting(dac,
     operatingSystem.generateSourceAddressContainer());
}

public void sendMessage(PlatoonMessage message){
  GroupKeys groupKeys = GroupKeys.getInstance();
  SealedObject sealedObject = new SealedObject(message,
     groupKeys.getKey("veh_0").getAesEncrypt());
  PrivateKey privateKey =
     groupKeys.getKey(operatingSystem.getId())
     .getRsaKeys().getPrivate();
  Signature signature =
     Signature.getInstance("SHA256withRSA");
```

```
    SignedObject signedObject = new SignedObject(sealedObject,
        privateKey, signature);
    EncryptedMessage encryptedMessage = new
        EncryptedMessage(message.getRouting(),
        message.getId()+"", sealedObject, signedObject);
    operatingSystem.sendV2XMessage(encryptedMessage);
}

...

}
```

When a given vehicle finds a suitable *platoon*, it is able to perform a request in order to join it (Figure 5.4). The first vehicle to perform a *Join* operation is *Vehicle_1*. First, it sends a *Join Request* to the *Leader* and awaits for a response. Upon receiving the request, the *Leader Vehicle_0* computes the performance value and the position *Vehicle_1* should assume, sending this information back to the requester in a *Join Acknowledge* message (if the maneuver is possible). Since it is the first vehicle attempting to join, *Vehicle_1* moves to the rear of the *platoon* and informs that he has reached the correct position and that the maneuver is finished.

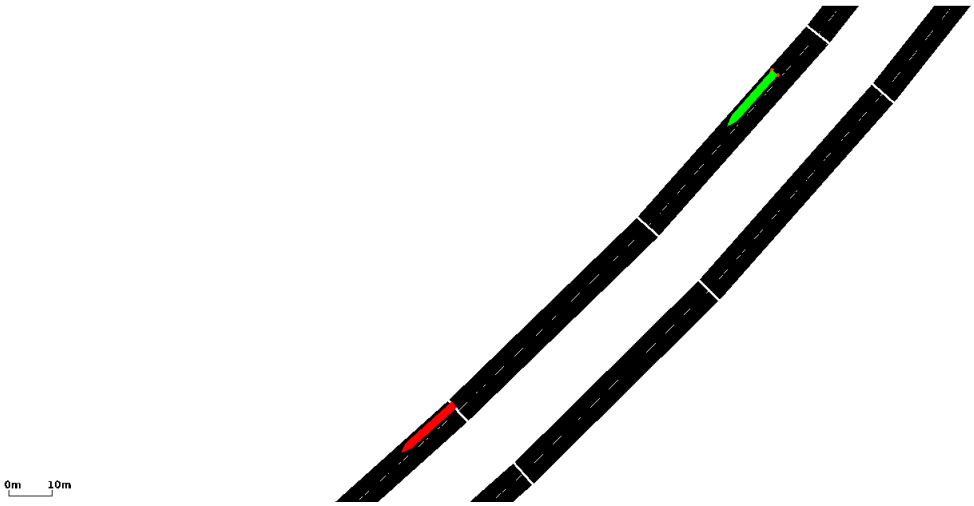


Figure 5.4: *Vehicle_1* sends a *Join Request* towards *Vehicle_0*

The method responsible for sending a *Join Request - joinGroup() from FollowerHandler.java* - is detailed below.

```
public void joinGroup(PlatoonMessage platoonMessage, byte[]
    address){
  setPlatoonMSG(platoonMessage);
  setAddress(address);
  setNextEvent(1);
  PlatoonJoin platoonJoinRequest = new
      PlatoonJoinRequest(getPlatoonGroup().getGroupName(),
      getOperatingSystem().getId(),
      getOperatingSystem().getVehicleParameters()
      .getMaxAcceleration(),
      getOperatingSystem().getVehicleParameters()
      .getMaxDeceleration(),
      getOperatingSystem().getVehicleParameters()
      .getMaxSpeed(),
      getOperatingSystem().getInitialVehicleType()
      .getLength());
  sendUnicastMessage( platoonJoinRequest,
      getPlatoonMSG().getRouting().getSourceAddressContainer()
      .getSourceAddress().getIPv4Address().getAddress());
  getOperatingSystem().applyVehicleParametersChange(
      getOperatingSystem().
      requestVehicleParametersUpdate().changeColor(
      StaticFuncions.getColor(getOperatingSystem(),
      "ORANGE")));
}
```

First, *Vehicle_1* saves information about the *Leader* address and then proceeds to send a unicast *Join Request* containing information about its own parameters. While awaiting for a response, the vehicle assumes the orange color.

The *Leader* method for computing the performance of the vehicle is actually random - since vehicles on this simulation are homogeneous, the performance value result would always have the same outcome. Using random values, the joining position of the request vehicles will have different outcomes, resulting in two different types of joins: *Rear* and *Side*.

The next vehicle to perform a *Join* operation is *Vehicle_2*. In this particular

case, and after receiving a *Join Request*, the *Leader* computed a performance value greater than *Vehicle_1* (that was already part of the string), which resulted in a situation where the joining vehicle should move to the front of the followers string (*side* join). Thus, in addition to acknowledge the *Join Request*, it also informs *Vehicle_1* to adjust its gap, so that the joining vehicle can join in the correct order.
When the adjusting vehicle reaches the correct position, it sends a *Acknowledge Adjust Gap* message to inform *Vehicle_0*. Similarly, the joining *Vehicle_2* vehicle informs he reached the correct joining position with a *Distance Achieved* message. *Vehicle_0* sends a *Start Maneuver* message to *Vehicle_2* only after he has received the message from both vehicles. When the maneuver is completed, *Vehicle_2* sends to the *Leader* a *Maneuver Completed* message. Upon receiving it, *Vehicle_0* notifies the vehicles that the maneuver is completed with a *Platoon Updated* message. The order of events is illustrated in Figures 5.5 to 5.8.

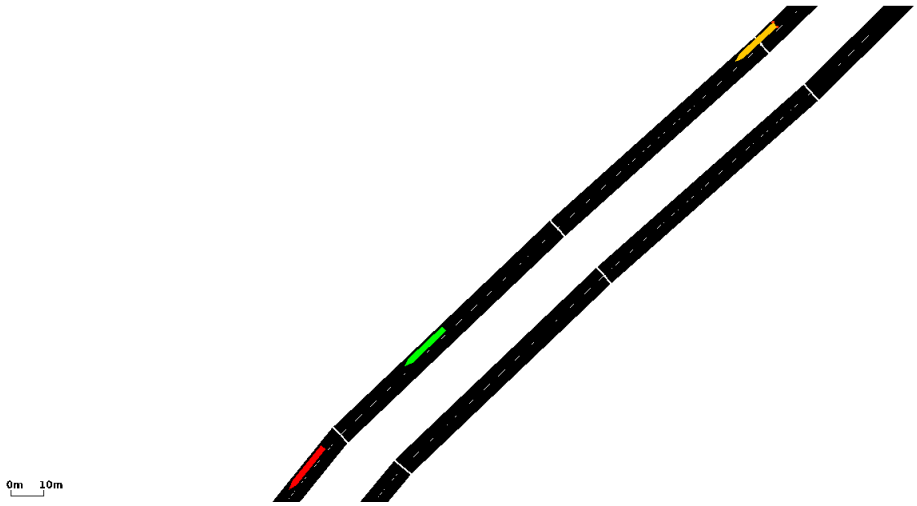


Figure 5.5: *Vehicle_0* acknowledges the *Join Request* from *Vehicle_2* and sends a *Adjust Gap* message to *Vehicle_1*

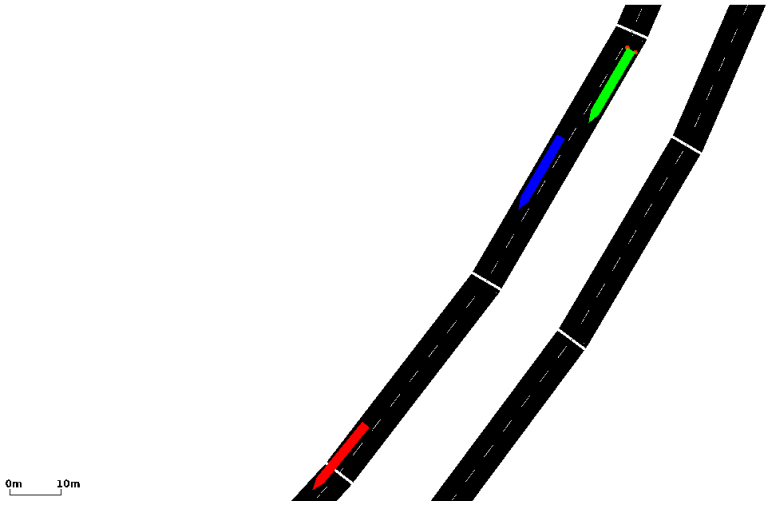


Figure 5.6: *Vehicle_1* informs the *Leader* that has reached the correct adjusting position

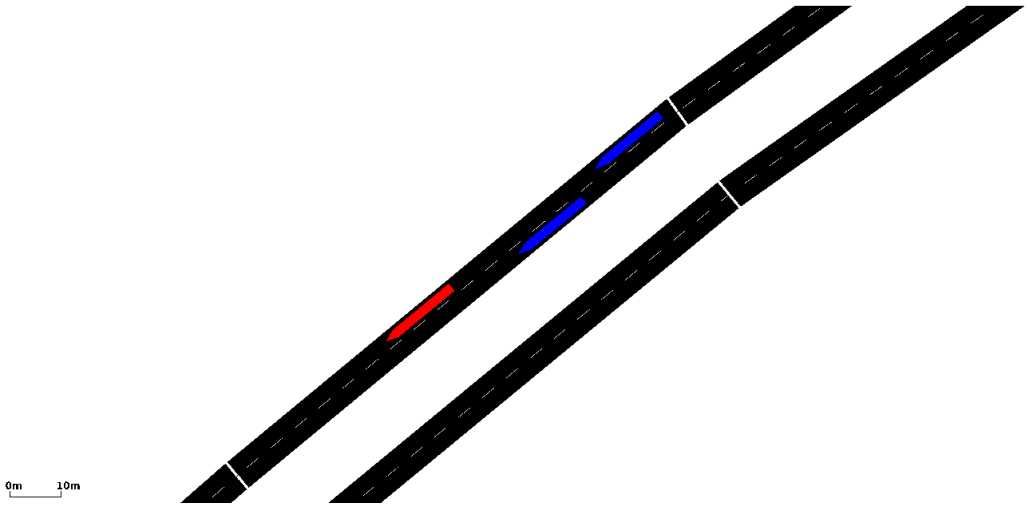


Figure 5.7: *Vehicle_2* reaches the correct joining position and sends a *Distance Achieved* message towards *Vehicle_0*

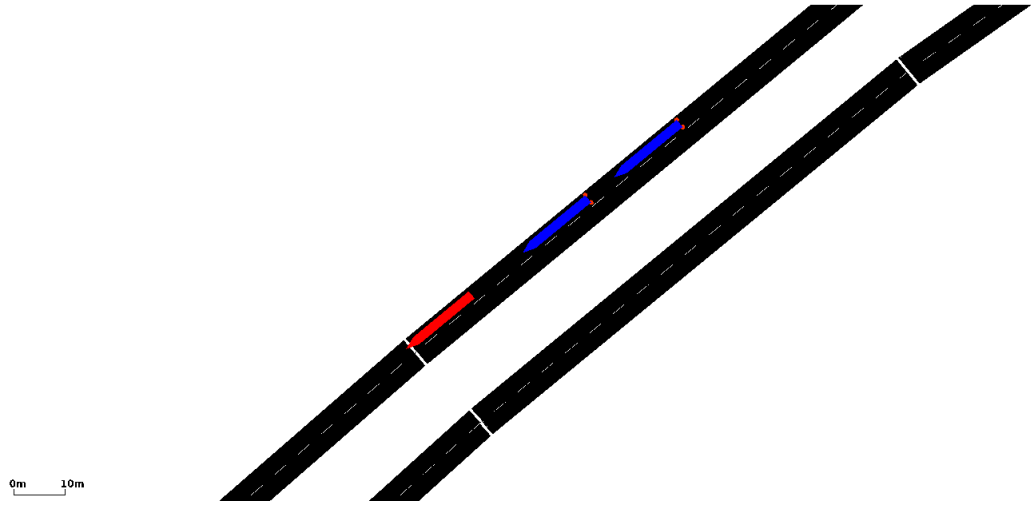


Figure 5.8: *Leader Vehicle_0* sends a *Start Maneuver* message to *Vehicle_2*. When the *Vehicle_2* informs that the maneuver is completed, *Vehicle_0* sends *Platoon Updated* messages to the string, and the *platoon* reaches a stable state - String is now composed of [*Vehicle_0, Vehicle_2, Vehicle_1*]

At this point of the simulation - while the *Vehicle_2* joining maneuver was still unfinished - *Leader Vehicle_0* received another *Join Request* from *Vehicle_3*. Even though the maneuver was still occurring, the *Leader* is able to process the request and check if the maneuver can be performed later when the current one is finished. Then, it proceeds to inform the requester about its decision with a *Platoon Reject*.

For that reason, a boolean was defined in the *Platoon Reject* messages, so that the requesting vehicle is able to understand if he can join the *platoon* later or not. A vehicles gets a negative response if the number of vehicles in the string plus the joining vehicle and the number of awaiting vehicles equals the maximum size a string can have.

The response construction is shown on the following code extract:

```
Boolean MAX_SIZE=
    (getVehicleHashMap().size()+WaitList.size()+1) >=
    Integer.parseInt(propertiesRead.getProperty(
    getPlatoonGroup() .getGroupName(),Vars.STRING_SIZE));
if(MAX_SIZE)
{
```

```
  sendUnicastMessage(new PlatoonJoinReject(getPlatoonGroup()
      .getGroupName(), id,true),
      getPlatoonMSG().getRouting().getSourceAddressContainer()
      .getSourceAddress().getIPv4Address().getAddress());
}
else
{
  WaitListEntry waitListEntry = new
      WaitListEntry(platoonJoinRequest,getPlatoonMSG());
  WaitList.add(waitListEntry);
  sendUnicastMessage(new
      PlatoonJoinReject(getPlatoonGroup().getGroupName(), id,
      false),
      getPlatoonMSG().getRouting().getSourceAddressContainer()
      .getSourceAddress().getIPv4Address().getAddress());
}
```

In a positive response (such as this case where *Vehicle_3* is trying to join), the vehicle waits until further instructions from the *Leader* (as Figure 5.9 illustrates). Otherwise, if the join maneuver is not possible, the vehicle simply leaves and continues its trip.

Since there are cases where multiple requests can appear during a maneuver, the *Leader* keeps a list of requesting vehicles in a *wait list*. The *Leader* responds to those requests in order when a maneuver is finished. In this particular case, *Vehicle_3* gets its response when the *Join* maneuver from *Vehicle_2* is finished, and joins the platoon at the rear of the string.

Meanwhile, *Platoon B* is already composed of *Leader Vehicle_4* and *Vehicle_5*. The *Vehicle_5 Join* operation was not scrutinized since it is similar to the *Join* maneuver of *Vehicle_1* in *Platoon A*. At this point, *Leader Vehicle_4* receives two *Join Request* messages from *Vehicle_6* and *Vehicle_7*. The request from *Vehicle_6* is acknowledged, while the request from *Vehicle_7* is immediately rejected, following the procedure described before. This happens because it is defined that this *platoon* has a very small maximum string size (only for testing purposes).

After receiving a negative response (through a *Join Reject* message), *Vehicle_7* changes to the non-platoon lane and continues its trip, following the

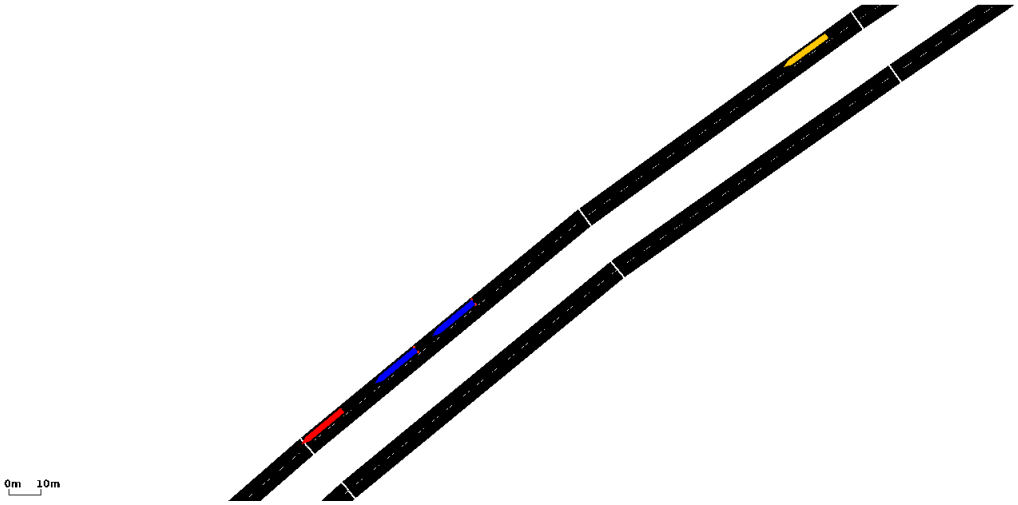


Figure 5.9: *Vehicle_3* awaiting instructions from *Vehicle_0*

predefined route. This moment is captured and shown in Figure 5.10.
It is possible to observe in the figure that *Vehicle_5* already adjusted its gap, and that *Vehicle_6* is moving to the correct position in order to change lane. When completing the maneuver, it sends a *Completed Maneuver* message to *Leader Vehicle_4*, which later informs its followers that the maneuver is completed (with a *Platoon Updated* message).
Platoon B stabilizes as shown in Figure 5.11.

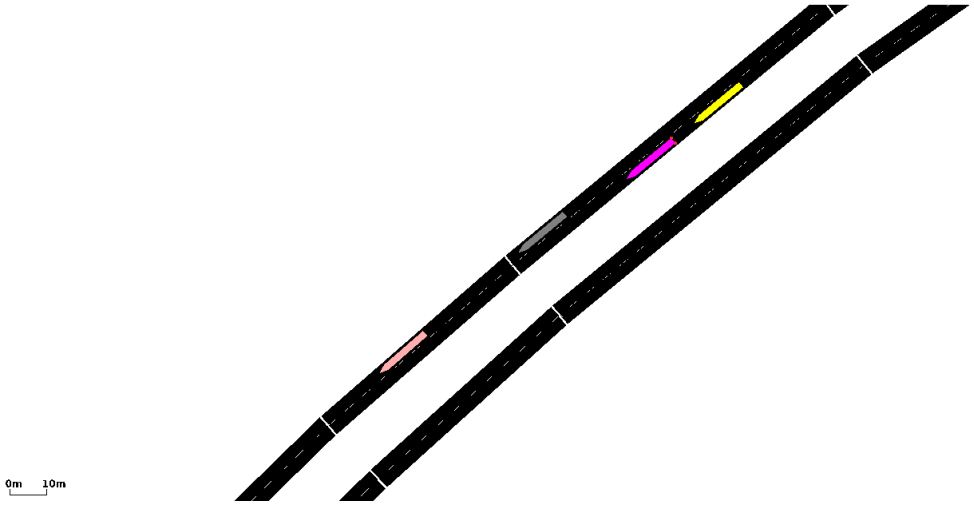


Figure 5.10: *Leader Vehicle_4* acknowledges the *Join Request* from *Vehicle_6* and then proceeds to reject the request from *Vehicle_7* (maximum string size is achieved)

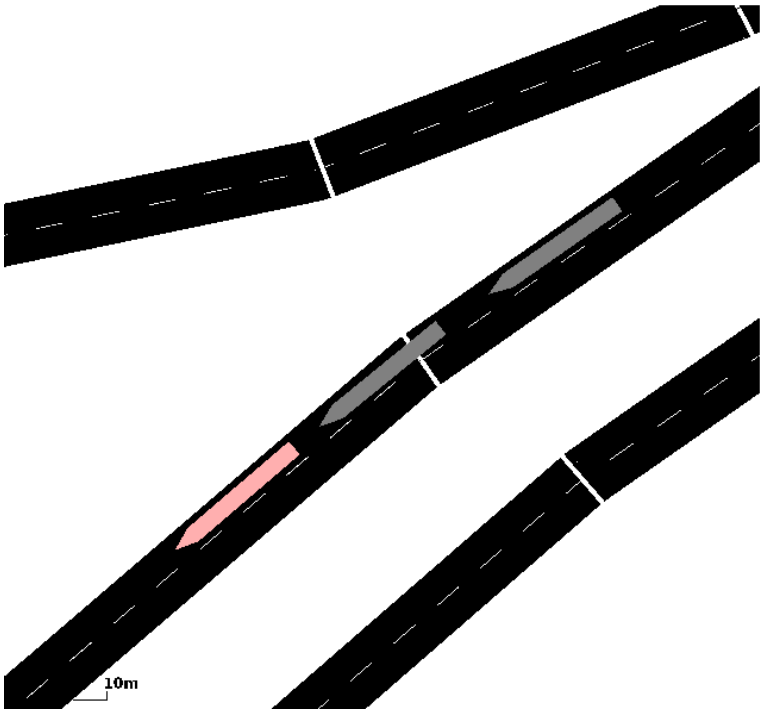
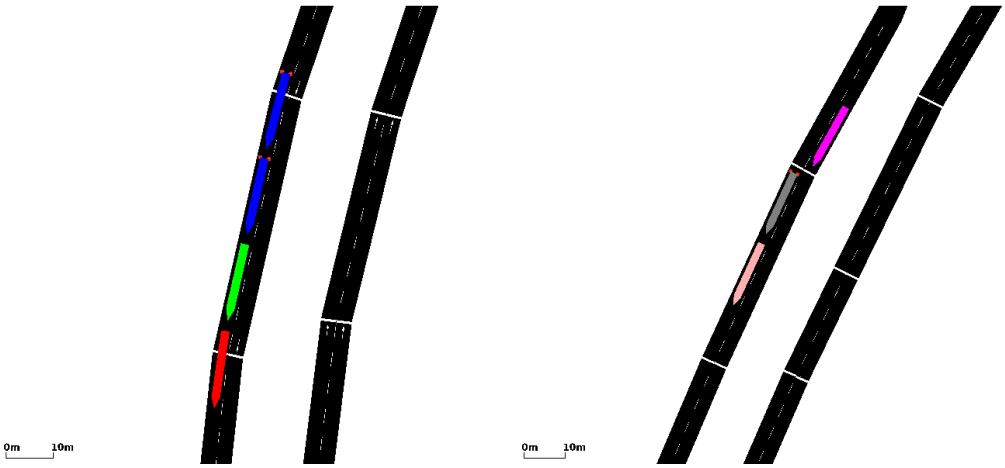


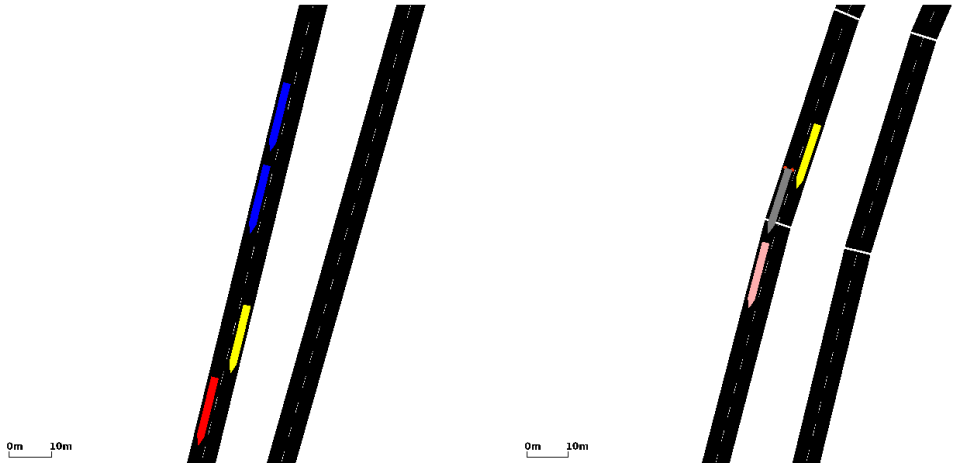
Figure 5.11: *Platoon B* stabilized after the *Join* maneuvers from *Vehicle_5* and *Vehicle_6* - String is now composed of [*Vehicle_4, Vehicle_6, Vehicle_5*]

The next maneuvers tested in the simulation were the *Leave* maneuvers. At 200 seconds of simulation time, both *Vehicle_2* and *Vehicle_5* perform a *Leave* operation in *Platoon A* and *Platoon B*, respectively. In this particular case, the *Vehicle_5 Leave* maneuver turns out to be simpler than the *Vehicle_2* maneuver, since the vehicle is at the rear of the platoon (which implies that no other vehicles need to adjust gaps in order for him to leave).
On other hand, *Vehicle_2* requires *Vehicle_1* and *Vehicle_3* to open up gaps in order for him to leave *Platoon A* (so the maneuver can be accomplished in a safe way). *Vehicle_2* is only allowed to start the maneuver when all the adjusting vehicles have confirmed to reach the required position. When the leaving vehicles receive the *Start Maneuver* message, they change lanes and leave the group, acknowledging that the maneuver is finished with a *Maneuver Completed* message, sent to the *Leader* of the group. The *Leader* then proceeds to inform its followers that the maneuver is over. The maneuvers are illustrated in Figures 5.12 and 5.13.



(a) *Vehicle_2* leaving *Platoon A* (b) *Vehicle_5* leaving *Platoon B*

Figure 5.12: Leave Maneuvers I



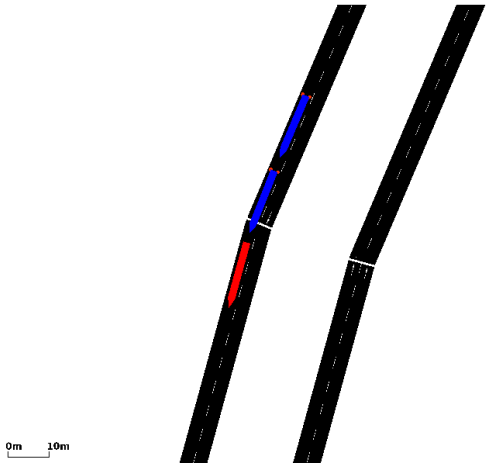
(a) *Vehicle_2* leaving *Platoon A* (b) *Vehicle_5* leaving *Platoon B*

Figure 5.13: Leave Maneuvers II

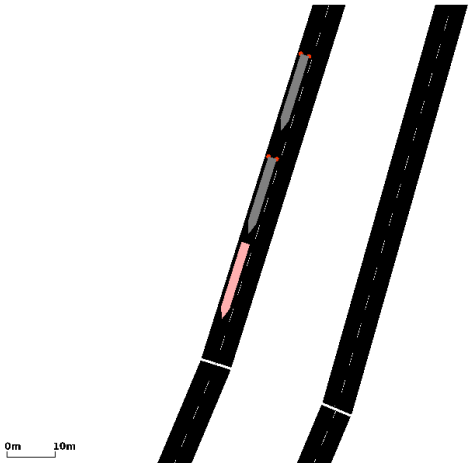
When the *Leave* maneuvers are finished, another *Join* maneuver is performed: *Vehicle_8* joins *Platoon B*. The vehicles joins at the rear of the *platoon* and the procedure is similar to the ones described before. The moment the vehicle joins is captured in Figure 5.14.
At this point, the *platoons* get in a stable state, as Figure 5.15 shows.
The most complex maneuver to be performed in the *Platooning* application is the *Merge* maneuver. This operation requires a lot of cooperation between the two leaders of the merging platoons. The first step of the *Merge* operation is the discovery of surrounding *platoons*. To accomplish so, *Leaders* send a *Merge Request* broadcast message every ten seconds, surveying other possible *Leaders* on the road for merge opportunities.
The process of sending the message is extracted from the code and presented next. *Leaders* set up an event every ten seconds that calls the *sendMerge-Broadcast()* method, which is responsible for sending a *Merge Request* geocast message. This process is interrupted if the *platoon* is already performing a *Merge* maneuver.

```
public class LeaderHandler extends PlatoonHandler
{
  public void mergeEventSetUp()
```

Figure 5.14: *Vehicle_8* joins *Platoon B* at the rear



(a) *Platoon A* stabilized - [*Vehicle_0, Vehicle_1, Vehicle_3*]



(b) *Platoon B* stabilized - [*Vehicle_4, Vehicle_6, Vehicle_8*]

Figure 5.15: Stabilized Platoons

```
{
  mergeBroadcastEvent = new
     Event(getOperatingSystem().getSimulationTime()
     +TIME.SECOND*10, this.getApp());
```

```
    getOperatingSystem().getEventManager().addEvent(
        mergeBroadcastEvent);
    sendMergeBroadcast();
  }

  private void sendMergeBroadcast()
  {
    if(!merging&&getPlatoonGroup()!=null&&getPlatoonGroup()
        .getGroupName()!=null &&
        getOperatingSystem().getId()!=null)
    {
      PlatoonMergeRequest message = new
          PlatoonMergeRequest(getPlatoonGroup().getGroupName(),
          getOperatingSystem().getId(),
          this.vehicleHashMap.size() +1,
          getOperatingSystem().getVehicleInfo()
          .getDistanceDriven());
      sendMessage(message);
    }
  }
...

}
```

Upon receiving a *Merge Request* message, *Leaders* verify if the maneuver can be performed. The maneuver is only possible if no other maneuver is occurring, the size of both strings is acceptable and if the requesting *Leader* is following behind on the road. If a given *Leader* is interested in merging and the message is received from a *platoon* following ahead on the road, the request is rejected but a new *Merge Request* towards the first requesting vehicle is immediately sent. The beginning of the maneuver is illustrated on Figure 5.16.
In this case, *Vehicle_0 (Leader A)* receives a *Merge Request* from *Vehicle_4 (Leader B)* which is acknowledged with a *Merge Request Acknowledgment*. The other way around would result in a *Merge Reject*, since *Platoon B* is following in the rear and the size is not acceptable - maximum string size in *Platoon B* is equal to three. After receiving the acknowledgment from the

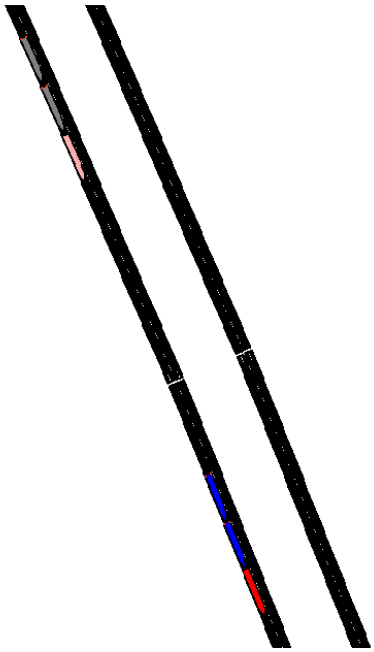


Figure 5.16: *Vehicle_4 (Leader B)* sends a *Merge Request* geocast message

front leader, *Vehicle_4* sends a unicast *Merge Info* message to *Vehicle_0* with information about its string - the vehicle hashmap with information about every vehicle composing *Platoon B*. *Vehicle_0* adds the new vehicles information to its own hashmap, and computes the distance that *Vehicle_4* should now assume (and, consequently, for the *Platoon B* followers), informing it with a *Adjust Gap* message. *Vehicle_4* starts to adjust its velocity in order to merge into the correct position, as Figure 5.17 shows.

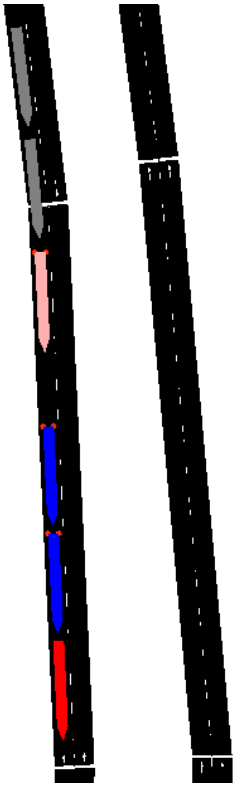


Figure 5.17: *Vehicle_4* (and *Platoon B*) approaching *Platoon A*

When achieving the correct position, every vehicle from the former *platoon* is informed with a *New Leader* message that they should now follow a new vehicle - in this case, *Vehicle_0*. When the maneuver is completed, the former *Leader* informs the new *Leader* with a *Adjust Gap Acknowledge* message and becomes a *Follower* himself. The final state of the maneuver is illustrated in Figure 5.18.

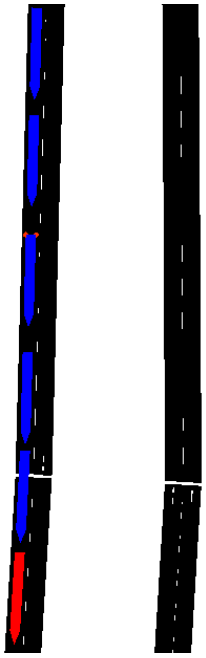
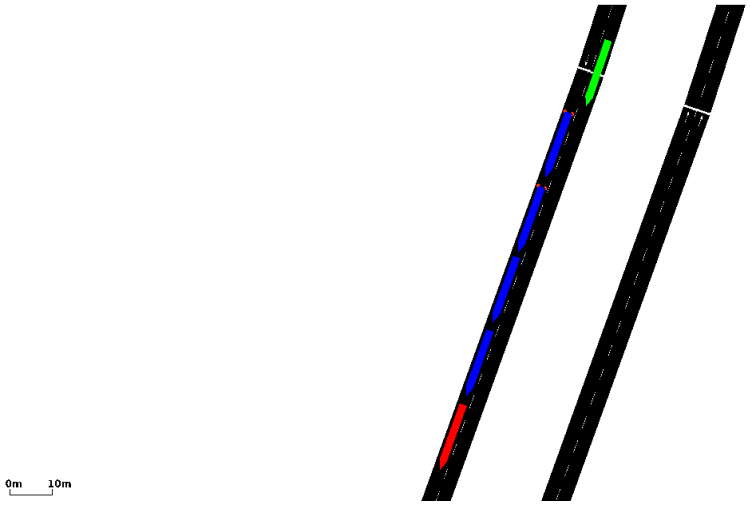
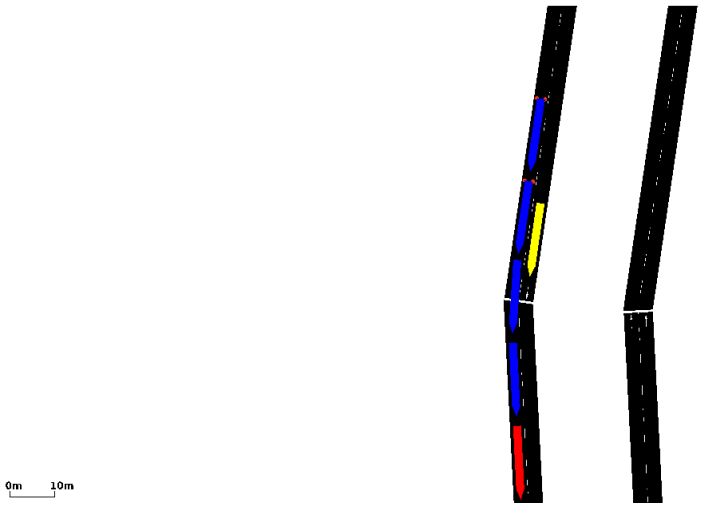


Figure 5.18: *Merge* maneuver final state - *Platoon A* is now composed of [*Vehicle_0, Vehicle_1, Vehicle_3, Vehicle_4, Vehicle_6, Vehicle_8*]

After the *Merge* is finished, another *Leave* maneuver happens in the simulation, resulting from a *Leave Request* sent by *Vehicle_8* to the new *Leader* of the whole *platoon* - *Vehicle_0*. Since *Vehicle_8* is the last vehicle of the string, no vehicles have the need to adjust its gap - the operation is similar to the *Vehicle_5 Leave* maneuver. This process is illustrated in Figure 5.19.



(a) *Vehicle_8* requests *Vehicle_0* to leave



(b) *Vehicle_8* leaves the *platoon*

Figure 5.19: *Vehicle_8 Leave* maneuver

Finally, the *platoon* reaches the last stable state (Figure 5.20) before the *Dissolve* operation. Before starting dismembering the *platoon*, *Leader_0* goes through a phase of velocity fluctuation, to test the *Followers* ability to adjust their velocities based on the messages received from the *Leader* every 100 ms. This part of the simulation is discussed later in chapter 6.

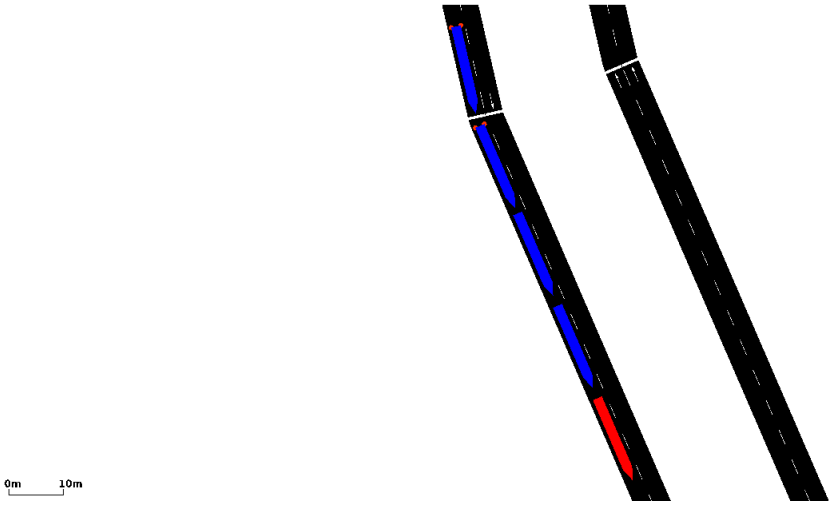


Figure 5.20: Stabilized *Platoon A* - [*Vehicle_0, Vehicle_1, Vehicle_3, Vehicle_4, Vehicle_6*]

The *Dissolve* maneuver is triggered by the *Leader Vehicle_0* when the simulation reaches the *dissolve time*, given as argument from the configuration files. When reaching *dissolve time*, the *Leader* sends a unicast *Platoon Dissolve Request* to each vehicle of the string. Since the *Leader* is only allowed to leave/dissolve the *platoon* when every single vehicle has acknowledged the request, it will continue this process until it is able to do so. The code used by the application in order to perform the dissolving process of the *platoon* is presented below.

```
public class LeaderHandler extends PlatoonHandler{
  ...

  public PlatoonHandler handleEvent(Event event)
  {
    ...
    int dissolveTime =
        Integer.parseInt(propertiesRead.getProperty(
        getOperatingSystem().getInitialVehicleType().getName(),
        Vars.DISSOLVE));
    if (time > dissolveTime)
    {
```

```
getOperatingSystem().applyVehicleParametersChange(
    getOperatingSystem().requestVehicleParametersUpdate()
    .changeColor(StaticFunctions.getColor(
    getOperatingSystem(), propertiesRead.getProperty(
    getPlatoonGroup().getGroupName(),
    Vars.MANEUVER_COLOR))));
ArrayList<Vehicle> vehicleArrayList = new
    ArrayList<>(vehicleHashMap.values());
for (int i=0; i<vehicleArrayList.size(); i++)
{
  Vehicle vehicle = vehicleArrayList.get(i);
  PlatoonDissolveReq platoonDissolveReq = new
      PlatoonDissolveReq(getPlatoonGroup().getGroupName(),
      vehicle.getId());
  sendUnicastMessage(platoonDissolveReq,
      getPlatoonMSG().getRouting()
      .getSourceAddressContainer().getSourceAddress()
      .getIPv4Address().getAddress());
}

if(AllLeft())
{
  getOperatingSystem().applyVehicleParametersChange(
      getOperatingSystem()
      .requestVehicleParametersUpdate().changeColor(
      StaticFuncions.getColor(getOperatingSystem(),
      propertiesRead.getProperty( getPlatoonGroup()
      .getGroupName(), Vars.LEFT_COLOR))));
  SecureRandom secureRandom =
      SecureRandom.getInstance("SHA1PRNG");
  double speed = secureRandom.nextInt((int)
      (vehicleParameters.getMaxSpeed()- 1)) + 1;
  speed = Math.abs(speed);
  getOperatingSystem().changeSpeedWithInterval(speed,
      StaticFuncions.getNextEventTime(100,
      getOperatingSystem()));
  return new LeftHandler(getOperatingSystem(),
      getLogger(), this.app);
}
```

```
    }
  ...
  }
...
}
```

When the process is complete and all vehicles have left the *platoon*, the simulation reaches its final state before shutting down, as it is possible to see in Figure 5.21.

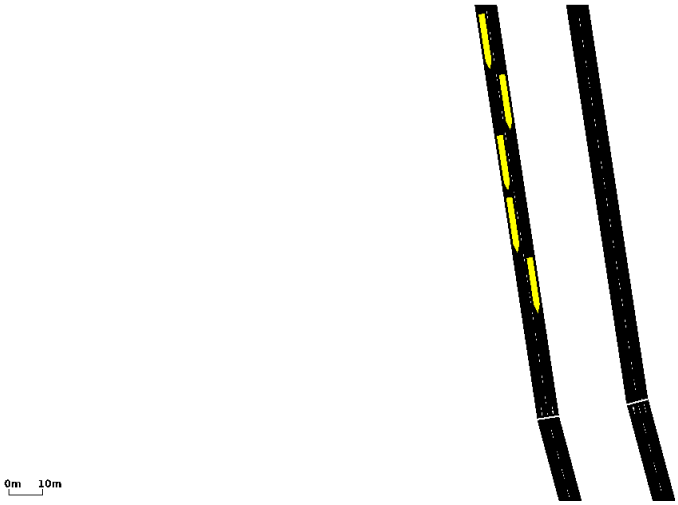


Figure 5.21: Dissolved

5.3 Messages

This section introduces the description of the parameters of the application-defined messages and the situation in which they are used. First, the common messages are presented, containing general messages used within the group and that are used in more than one maneuver. The messages presented later are grouped by the specific type of maneuver they belong to.

5.3.1 Common

Group

The *Group* messages are related to the process of exchanging information of the *platoon*.

Platoon is Group The *Platoon is Group* message is used as a trick in order to force a given vehicle to join a specific *platoon*. This happens so that it is easier to control the simulation behavior (e.g. *Vehicle_1* should search for *Platoon A* and not *Platoon B*). When a vehicle starts the application, it starts sending *Platoon is Group* messages until it finds the correct *Platoon* so that he can perform a *Join* maneuver.

Platoon Group This periodic broadcast message is used by the *Leader* to disseminate information on the group's name, creator, route, drive direction, speed, leader position and lane. It is also used as a response to the *Platoon is Group* requests.

Adjust Gap

The *Adjust Gap* messages are related to the use cases where vehicles should open up gaps to the preceding vehicle so maneuvers can be completed. These message are extensions of the *Platoon Change Distance* class.

Platoon Adjust Gap These unicast messages are used by the *Leader* to inform its *Followers* on which is the *distance* (given as argument) that they should keep towards him. They are useful during the maneuvers that require a given set of vehicles to open up or close gaps (e.g. during a *Join* maneuver, vehicles need to open up space so that the joining vehicle may merge into the platoon).

Platoon Adjust Gap Acknowledgment These unicast messages are used by *Followers* as a response to the *Platoon Adjust Gap* message, informing the *Leader* that they reach the correct position.

Platoon Updated The messages are used by the *Leader* to inform the *Followers* that the platoon is stabilized, i.e. the maneuver is finished.

5.3.2 Join

The list of messages below is used to accomplish the *Join* maneuver and they are extensions of the class of *Platoon Join* messages.

Platoon Join Request These periodic broadcast messages are sent from a vehicle that wants to join a platoon. They contain information about the vehicle parameters (maximum acceleration, deceleration, speed and size) which helps a given *Leader* to make a decision on whether to accept or reject the request.

Platoon Join Acknowledge – Platoon Join Reject These unicast messages are a response to the *Platoon Join Request* messages. The *Leader* is able to accept a request (using a *Platoon Join Acknowledge*) or to reject it (using a *Platoon Join Reject*). The *Leader* may reject a request to join if the size of the string reached its maximum, the platoon is performing another maneuver, or if the received vehicles parameters are not in conformance with the platoon characteristics (e.g. vehicle is not able to reach the platoon traveling speed). However, this situation never occurs in the simulation, since vehicles are homogeneous. The *Platoon Join Acknowledge* contains information about the distance that the joining vehicle should establish from the leader and the lane the platoon is traveling. The *Platoon Join Reject* contains information on whether the reject is based on the string size or if a maneuver is occurring. In the last case, it means that the maneuver can be performed later.

Platoon Join Distance Achieved This unicast message is used by the joining vehicle to inform the *Leader* that it has arrived the correct position in order to merge to the correct lane. It possesses no special arguments.

Platoon Join Start Maneuver The *Leader* sends this unicast message to the joining vehicle, informing that the maneuver can be accomplished.

Platoon Join Maneuver Completed This unicast message is sent from

the joining vehicle to the *Leader*, informing that the maneuver has terminated successfully. It contains no arguments.

5.3.3 Leave

The list of messages below is used to accomplish the *Leave* maneuver and they are extensions of the class of *Platoon Leave* messages.

Platoon Leave Request These unicast messages are sent from a vehicle that wants to leave a platoon to the *Leader*. They do not contain any information.

Platoon Leave Reject This unicast message is sent by the *Leader* if the *leave* maneuver is not possible to perform at this moment. It contains no payload.

Platoon Leave Start Maneuver The *Leader* sends this unicast message to the leaving vehicle if the maneuver is possible. If the leaving vehicle is at the rear of the platoon, the *Leader* sends this message immediately. Otherwise, it is sent after the vehicles adjust their gaps, so that the leaving vehicle can perform the maneuver safely. These messages do not contain information.

Platoon Leave Maneuver Complete This unicast message is sent from the leaving vehicle, informing the *Leader* that the maneuver is completed. Similarly to the *Platoon Leave Start Maneuver* messages, it does not contain payload.

5.3.4 Merge

Platoon Merge Request This periodic broadcast message is sent from the platoon *Leaders*, surveying possible merge opportunities. In this message is included information on the platoon size and the position of the leader on the road. These messages provide enough information to help another *Leader* to accept or reject the request.

Platoon Merge Reject – Acknowledge These messages are used by the front *Leader* to inform the requesting *Leader* if a merge is possible or not. When it's possible, the front *Leader* returns a *Platoon Merge Acknowledge* to the following *Leader*, with no special information. The *Leader* may reject a request (resorting to a *Platoon Merge Reject* message) if another maneuver is occurring, or if the size is not acceptable. Additionally, a *Leader* may reject a request if it comes from a *Leader* that is following more ahead on the road. On this particular case, it delivers another *Platoon Merge Request* to the *Leader* that first sent the request. This happens, so that the maneuver is easier to accomplish - the rear *Platoon* moves to the rear of the front *Platoon*.

Platoon Merge Info When receiving an affirmative response from the front *Leader*, the rear *Leader* sends a unicast *Platoon Merge Info* message containing the *hashmap* of vehicles which are part of its *Platoon*, containing information on all vehicles of the string.

Platoon Merge Adjust Gap After receiving a *Platoon Merge Info* message and merging the received *hahsmap* with its own, the front *Leader* computes the distance that the rear *Leader* should now assume, and sends it as an argument via a *Platoon Merge Adjust Gap* message.

Platoon Merge Adjust Gap Acknowledge When the rear *Leader* arrives at the correct distance to the front *Platoon*, it sends a *Platoon Merge Adjust Gap Acknowledge* message informing that he has reached the position.

Platoon Merge New Leader The *Platoon Merge New Leader* messages are used by the *Leader* to inform its followers that they now should follow a new *Leader* and that the *Merge* maneuver is finished. It contains information on the distance to the front *Leader* and on the new *Platoon* Group.

5.4 Implementation Challenges

When first starting the implementation of the PMP, it was intended to use the standard ITS messages to communicate in the *platoons*. However, it was more efficient to built self-defined messages that the vehicles could easily process and understand. Initially, the PMP was defined to use *geocast* messages every time the vehicles needed to communicate. Soon this proved to be a inefficient and to make the simulation slow down. Thus, only the *Platoon Group* messages stayed as *geocast*, while the remaining messages used the *Topocast* method, which proved to be more efficient. The *Topocast* method is used to communicate with an individual destination node in the direct communication range of the sender.

The default *time-step* used in SUMO lead vehicles to keep a large distance to the vehicle in front, even when the application was forcing vehicles to approach and it was not possible to send messages every 100 ms. The distance to the front leader is calculated by SUMO using τ (driver reaction time) and *minimum gap* values. For instance, if the τ value is equal to 0 and vehicle speed is 15 m/s, the minimum calculated distance to the front vehicle is 15 m (not desirable in the *platooning* application). As SUMO does not allow the *time-step* value to be greater than the τ value, the *time-step* was defined to be equal to 50 ms instead of the predefined value of 1000ms. However, this solution had as drawback the decreasing of the simulation performance. Additionally, the constant use of the *in-vehicle* sensor and the commands to change lane and adjust speed caused the simulation to degrade its performance. The constant commands could not be moved, because vehicles are not "smart" in SUMO - one most force them to move to a given place with constant indications. To overcome the sensor problem, the distance information is sometimes taken by GPS while the cars are maneuvering and by the sensors when stable in the *platoon*. Also, since SUMO and VSimRTI do not provide any special function to compare which vehicle follows in front on the road, this information is actually based on the distance driven on the defined route. However, this solution only works on this particular scenario, since the route is the same to all vehicles.

The PMP suffered some alterations from its original version when the implementation started. When testing the maneuvers in the simulation environment, some steps were modified to strengthen the solution. In the *Join* maneuver, the vehicle is now only allowed to change to the correct lane when every adjusting vehicles has finished its operation. At first, the vehicle would simply try to merge to the lane as soon as it reached the position, which is not advised or secure. Also, when the maneuver is finished, the joining vehicle he notifies the *Leader*. This allows the *Leader* to know when to alert the remaining *Followers* that the maneuver is finished and that they can now assume the correct position. Previously, vehicles assumed that a given operation was finished when they reached the exact computed position. Now they are able to finish an operation when they reach an acceptable distance to that computed point. This makes the simulation more realistic (e.g. in the real world, a vehicle will merge to the correct lane as soon as he is able to when in manual mode) and the maneuver durations become faster as well. Regarding the *Merge* maneuver, the *Rear Leader* now only informs its followers that they have a new *Leader* when he reaches the correct position in the merged *Platoon*. In the first solution, this was performed as soon as he received a *Merge Acknowledgment*. This way, the maneuver is safer and the *adjusting gap* operation of the rear *platoon* is smoother - rear *Followers* will still be "listening" to the rear *platoon Leader* until the maneuver is finished. In the first description of the *Dissolve* maneuver, the *Followers* did not inform the *Leader* that they had in fact left, and the *Leader* would simply leave the *platoon*. This could potentially lead to severe problems - for example, if a given *Follower* had not received the *Dissolve Request*, it would be still waiting for instruction from the *Leader* (which would already left the *platoon*). Finally, the *Leave* maneuver was also modified so that vehicles following behind the leaving vehicle would open up a gap. In the first description, the vehicle would simply change lanes. In the real world, performing the *Leave* maneuver in such a tight space could lead to accidents. Thus, the adjusting operation was introduced so that the maneuver can be performed safely.

Chapter 6

Results and Analysis

In general, the behavior of the vehicles in ITS applications simulation tends to be extremely dynamic: typically, the mobility simulator runs with hundreds of vehicles equipped with applications at a given penetration rate and they follow computer generated routes. However, the simulation deployment on this work was proposed to be slightly more static, in the sense that the maneuvers (and respective maneuver start timings), routes and even the vehicles running the application are predefined. Although not being the most desired situation, this happens due to the high difficulty level of controlling and evaluating the vehicles and application behavior during the complex maneuvers that result from the PMP. Nevertheless, independent simulation runs will alway generate different outputs, since the *Join* maneuvers are dynamic (due to the performance ordering), and consequently the *Leave* maneuvers and adjusting operations will also be different in each run.
Although the VSimRTI framework provides some result *logs*, the application was built to generate more specific results regarding the exchanged messages and the behavior of each vehicle. In particular, the PMP generates logs regarding the exchanged messages (group and maneuver related messages), vehicles distance (towards their correct position), speed values and the lane capacity. The obtained results are discussed in the following sections.

6.1 Lane Capacity

The first immediate results that can be obtained from the use of *Platooning* is increased lane capacity. According to [78], *platoons* are able to increase traffic capacity due to its capability to use tight spaces between vehicles (and between different platoons). The presented formula to compute the capacity is:

$$\phi = v \times \frac{n}{ns + (n-1)d + D} \quad \text{vehicles/lane/min} \tag{6.1}$$

where v is the steady state speed (*meters/min*), d the intra-platoon spacing (*meters*), D the intra-platoon spacing (*meters*), s the vehicle length (*meters*) and n the number of cars composing the string.

In the PMP definition, where v is equal to 1500 m/min (25 meters/second), d is 2 meters, D is 30 meters (although not defined initially and not taking into account on the application itself, 30 meters seems a reasonable value), s is 15 meters and n is 15 vehicles, the capacity result is $\phi = 71.88$ vehicles/lane/min. Assuming that the typical lane capacity value is $\phi = 35$ vehicles/lane/min [78], the PMP is able to theoretically more than double the capacity of the road.

To compare this analytical value to the actual application (which has dynamic parameters, namely the speed and number of vehicles), the capacity value was computed and logged by each leader during the runtime every second. The results were then processed in *Microsoft Excel*.

The obtained results that are presented on Figure 6.1 were taken from a single simulation - since the number of vehicles in the platoons and velocities are the same in each simulation run (as discussed before, the maneuvers are static), the outcome of the capacity value will always be similar.

As expected, the capacity value is typically lower than the theoretical value, since *platoons* have in fact different group speeds and the number of vehicles in the string is not the same as the maximum defined values. Also, these values differ in both *platoons*, which implies that the capacity values are different between them.

Platoon B tends to have higher capacity values, which is explained by the

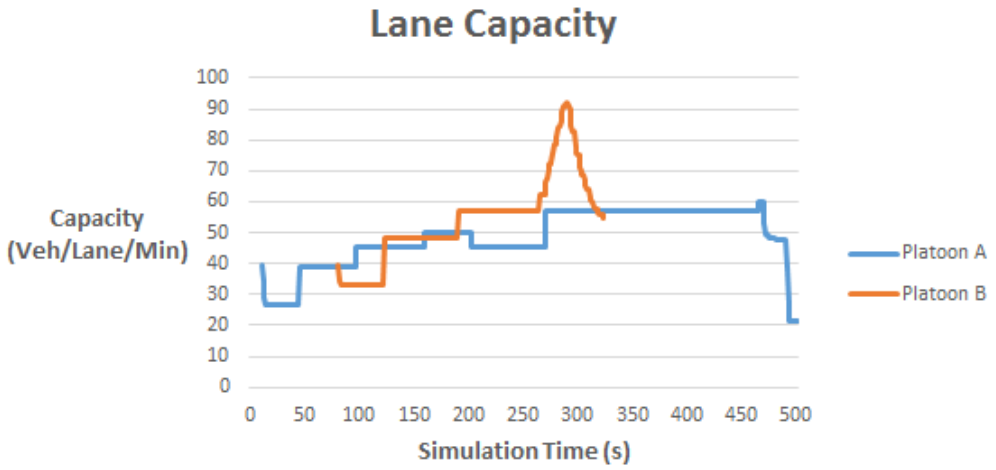


Figure 6.1: Lane Capacity during simulation time

fact that the group speed is higher than in *Platoon A*, even though *Platoon B* has less vehicles in the string. In general, the capacity value increases when vehicles join the string and decrease when they leave. During the speed fluctuation in *Platoon A* (around 450 seconds), it is also possible to verify the impact the speed has on the capacity - capacity increases when speed increases and vice-versa. Furthermore, the computed capacity also decreases abruptly when vehicles start dissolving (around 500 seconds of simulation time).

Table 6.1 presents the mean values for the capacity in the *platoons* during the simulation. Although the application is not able to meat the theoretical values (in this scenario), it is still possible to conclude that it is able to achieve much better results than when *platooning* is not implemented.

Capacity	
Vehicle	**Mean value (vehicles/lane/min)**
Platoon A	48.388
Platoon B	54.166

Table 6.1: Mean capacity values during simulation runtime

6.2 Maneuvers

This section describes the behavior of the *Platoons* during the application runtime, focusing and discussing on the duration of the maneuvers and what are the possible reasons behind those results. The presented outcomes for the *Join* and *Leave* maneuver duration times result from a single simulation. Taking into account mean results of multiple simulations would not make sense, since these maneuvers are dynamic. However, the *Merge* and *Dissolve* maneuvers discuss mean results from all simulation runs.

6.2.1 Join Maneuver

This subsection discusses the duration of the *Join* maneuver. With exception to the *Leader* vehicles (creators of *platoons*), every vehicle must perform a *Join* maneuver in order to become part of a *platoon*. The duration of these maneuvers, along with their mean values, is presented in Table 6.2. The table is divided in two parts: *Vehicle_1, Vehicle_2 and Vehicle_3* maneuvers were performed in *Platoon A*, while *Vehicle_5, Vehicle_6 and Vehicle_8* maneuvers were performed in *Platoon B*. The *waiting time* value represents the amount of time a vehicle awaits until it receives a *Join Acknowledgment* after sending a *Join Request*.

Join				
Vehicle	**Join Type**	**Maneuver Duration (s)**	**Waiting Time (s)**	**Total Duration (s)**
Veh_1	Rear	32.980	–	32.980
Veh_2	Side	43.001	16.284	59.285
Veh_3	Rear	35.000	40.181	75.181
Veh_5	Rear	42.943	–	42.943
Veh_6	Side	44.996	17.989	62.985
Veh_8	Rear	37.885	–	37.885
Mean		39.467	24.818	51.876

Table 6.2: *Join* maneuver duration

When looking at the *Join* duration results, the first conclusion one draws is that joining a *platoon* at the rear is slightly faster than joining a *platoon* by the side. The rear joins at *Platoon B* seem to take a bit longer than in *Platoon A*, which may be explained by the fact that *Platoon B* is traveling at a greater speed, which makes the maneuver harder for the joining vehicles. The second remark is that despite the speed differences, the *Join* maneuvers in both *platoons* have similar durations, with no relevant discrepancies in the values. Even regarding the wait times, the values seem acceptable and similar between them, with exception to the *Vehicle_3* join operation. The value seems somewhat high, but is explained by the fact that the *Join Request* was sent when the *Vehicle_2* side maneuver was in a early stage (and side operations by themselves already takes longer than rear operations).
Still regarding the *Join* maneuver, it is also important to analyze the duration of a negative response to a rejected *Join Request*. As shown on Table 6.3, the reject situation only happens once during the simulation runtime - when *Vehicle_7* attempts to join *platoon B*. It is possible to observe that between the request and response, only 1 ms has elapsed. This happens because the *Leader* is able to respond immediately if a given requester is able to perform the maneuver, even if another maneuver is already occurring. At this point of the simulation, *Platoon B* was already at its maximum size.

Join Reject	
Vehicle	**Duration (s)**
Vehicle_7	0.001

Table 6.3: Rejected *Join Request* duration

6.2.2 Leave Maneuver

Similarly to the *Join* maneuver, the *Leave* maneuver may also assume two types: side and rear. In side leaves, the vehicles that follow behind the requesting vehicles are required to open up gaps, so that the maneuver can be accomplished in a safe way. In rear leaves, and since the vehicle requesting

to perform the maneuver is the last one of the string, other vehicles do not need to adjust their gaps - the leaving vehicle simply changes the lane and continues its trip. For this reasons, as it is possible to see in Table 6.4, there is a huge difference in the duration of the maneuver, depending on the type.

Leave		
Vehicle	**Leave Type**	**Duration (s)**
Vehicle_2	Side	27.000
Vehicle_5	Rear	0.999
Vehicle_8	Rear	1.000
Mean		9.666

Table 6.4: *Leave* maneuver duration

6.2.3 Adjusting Gaps

Although the *Adjust gap* situations are not qualified as maneuvers themselves, they play an important role on the maneuver's course of actions and duration times. Vehicles may adjust their gap during the *Join, Leave* and *Merge* maneuvers. However, the results regarding the *Merge* maneuver are discussed later in subsection 6.2.4, and thus not included on Table 6.5. The duration of these operations seem to be in a reasonable interval of time. However, there is a discrepancy between the values for the *Vehicle_2* during the *Join* maneuver and *Vehicle_6* in a similar situation. The reason for this result is not clear, but may also be related to the fact that the speed of the *platoon B* is greater than *platoon A*.

6.2.4 Merge Maneuver

The merge maneuver can be divided in three steps: exchanging the information between the *Leaders*, the adjusting gap operation and the *New Leader* information dissemination. Table 6.6 presents the duration of each of these

Adjusting Gaps		
Maneuver	**Adjusting Vehicles**	**Duration (s)**
Vehicle_2 Join	*Vehicle_1*	6.998
Vehicle_6 Join	*Vehicle_5*	19.999
Vehicle_2 Leave	*Vehicle_1, Vehicle_3*	24.996
	Mean	17.331

Table 6.5: *Adjusting Gap* durations

steps in seconds. The *Merge* maneuver was accomplished at a rather surprising short time - even faster than the *Join* maneuvers. The expected results were for the maneuver to take at least the same amount of time that the fastest *Join* maneuver took - a *Merge* operation can almost be seen as one *Leader* joining another *platoon* that follows in front of him. Still, the adjust gap operation takes most of the time - approximately 99% of the total time - while the maneuver set up and finishing steps are very fast - 8 milliseconds.

Merge			
Info Exchange (s)	**Adjusting Gap (s)**	**New Leader Information (s)**	**Total (s)**
0.005	28.172	0.003	28.180

Table 6.6: *Merge* maneuver duration

6.2.5 Dissolve

The *Dissolve* maneuver duration time is estimated from the moment when the *Dissolve Request* is issued by the *Leader* until the last *Dissolve Acknowledgment* is received as a response. As seen on Table 6.7, the maneuver performs quickly - 4.1 milliseconds. This happens because all vehicles simply acknowledge the request and turn into manual driving instantaneously, which makes the result unrealistic - in a real situation, the maneuver would for sure last longer, since the driver would be required to answer to the request manually before the vehicle can stop automatic control. In the ap-

plication simulation, and since the switch is performed automatically, the operation is performed without any delay.

Dissolve
Duration (s)
0.0041

Table 6.7: *Dissolve* maneuver duration

6.3 Messages

This next section presents the results regarding the delay (time that elapses from the message creation timestamp until it is received at the destination) of the messages that are sent on the application. The results comprise all types of messages exchanged during the simulation runtime, including both the maneuver messages and the *Platoon Group* messages sent regularly by the *Leaders* (every 100 ms). The obtained results were processed by the *Analysis Toolpak* provided by *Microsoft Excel* for a confidence level of 95%. One analysis example taken from the first simulation run is presented on Table 6.8.

Messages Latency (s)	
Mean	0.0299
Standard Error	$< 0,0001$
Median	0.0267
Mode	0.0009
Standard Deviation	0.0141
Sample Variance	0.0002
Range	0.1749
Minimum	0.0004
Maximum	0.1753
Total number of Messages	
774241	

Table 6.8: Statistic results from messages latency of the first simulation run

The first important remark to be made is that there a lot more operations to handle messages than the expected. The number of messages transmitted by *Followers* are higher due to the need to force the vehicles to constantly search for their *platoon* (using the *Platoon is Group* messages) until they can perform the *Join* operation. Additionally, the exchange of broadcast messages results in multiple copies of the same message to be received by different vehicles with different timestamps.
Nonetheless, the calculated values present a very satisfactory result. They indicate that the PMP is mostly able to deliver the messages on time, and it is able to conform with the very strict communication requirements of the *platooning* application - the messages are able to be generated every 100 ms and the requirement for the maximum delay allowed (100 ms) can be fulfilled. This also means that the impact of the security mechanisms used to encrypt and sign the messages is almost negligible - vehicles can still receive messages in a valid time interval. This way, the data content can be secured while the communication is not compromised.
Table 6.9 presents the number of messages that exceed the expected latency value. It is possible to see that there are a total of 943 messages that are delivered with a latency time greater than 100 ms. From those 943 messages, 81 of them are delivered with a latency value greater than 125 ms, 11 with more than 150 ms and only one message exceeds a latency value of 175 ms. Despite the results not being perfect, these messages represent a universe of only 0,1218% of the total of exchanged messages. Thus, the results are still considered valid.

Latency (ms)	**Number of Messages**	**Percentage (%)**
> 100	943	0.1218
> 125	81	0.0105
> 150	11	0.0014
> 175	1	0.0001

Table 6.9: Messages with latency greater than 100 ms

The mean values regarding the delay from each simulation run is presented in Figure 6.2. As it is possible to see, the values are very close to each other,

which shows that the application can smoothly handle the messages within the expected latency every simulation run.

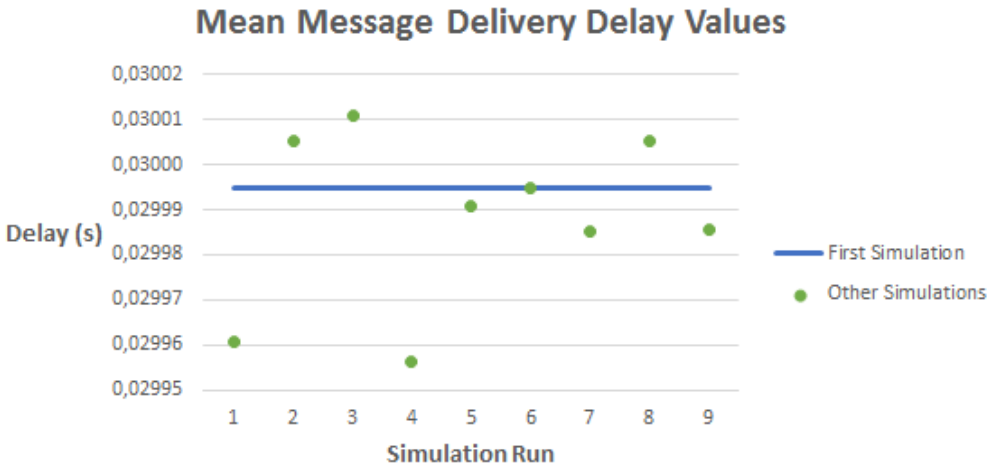


Figure 6.2: Mean message delivery delay values for each simulation

6.4 Distances

This section presents an example result from one simulation run that analyzes the distances that the vehicles should achieve during the application runtime. Vehicles log their *distance to go* value (distance that they should achieve) every second, in order to conclude the behavior of the vehicles when they try to reach the correct position. The vehicle logs are represented as functions (one color for each vehicle) on Figure 6.3. The x axis represents the simulation time and the y axis the distance to achieve in meters. It is important to point out that the "breaks" in the functions happen when the vehicles switch from the *GPS* distance sensor to the *in-vehicle* distance sensor (and vice-versa). The results comprise only the *Follower* logs, since *Leader* vehicles do not keep distances (with exception to *Vehicle_4, that becomes a* Follower *after the* Merge *maneuver*.

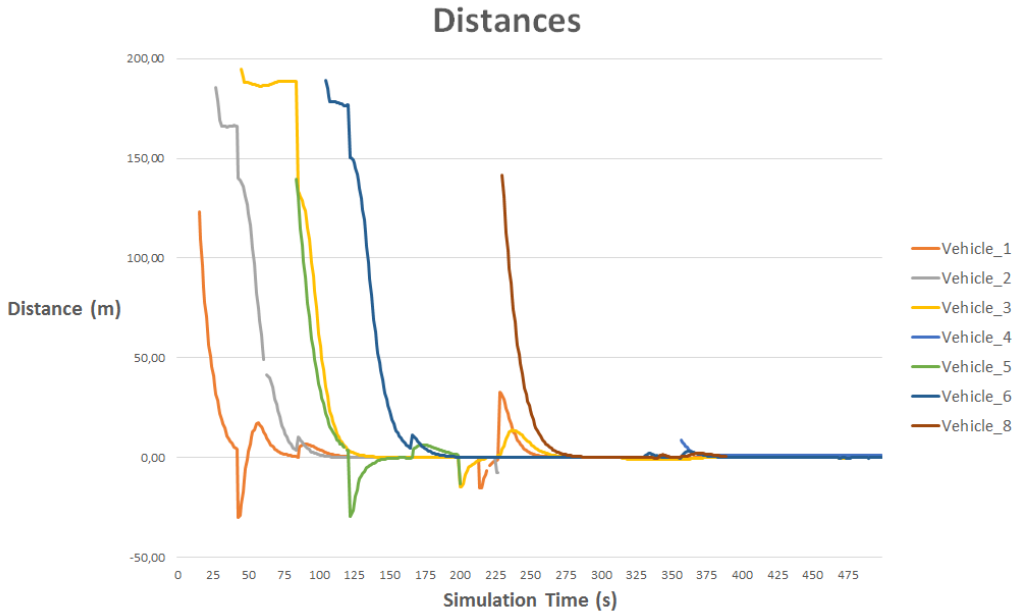


Figure 6.3: Vehicle's *distance to go* value during simulation

The function values start to be recorded when a *Join Request* is sent. At this point, the vehicle starts immediatly to adjust its speed to move to the correct position. In the cases where the Join is immediate (e.g. *Vehicle_1*), the vehicle starts moving right away, which results in a fast descending curve. However, when a vehicle needs to wait for its request to be fulfilled, the *distance to go* value stays in a "stable" state until it receives orders to move to the correct position (e.g. *Vehicle_2* enters this state around the 30 seconds of simulation time mark, lasting for sensibly 16 seconds).
At this point, if the joining maneuver requires other vehicles to adjust their gap (e.g. *Vehicle_1* starts adjusting its gap when *Vehicle_2* receives the *Join Acknowledge*), their *distance to go* value becomes negative. This means that the vehicle should slow down and open a space in the string. The process of adjusting is finished when the *distance to go* values reaches zero again - the vehicle as successfully opened a gap. When the joining vehicle finally joins, the adjusting vehicles receive a *Platoon Update* message from the *Leader*. This means that the vehicle should move forward (the *distance to go* value

becomes positive again), and the vehicles should adjust their speed so the *distance to go* is zero again. At this point, a zero value means that a vehicle is in the right position, at the expected intra-platoon distance.
This process occurs every time there is a maneuver being performed in the simulation. When the vehicles are not maneuvering, the *distance to go* seems to be pretty stable, which means that the vehicles can rapidly adjust their speed to reach the correct position based on the frequent *Platoon Group* messages sent by the *Leader*.
From 450 to 500 seconds of simulation runtime, where the *Leader* starts fluctuating the speed (and consequently, the group speed), the adjusting operation is also very smooth - the *distance to go* values barely suffer alterations.

6.5 Speed

This section presents the results from the speed values that vehicles maintain during the application runtime (vehicles log their *speed* value every second). These results were also obtained from the same simulation run that was used in the *distance* analysis.
The speed logs are represented as functions (one color for each vehicle) on Figure 6.4. The x axis represents the simulation time and the y axis the speed in meters/second. The first descending curve from the *Leaders* happens during the time the *Leader* is reading the configuration files and creating the *Platoon*, before assuming the correct group speed.
Similarly to the distances chart, the *Followers* function values start to be recorded when a *Join Request* is sent. When a given vehicle receives a *Join Acknowledge* from the *Leader*, they start immediately adjusting their speed to move to the correct position. This actually results in vehicles decreasing their *speed* values as they move towards the correct distance, since vehicles travel at their maximum speed until they join a platoon (which have lower group speed values). For example, when *Vehicle_1* joins, the speed decreases immediately (at around 15 seconds of simulation time) to match the *platoon A* group speed of 20 m/s.
After joining a *platoon*, the vehicle's speed stabilize and match the respec-

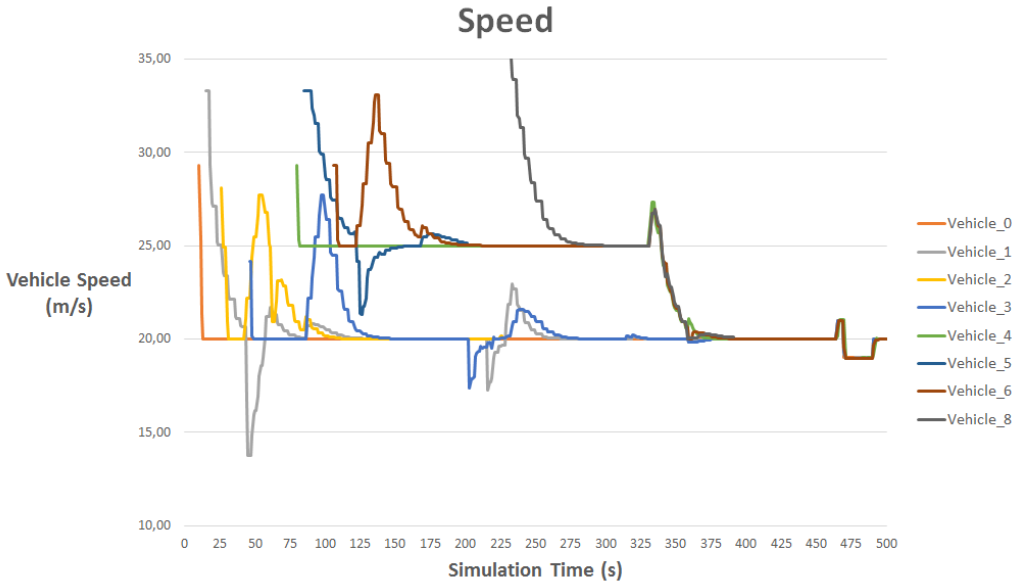


Figure 6.4: Vehicle's *speed* value during simulation

tive *platoon* speed. The fact that the *platoon* speed is constant is a little unrealistic - in the real world, the *Leader* would not be traveling at exactly the same speed during the whole trip. During the forced speed fluctuations introduced from around 450 seconds until 500 seconds of simulation time, the vehicles can easily and smoothly adjust their speed to meet the *Leader* speed - announced to the *followers* through *Platoon Group* messages.
Another important aspect of the speed values that the vehicles assume during the simulation is that they are intimately related to the computed *distance to go* values. This means that the vehicle must increase its speed when the *distance to go* value its positive and to slow down when the *distance to go* is negative. For example, when *Vehicle_2* is joining *Platoon A*, *Vehicle_1* starts decreasing its speed until he opens up a gap in the string in order for *Vehicle_2* to merge into the lane. When this maneuver is finished, *Vehicle_1* increases its speed again to meet the required intra-platoon distance.

Chapter 7

Conclusions and Future Work

Intelligent Transportation Systems (ITS) are systems that aim to assure a more efficient and improved usage of the roads, leading to potential improvements in terms of safety, traffic management and comfort, by controlling traffic operations and drivers behavior. ITS enables the creation of many applications that use the information from vehicles and infrastructures that compose Vehicular Ad Hoc Networks (VANETs) to implement better driving practices and to improve traffic flow. A typical example of one of these applications is the *Platooning* use case.

In the first chapters, this thesis introduces and discusses the related work and general ITS simulation considerations (along with some important tools). Then, the ITS applications taxonomy is presented, giving emphasis to the *Platooning* use case. The *Platooning* application is described in detail and the Platooning Management Protocol (PMP) is introduced, containing the description of the maneuvers and general considerations. Additionally, the PMP requirements are also presented, mostly based on ITS standards defined by the European Telecommunications Standards Institute (ETSI).

The second part of the thesis details the process of deploying the practical PMP implementation and obtaining the results from the simulation runs. The PMP application was implemented using the V2X Simulation Runtime Infrastructure (VSimRTI) framework, coupling Simulation of Urban MObility (SUMO) and Network Simulator 3 (ns-3). The choice of the tools was

not a difficult decision, taking into account that these tools are proven to be very powerful and well-established within the research community.
The deployment chapter describes the process of creating the simulation scenario and associated decisions as well. The *Platooning* application deployment was not an easy task - from the study on the state of the art, it was possible to conclude that the application is immensely complex and sometimes very subjective. For each particular problem that arises from *Platooning*, there are usually a lot of different proposed solutions (e.g. some researchers believe that the distance one vehicle should keep to the preceding vehicle must be based on a constant time gap while others propose a constant distance gap). This seems to be an indicator that the *Platooning* specification is prone to ambiguity. Thus, this work resulted from an effort to trying to meet a "common ground" between the existent proposals. Also, the process of deploying the application required a lot of effort to overcome some lack of "intelligence" the chosen tools present (mainly SUMO simulator). The constant trade-off between a more realistic application and the simulation performance caused some difficulties to evaluate the application behavior.
From the simulation, it is possible to conclude that the PMP is able to work smoothly and efficiently - the duration of the maneuvers are within an acceptable interval, the messages are able to meet the hard communication requirements and the lane capacity is proven to be increased.
The future work could be extended by improving the PMP in order to take into account the existence of abnormal situations, such as obstacles on the road, cut-ins in the middle of the *platoon*, and so on. Furthermore, the simulation scenario could be improved to allow a full dynamic flow of events, in the sense that the maneuvers are not controlled and *platoons* and vehicles travel freely in the roads. The models to calibrate the speed and the vehicles parameters may also be improved. Finally, it would be interesting to evaluate the proposed PMP through experimental testing, instead of simulation means. The PMP could be tested using a series of On-Board Units (OBUs), with every device running the application individually. Since manufacturers wouldn't probably let third parties use the actuators (e.g. brakes, accelera-

tor) on the vehicles for security reasons, the protocol could be adapted to give visual advise to drivers through a Graphical User Interface (GUI) running in a screen installed on the vehicle. For example, the application could advise the driver to open up a gap, to reduce the distance to the front vehicle, etc.

Bibliography

[1] Luca Delgrossi. The Future of the Automobile Vehicle Safety Communications. ME302 - Stanford University, April 1 2014.

[2] Kashif Dar, Mohamed Bakhouya, Jaafar Gaber, Maxime Wack, and Pascal Lorenz. Wireless Communication Technologies for ITS Applications [Topics in Automotive Networking]. *Communications Magazine, IEEE*, 48(5):156–162, 2010.

[3] Mohamed Morsi Mahmod, Issam Khalil, Elisabeth Uhlemann, and Niclas Nygren. Wireless Strategies for Future and Emerging ITS Applications. In *15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting*, 2008.

[4] ETSI. ETSI TR 102 638 V1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions, 2009.

[5] Roberto Baldessari, Bert Bödekker, Matthias Deegener, Andreas Festag, Walter Franz, C Christopher Kellum, Timo Kosch, Andras Kovacs, Massimiliano Lenardi, Cornelius Menig, et al. Car-2-Car Communication Consortium-Manifesto. 2007.

[6] ABI Research. V2V Penetration in New Vehicles to Reach 62% by 2027. `https://www.abiresearch.com/press/v2v-penetration-in-new-vehicles-to-reach-62-by-202/`, 19 Mar 2013. [Online; accessed 28-December-2014].

[7] ABI Research. Mandates, Consortiums, and Autonomous Vehicles to Drive Cooperative V2X Technology Deployments by 2020.

https://www.abiresearch.com/press/mandates-consortiums-and-autonomous-vehicles-to-dr/, 01 Jul 2014. [Online; accessed 28-December-2014].

[8] Cadillac Pressroom. Cadillac to Introduce Advanced "Intelligent and Connected" Vehicle Technologies on Select 2017 Models. http://media.gm.com/media/us/en/cadillac/news.detail.html/content/Pages/news/us/en/2014/Sep/0907-its-overview.html, 07 September 2014. [Online; accessed 29-December-2014].

[9] Toyota Motor Corporation. Toyota to Bring Vehicle-Infrastructure Cooperative Systems to New Models in 2015. http://newsroom.toyota.co.jp/en/detail/4228471/, 26 Nov 2014. [Online; accessed 19-January-2016].

[10] José Santa, Antonio F Gómez-Skarmeta, and Marc Sánchez-Artigas. Architecture and Evaluation of a Unified V2V and V2I Communication System Based on Cellular Networks. *Computer Communications*, 31 (12):2850–2861, 2008.

[11] The European Parliament, Council of European Union. DIRECTIVE 2010/40/EU. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010L0040&from=EN, July 2010.

[12] Oyunchimeg Shagdar, Inria Thierry Ernst, Mines Paris Tech. ITS Standardization. 2013.

[13] Hannes Hartenstein and Kenneth P Laberteaux. A Tutorial Survey on Vehicular Ad Hoc Networks. *Communications Magazine, IEEE*, 46(6): 164–171, 2008.

[14] Yacine Khaled, Manabu Tsukada, José Santa, and Thierry Ernst. On the Design of Efficient Vehicular Applications. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5. IEEE, 2009.

[15] Jayanthi Rao and Thomas J Giuli. Evaluating Vehicular Ad hoc Networks for Group Applications. In *Pervasive Computing and Commu-*

nications Workshops (PERCOM Workshops), 2011 IEEE International Conference on, pages 594–599. IEEE, 2011.

[16] Christian Weiß. V2X Communication in Europe – From Research Projects Towards Standardization and Field Testing of Vehicle Communication Technology. *Computer Networks*, 55(14):3103–3119, 2011.

[17] SARTRE - Safe Road Trains for the Environment. `http://www.sartre-project.eu/`. [Online; accessed 15-Oct-2016].

[18] COMPANION - Cooperative Dynamic Formation of Platoons for Safe and Energy-Optimized Goods Transportation. `http://www.companion-project.eu/`. [Online; accessed 15-Oct-2016].

[19] iGAME - Interoperable Grand Cooperative Driving Challenge AutoMation Experience. `http://gcdc.net/en/i-game`. [Online; accessed 09-May-2016].

[20] SAE. Automated Driving - Levels of Driving Automation are Defined in New SAE International Standard J3016. Technical report, SAE, 2014. URL `http://www.sae.org/misc/pdfs/automated_driving.pdf`. [Online; accessed 15-Oct-2016].

[21] U.S. Department of Transportation Releases Policy on Automated Vehicle Development, May 2013. URL `http://www.nhtsa.gov/About-NHTSA/Press-Releases/U.S.-Department-of-Transportation-Releases-Policy-on-Automated-Vehicle-Development`. [Online; accessed 15-Oct-2016].

[22] Vicente Milanés, Steven E Shladover, John Spring, Christopher Nowakowski, Hiroshi Kawazoe, and Masahide Nakamura. Cooperative Adaptive Cruise Control in Real Traffic Situations. *IEEE Transactions on Intelligent Transportation Systems*, 15(1):296–305, 2014.

[23] Konstantinos Katsaros, Ralf Kernchen, Mehrdad Dianati, and David Rieck. Performance Study of a Green Light Optimized Speed Advisory (GLOSA) Application Using an Integrated Cooperative ITS Simulation

Platform. In *2011 7th International Wireless Communications and Mobile Computing Conference*, pages 918–923. IEEE, 2011.

[24] Carl Bergenhem, Steven Shladover, Erik Coelingh, Christoffer Englund, and Sadayuki Tsugawa. Overview of Platooning Systems. In *Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria (2012)*, 2012.

[25] Levent Guvenc et al. Cooperative Adaptive Cruise Control Implementation of Team Mekar at the Grand Cooperative Driving Challenge. *IEEE Transactions on Intelligent Transportation Systems*, 13(3):1062–1074, 2012.

[26] Konstantinos Katsaros, Ralf Kernchen, Mehrdad Dianati, David Rieck, and Charalambos Zinoviou. Application of Vehicular Communications for Improving the Efficiency of Traffic in Urban Areas. *Wireless Communications and Mobile Computing*, 11(12):1657–1667, 2011.

[27] Michele Segata, Bastian Bloessl, Stefan Joerer, Falko Dressler, and Renato Lo Cigno. Supporting Platooning Maneuvers Through IVC: An Initial Protocol Analysis for the JOIN Maneuver. In *Wireless On-demand Network Systems and Services (WONS), 2014 11th Annual Conference on*, pages 130–137. IEEE, 2014.

[28] Michele Segata, Stefan Joerer, Bastian Bloessl, Christoph Sommer, Falko Dressler, and Renate Lo Cigno. Plexe: A platooning extension for Veins. In *2014 IEEE Vehicular Networking Conference (VNC)*, pages 53–60. IEEE, 2014.

[29] Mani Amoozadeh, Hui Deng, Chen-Nee Chuah, H Michael Zhang, and Dipak Ghosal. Platoon Management With Cooperative Adaptive Cruise Control Enabled by VANET. *Vehicular Communications*, 2(2):110–123, 2015.

[30] Raik Aissaoui, Hamid Menouar, Amine Dhraief, Fethi Filali, Abdelfettah Belghith, and Adnan Abu-Dayya. Advanced Real-Time Traffic Mon-

itoring System Based on V2X Communications. In *2014 IEEE International Conference on Communications (ICC)*, pages 2713–2718. IEEE, jun 2014.

[31] Paolo Bellavista, Federico Caselli, and Luca Foschini. Implementing and Evaluating V2X Protocols Over iTETRIS: Traffic Estimation in the COLOMBO Project. In *Proceedings of the fourth ACM international symposium on Development and analysis of intelligent vehicular networks and applications*, pages 25–32. ACM, 2014.

[32] Michele Segata, Bastian Bloessl, Stefan Joerer, Christoph Sommer, Mario Gerla, Renato Lo Cigno, and Falko Dressler. Toward Communication Strategies for Platooning: Simulative and Experimental Evaluation. *IEEE Transactions on Vehicular Technology*, 64(12):5411–5423, 2015.

[33] Norbert Goebel, Raphael Bialon, Martin Mauve, and Kalman Graffi. Coupled Simulation of Mobile Cellular Networks, Road Traffic and V2X Applications Using Traces. In *2016 IEEE International Conference on Communications (ICC)*, pages 1–7. IEEE, May 2016.

[34] Peppino Fazio, Floriano De Rango, and Andrea Lupia. Vehicular Networks and Road Safety: An Application for Emergency/Danger Situations Management Using the WAVE/802.11p Standard. *Advances in Electrical and Electronic Engineering*, 11(5):357, 2013.

[35] Daniel Krajzewicz, Laura Bieker, and Jakob Erdmann. Preparing Simulative Evaluation of the GLOSA Application. In *ITS World Congress*, number October, 2012.

[36] Söenke Eilers, Jonas Mårtensson, Henrik Pettersson, Marcos Pillado, David Gallegos, Marta Tobar, Karl Henrik Johansson, Xiaoliang Ma, Thomas Friedrichs, Shadan Sadeghian Borojeni, et al. COMPANION–Towards Co-operative Platoon Management of Heavy-Duty Vehicles. In *2015 IEEE 18th International Conference on Intelligent Transportation Systems*, pages 1267–1273. IEEE, 2015.

[37] COLOMBO - Cooperative Self-Organizing System for low Carbon Mobility at low Penetration Rates. www.colombo-fp7.eu/. [Online; accessed 15-Oct-2016].

[38] KONVOI Project. http://vra-net.eu/wiki/index.php?title=KONVOI. [Online; accessed 15-Oct-2016].

[39] Chauffeur II Project. http://www.transport-research.info/project/promote-chauffeur-ii. [Online; accessed 15-Oct-2016].

[40] Energy ITS Project. http://vra-net.eu/wiki/index.php?title=Energy_ITS_-_Automated_Truck_Platoon. [Online; accessed 29-March-2016].

[41] MOTO - Mobile OpportunisTic Traffic Offloading Project. http://cordis.europa.eu/project/rcn/105191_en.html. [Online; accessed 15-OCtober-2016].

[42] PATH - Partners for Advanced Transportation Technology Truck Platooning Project. http://www.path.berkeley.edu/research/automated-and-connected-vehicles/truck-platooning. [Online; accessed 15-Oct-2016].

[43] ns-3: Network Simulator 3. https://www.nsnam.org/. [Online; accessed 15-Oct-2016].

[44] ns-2: Network Simulator 2. http://www.isi.edu/nsnam/ns/. [Online; accessed 15-Oct-2016].

[45] GTNetS - Georgia Tech Network Simulator. http://www2.ece.gatech.edu/research/labs/MANIACS/GTNetS/. [Online; accessed 15-Oct-2016].

[46] OMNeT++ - Objective Modular Network Testbed in C++. https://omnetpp.org/. [Online; accessed 15-Oct-2016].

[47] MiXiM - Mixed Simulator. http://mixim.sourceforge.net/. [Online; accessed 15-Oct-2016].

[48] INET Framework. https://inet.omnetpp.org/. [Online; accessed 15-Oct-2016].

[49] JiST/SWANS - Java in Simulation Time / Scalable Wireless Ad hoc Network Simulator. http://jist.ece.cornell.edu/. [Online; accessed 15-Oct-2016].

[50] SUMO - Simulation of Urban MObility. http://sumo.dlr.de/, . [Online; accessed 15-Oct-2016].

[51] Michael Behrisch, Laura Bieker, Jakob Erdmann, and Daniel Krajzewicz. SUMO – Simulation of Urban Mobility: an Overview. In *Proceedings of SIMUL 2011, The Third International Conference on Advances in System Simulation*. ThinkMind, 2011.

[52] OSM - OpenStreetMap. http://www.openstreetmap.org/, . [Online; accessed 15-Oct-2016].

[53] Feliz Kristianto Karnadi, Zhi Hai Mo, and Kun-chan Lan. Rapid Generation of Realistic Mobility Models for VANET. In *2007 IEEE Wireless Communications and Networking Conference*, pages 2506–2511. IEEE, 2007.

[54] PTV VISSIM - Verkehr In Städten SIMulationsmodell. http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/. [Online; accessed 15-Oct-2016].

[55] VanetMobiSim. http://vanet.eurecom.fr/. [Online; accessed 15-Oct-2016].

[56] CanuMobiSim - CANU Mobility Simulation Environment. http://canu.informatik.uni-stuttgart.de/mobisim/. [Online; accessed 15-Oct-2016].

[57] TSIS-CORSIM: Traffic Software Integrated System - Corridor Simulation. http://mctrans.ce.ufl.edu/mct/index.php/tsis-corsim/. [Online; accessed 15-Oct-2016].

[58] VEINS - Vehicles in Network Simulation. `veins.car2x.org`. [Online; accessed 15-Oct-2016].

[59] iTETRIS Open Simulation Platform. `www.ict-itetris.eu/`. [Online; accessed 15-Oct-2016].

[60] VSimRTI - V2X Simulation Runtime Infrastructure. `https://www.dcaiti.tu-berlin.de/research/simulation/`. [Online; accessed 15-Oct-2016].

[61] Marie-Ange Lèbre, Frédéric Le Mouël, Eric Ménard, Julien Dillschneider, and Richard Denis. VANET Applications: Hot Use Cases. *arXiv preprint arXiv:1407.4088*, 2014.

[62] Panos Papadimitratos, A La Fortelle, Knut Evenssen, Roberto Brignolo, and Stefano Cosenza. Vehicular Communication Systems: Enabling Technologies, Applications, and Future Outlook on Intelligent Transportation. *Communications Magazine, IEEE*, 47(11):84–95, 2009.

[63] Car 2 Car Communication Consortium. `https://www.car-2-car.org/`. [Online; accessed 29-March-2016].

[64] SAFESPOT Project. `http://www.safespot-eu.org/`. [Online; accessed 29-March-2016].

[65] Cooperative Vehicle-Infrastructure Systems Project. `http://www.cvisproject.org/`. [Online; accessed 29-March-2016].

[66] Research NHTSA Headquarters and Innovative Technology Administration. Vehicle Safety Communications - Applications (VSC-A) First Annual Report - December 7, 2006 through December 31, 2007. *DOT HS 811 073*, 4 Sep 2008.

[67] M Sepulcre and J Gozalvez. On the Importance of Application Requirements in Cooperative Vehicular Communications. In *Wireless On-Demand Network Systems and Services (WONS), 2011 Eighth International Conference on*, pages 124–131. IEEE, 2011.

[68] Maziar Nekovee. Quantifying Performance Requirements of Vehicle-to-Vehicle Communication Protocols for Rear-end Collision Avoidance. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5. IEEE, 2009.

[69] Georgios Karagiannis, Onur Altintas, Eylem Ekici, Geert Heijenk, Boangoat Jarupan, Kenneth Lin, and Timothy Weil. Vehicular Networking: A Survey and Tutorial on Requirements, Architectures, Challenges, Standards and Solutions. *Communications Surveys & Tutorials, IEEE*, 13(4):584–616, 2011.

[70] PRE-DRIVE C2X. `http://www.drive-c2x.eu/`. [Online; accessed 29-March-2016].

[71] MA Zabat, NS Stabile, and FK Browand. Estimates of Fuel Savings from Platooning. In *Intelligent Transportation: Serving the User Through Deployment. Proceedings of the 1995 Annual Meeting of ITS America*, 1995.

[72] Mark Michaelian, Fred Browand, et al. *Field Experiments Demonstrate Fuel Savings for Close-following.* California PATH Program, Institute of Transportation Studies, University of California at Berkeley, 2000.

[73] Assad Al Alam, Ather Gattami, and Karl Henrik Johansson. An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning. In *Intelligent Transportation Systems (ITSC), 2010 13th International IEEE Conference on*, pages 306–311. IEEE, 2010.

[74] Assad Alam. Fuel-efficient Distributed Control for Heavy Duty Vehicle Platooning. *KTH Royal Institute of Technology*, 2011.

[75] Christopher Nowakowski, Jessica O'Connell, Steven E Shladover, and Delphine Cody. Cooperative Adaptive Cruise Control: Driver Acceptance of Following Gap Settings Less Than One Second. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 54, pages 2033–2037. SAGE Publications, 2010.

[76] Steven Shladover, Dongyan Su, and Xiao-Yun Lu. Impacts of Cooperative Adaptive Cruise Traffic Flow Control on Freeway Traffic Flow. *Transportation Research Record: Journal of the Transportation Research Board*, (2324):63–70, 2012.

[77] Jeroen Ploeg, Nathan Van De Wouw, and Henk Nijmeijer. Lp String Stability of Cascaded Systems: Application to Vehicle Platooning. *IEEE Transactions on Control Systems Technology*, 22(2):786–793, 2014.

[78] Pravin Varaiya. Smart Cars on Smart Roads: Problems of Control. *IEEE Transactions on automatic control*, 38(2):195–207, 1993.

[79] Tom Robinson, Eric Chan, and Erik Coelingh. Operating Platoons on Public Motorways: An Introduction to the SARTRE Platooning Programme. In *17th world congress on intelligent transport systems*, volume 1, page 12, 2010.

[80] ETSI. ETSI TS 102 637-1 V1.1.1Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 1: Functional Requirements, 2010-09.

[81] ETSI. ETSI TS 102 636-3 V1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; GeoNetworking; Part 3: Network architecture, 2010-03.

[82] ETSI. ETSI EN 302 637-2 V1.3.1 (Final Draft) Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, 2014-09.

[83] ETSI. ETSI EN 302 637-3 V1.1.1 Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service, 2010-09.

[84] Christoph Sommer, Jérôme Härri, Fatma Hrizi, Björn Schünemann, and Falko Dressler. Simulation Tools and Techniques for Vehicular Commu-

nications and Applications. In *Vehicular ad hoc Networks*, pages 365–392. Springer, 2015.

[85] Junling Bu, Guozhen Tan, Nan Ding, Mingjian Liu, and Caixia Son. Implementation and Evaluation of WAVE 1609.4/802.11p in ns-3. In *Proceedings of the 2014 Workshop on ns-3*, page 1. ACM, 2014.

[86] Daniele Azzarelli and Eva Pierattelli et al. D5.1.2 - Deliverable Name Description and Development of MOTO Simulation Tool Environment (Release b) V1.1. Technical report, Mobile Opportunistic Traffic Offloading (MOTO), 2014.

[87] iTETRIS Project. iTETRIS Community. `http://www.ict-itetris.eu/10-10-10-community/activity/`. [Online; accessed 19-September-2016].

[88] Bruno Ribeiro, Alexandre Santos, and Maria João Nicolau. A Survey on Vehicular Communication Technologies. In *Intelligent Environments 2016*, volume 21 of *Ambient Intelligence and Smart Environments*, pages 308–317. IOS Press, 2016.

[89] Ami Uchikawa, Ryohei Hatori, Tomoya Kuroki, and Hiroshi Shigeno. Filter Multicast: a Dynamic Platooning Management Method. In *2010 7th IEEE Consumer Communications and Networking Conference*, pages 1–5. IEEE, 2010.

[90] Shohei Kanda, Masaki Suzuki, Ryo Harada, and Hiroshi Shigeno. A Multicast-based Cooperative Communication Method for Platoon Management (Poster). In *Vehicular Networking Conference (VNC), 2011 IEEE*, pages 185–192. IEEE, 2011.

[91] SUMO: Vehicle Type Parameter Defaults. `http://sumo.dlr.de/wiki/Vehicle_Type_Parameter_Defaults`, . [Online; accessed 20-April-2016].

[92] ETSI. ETSI TS 103 097 V1.1.1 Intelligent Transport Systems (ITS); Security; Security header and certificate formats, 2013-04.

[93] OSM - OpenStreetMap. https://www.openstreetmap.org, . [Online; accessed 21-Oct-2016].

[94] Osmosis. https://wiki.openstreetmap.org/wiki/Osmosis, . [Online; accessed 21-Oct-2016].