Vehicular System for Traffic and Collision Avoidance in Urban Areas

Thesis

Submitted to the Faculty of Fachhochschule Aachen
and Centro de Ingeniería y Desarrollo Industrial

By

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In Partial Fulfillment of the requirements for the degree of
Master of Science in Mechatronics

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To my friends, those who are far away and have always supported me whenever I needed it. Also, to those who studied with me the master's degree and have spent with me these last two years sharing experiences.

Last but not least, to my family: my mother, my father and my sister for supporting me to achieve my goals and never give up. I definitely would not be the person I am now without them.

This work is dedicated to my lovely grandmother and in memory of my grandparents.

“This book of the law shall not depart out of your mouth; you shall meditate on it day and night, so that you may be careful to act in accordance with all that is written in it. For then you shall make your way prosperous, and then you shall be successful. I hereby command you: Be strong and courageous; do not be frightened or dismayed, for the Lord your God is with you wherever you go.´´

Joshua 1:8-9

ABSTRACT

Transport delays due to traffic jams are manifest in many urban areas worldwide. To make road traffic networks more efficient, Intelligent Transport Systems (ITS) are currently being developed to mitigate congestions. New technologies such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications provide means for cooperation, and intelligent route management in transportation networks. As a proposal to contribute in this area, the definition, and conceptual design of a vehicular system for traffic and collision avoidance in urban areas are presented in this thesis.

The methodology used for the creation of the system concept is based on the V-Model for development of projects and the "Inclusive concept design process". In a first approach, the problem statement and the use cases to be solved by the system such as frontal collision, intersection incident, and traffic efficiency were defined. The general and particular objectives were clarified, and the main functions were established based on them. The description of the concept of operation giving the user point of view and the established high-level requirements that need to be accomplished for a successful system are presented in the third section. An analysis of the system functions for the safe distance determination, comparison of vehicle speeds, and determination of situations was done, with it the principles for the position, direction, messages, and detection solutions were elaborated. This analysis helped to obtain the final concept by using the System Modeling Language (SysML) to create a preliminary model that defines the general-purpose architecture of the system. The resulting concept consists of a vehicular system with a communication subsystem based on V2V and V2I technologies, and a sensor subsystem for acquiring data from the surrounding vehicles and infrastructure. Finally, a simulation of the interactions of several systems with similar capabilities to the desired one was done, to obtain valuable data from the expected response times, message frames, and possible anomalies on the system.

The presented system development concluded between the system concept and the preliminary design of the engineering model. The simulation of the system showed that it is possible to transmit and receive messages among the units with security architecture, faster than a normal driver recognition time. Concluding that it is possible to alert the driver before he notices the danger. Also, that it is viable for future works to proceed with a hardware test to obtain a real processing system time, and continue with the further steps of the V-Model to accomplish a fully operational system.

KURZFASSUNG

Verzögerungen aufgrund von Staus im Straßenverkehr sind in vielen städtischen Gebieten weltweit zu beobachten. Um die Effizienz der Straßenverkehrsnetze zu steigern, werden derzeit “Intelligent Transport Systems” (ITS) entwickelt, um Staus zu vermeiden. Neue Technologien wie “Vehicle- to-Vehicle” (V2V) und “Vehicle-to-Infrastructure” (V2I) Kommunikation bieten Mittel zur Zusammenarbeit und zum intelligenten Routenmanagement in Verkehrsnetzen. Als Vorschlag, in diesem Bereich einen Beitrag zu leisten, werden in dieser Arbeit die Definition und das Konzept eines Fahrzeugsystems zur Vermeidung von Verkehrsstaus und Kollisionen in städtischen Gebieten vorgestellt.

Die für die Erstellung des Systemkonzepts verwendete Methodik basiert auf dem V-Modell für die Projektentwicklung und dem “Inclusive concept design process”. In einem ersten Ansatz wurden die Problemstellung und die vom System zu lösenden Anwendungsfälle wie: Frontalkollision, Kreuzungsereignis und Verkehrseffizienz definiert. Die allgemeinen und besonderen Ziele wurden geklärt und darauf aufbauend die Hauptfunktionen festgelegt. Die Beschreibung des Betriebskonzepts aus Anwendersicht und die festgelegten übergeordneten Anforderungen, die für ein erfolgreiches System erfüllt werden müssen, werden im dritten Abschnitt vorgestellt. Es wurde eine Analyse der Systemfunktionen zur Sicherheitsabstandsbestimmung, zum Vergleich von Fahrzeuggeschwindigkeiten und zur Ermittlung von Situationen durchgeführt, mit der die Prinzipien für die Position, Richtung, Meldungen und Erkennungslösungen erarbeitet wurden. Diese Analyse trug dazu bei, das endgültige Konzept zu erhalten, indem eine vorläufige Beschreibung des Systems mit “System Modeling Language” (SysML) erstellt wurde, welche die generelle Architektur des Systems beschreibt. Das daraus resultierende Konzept besteht aus einem Fahrzeugsystem mit einem auf V2V und V2I Technologien basierenden Kommunikationssubsystem und einem Sensorsubsystem zur Erfassung von Daten aus den umliegenden Fahrzeugen und der Infrastruktur. Schließlich wurde eine Simulation der Interaktionen mehrerer Systeme mit ähnlichen Fähigkeiten wie der gewünschten durchgeführt, um wertvolle Daten aus den erwarteten Antwortzeiten, Nachrichtenrahmen und möglichen Anomalien auf dem System zu erhalten.

Die vorgestellte Systementwicklung endet zwischen dem Systemkonzept und dem vorläufigen Entwurf des Engineering-Modells. Die Simulation des Systems hat gezeigt, dass es möglich ist, Nachrichten zwischen den Einheiten mit Sicherheitsarchitektur zu senden und zu empfangen, und zwar schneller als bei einer normalen Menschlichen Fahrer. Abschließend wird festgestellt, dass es für zukünftige Arbeiten sinnvoll ist, einen Hardwaretest durchzuführen und mit den weiteren Schritten des V-Modells fortzufahren, um ein voll funktionsfähiges System zu erhalten.

RESUMEN

Los retrasos en el transporte debido a los congestionamientos de tráfico se manifiestan en muchas áreas urbanas de todo el mundo. Para hacer que las redes de tráfico por carretera sean más eficientes, actualmente se están desarrollando "Sistemas Inteligentes de Transporte" (ITS) para mitigar las congestiones. Las nuevas tecnologías, como las comunicaciones "Vehículo a Vehículo" (V2V) y "Vehículo a Infraestructura" (V2I) proporcionan medios para la cooperación y la gestión inteligente de rutas en las redes de transporte. Como una propuesta para contribuir en esta área, en esta tesis se presenta la definición y el diseño conceptual de un sistema vehicular para evitar el tráfico y las colisiones en áreas urbanas.

La metodología utilizada para la creación del concepto de sistema se basa en el "Modelo-V" para el desarrollo de proyectos y el "Proceso de diseño de concepto inclusivo". En un primer enfoque, se definió el problema y los casos a resolver por el sistema, tales como colisión frontal, incidente de intersección y eficiencia del tráfico. Se aclararon los objetivos generales, y las funciones principales se establecieron en base a ellos. En la tercera sección se presenta la descripción del concepto de operación del punto de vista del usuario y los requisitos de alto nivel que deben cumplirse para obtener un sistema exitoso. Se realizó un análisis de las funciones del sistema para la determinación segura de la distancia, la comparación de las velocidades del vehículo y la determinación de situaciones, con lo cual se definieron los principios para obtener la posición, dirección, mensajes y las soluciones de detección. Este análisis ayudó a obtener el concepto final, y crear un modelo preliminar basado en "System Modeling Language" (SysML) que define la arquitectura general del sistema. El concepto resultante consiste en un sistema vehicular con un subsistema de comunicación basado en tecnologías V2V y V2I, y un subsistema de sensores para adquirir datos de los vehículos y la infraestructura circundantes. Finalmente, se realizó una simulación de las interacciones de varios sistemas con capacidades similares a la deseada para obtener datos valiosos de los tiempos de respuesta esperados, marcos de mensajes y posibles anomalías en el sistema.

El desarrollo del sistema presentado concluyó entre el concepto del sistema y el diseño preliminar del modelo de ingeniería. La simulación del sistema mostró que es posible transmitir y recibir mensajes entre las unidades con una arquitectura de seguridad, más rápido que el tiempo de reacción de una persona normal. Concluyendo que es viable para futuros trabajos proceder con una prueba de hardware para obtener el tiempo real del sistema de procesamiento, y continuar con los pasos adicionales del "Modelo-V" para lograr un sistema completamente operativo.

Contents

1 Introduction

During the last years, road traffic has been increasing steadily, especially in urban areas. Traffic jams cause a huge public cost for cities or countries, and should therefore be reduced. For that reason, it is important to learn and understand how to deal with this problem, and achieve an improvement using intelligent control and management of traffic, or try to reduce traffic emergence.

1.1 Vehicle Collision Facts

The number of road traffic deaths continues to rise steadily, reaching 1.35 million in 2016, the distribution is shown in Figure 1-1. Each region has a different approach to this type of problem, some regions have implemented high vehicle standards for car occupants, others have planned, and designed a better road infrastructure. When considered in the context of the increasing global population and rapid motorization that has taken place over the same period, this suggests that existing road safety efforts may have mitigated the situation from getting worse. Road traffic injuries are the eighth leading cause of death for all age groups and are currently the leading cause of death for children and young adults aged 5–29 years [WHO18].

In 2000, light vehicle crashes (6.1M) accounted 96% of the total crashes on the United States of America (USA) roadways. The four dominant types were: lead vehicle stopped, crossing paths, control loss and lane change. The majority of them, 40% of the light vehicle crashes, happened away from junctions [NSSC03].

According to a survey conducted between 2005 and 2007 by the U.S. Department of Transportation, National Highway Traffic Safety Administration (NHTSA), 94% of the critical reasons in the crash causal chain of light vehicles were assigned to drivers. The main causes were: recognition errors (41%) and decision errors (33%) [Sin18].

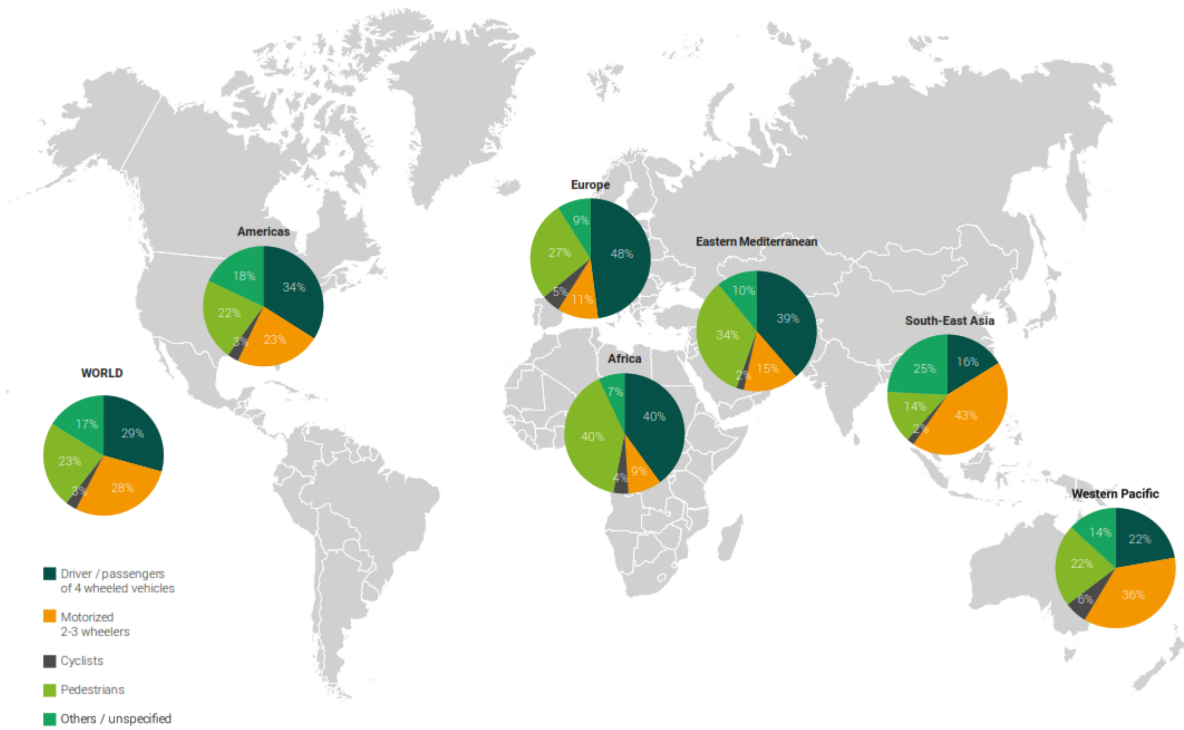


Figure 1-1: Distribution of deaths by region by road user type [WHO18].

The results of the facts presented previously for vehicle collision lead to loss of human lives, harm people, material and monetary personal loss. These facts are not the problem of a single nation, they are a worldwide problem. That is why most of them can be found mentioned in the thesis motivation (Section 1.3).

1.2 Intelligent Transport Systems (ITS)

Vehicle communications show significant promises and contributions to new types of applications in cooperative behaviors, in both automated and autonomous vehicles. Intelligent Transport Systems (ITS) provide a set of strategies for advancing transportation safety, mobility, and environmental sustainability by integrating communication and information technology into the management and operation of the transportation system. With this, offering a connected environment among vehicles, the infrastructure and passengers, allowing drivers to send and receive real-time information about potential hazards and road conditions.

There are several ways for a vehicle to gather information from the surroundings. The most common solutions are Light Detection and Ranging (LiDAR) sensors, radars and sonars. Vision sensors are more widely used in cases where artificial neural networks are applied as an image processing component. Another approach to gather information is to introduce communication among intelligent vehicles, using modern wireless network technologies. Such vehicle communication is more commonly known as Vehicle-to-Everything (V2X), which uses the Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N) communications together (see Figure 1-2).

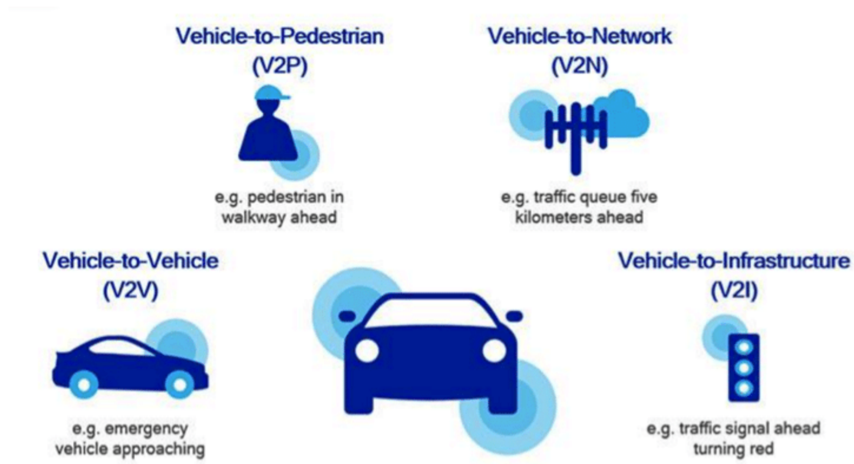


Figure 1-2: Types of V2X [Kin18].

Currently the previous mentioned communications use the Dedicated Short Range Communications (DSRC) network, a vehicular technology mainly built on a similar Wi-Fi standard, and Cellular Vehicle-to-Everything (C-V2X), a 3rd Generation Partnership Project (3GPP) technology standard.

1.2.1 Vehicular networks

When talking about Mobile Ad Hoc Networks (MANETs) we mean a series of computing and communicating devices (nodes) connecting with each other by wireless links, forming an arbitrary graph. In the last decades the main interest was on the idea of smart cities, focusing on bringing this type of networks to high urbanized areas. Vehicular networks are a particular case of MANETs, named Vehicle Ad Hoc Networks (VANETs), the network architecture is shown in Figure 1-3.

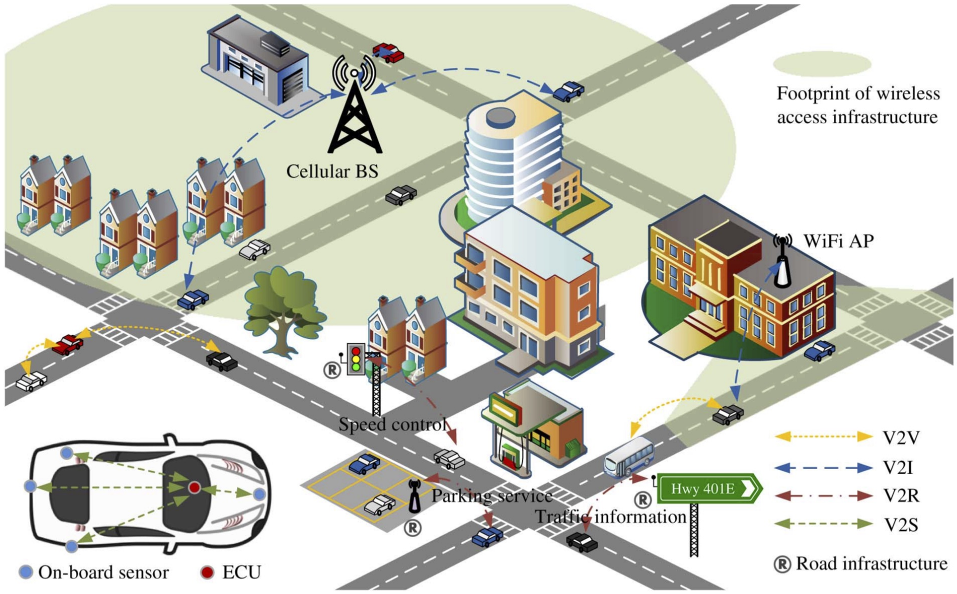


Figure 1-3: VANETs architecture showing the V2V, V2I, Vehicle-to-Roadside Unit (V2R), and Vehicle-to-Sensor (V2S) communication [BBC19].

1.2.2 General overview of VANETs

Unlike other communication systems, in which the primary goal is to achieve high message volume, VANETs aim primarily for communication reliability and fast dissemination.

Communication pathways include [LS18]:

- Vehicle-to-Sensor (V2S): Intra-vehicle messages sent from the sensors to the Electronic Control Unit (ECU), using Controller Area Network (CAN), Local Interconnect Network (LIN) or FlexRay protocol.
- Vehicle-to-Vehicle (V2V): Messages are transmitted between neighboring vehicles. This includes one-hop and multi-hop messaging scenarios in which vehicles communicate directly with other vehicles or through intermediary vehicles.
- Vehicle-to-Infrastructure (V2I): Messages are transmitted between vehicles and roadside units (also called V2R) located on nearby arterial road intersections or highway on-ramps.
- Vehicle-to-Pedestrian (V2P): Messages are transmitted between vehicles and pedestrians who send and receive messages via their phones or other wireless devices.
- Vehicle-to-Network (V2N): Messages are transmitted between vehicles and servers that provide V2N applications.

1.3 Motivation

Congestion on the road is a major problem throughout the world, especially in urban and metropolitan areas. Increasing emergence of individual transport leads to big challenges in traffic management and air pollution. Without a doubt, traffic jams are manifest in many urban areas worldwide and are disadvantageous for travel costs, safety and health. A growing number of vehicles makes these problems more serious.

The INRIX Global Traffic Scorecard, which is a well known and very detailed study of vehicular congestion to date, brings these facts to numbers. The urban area of Mexico City is ranked 4th worldwide for congested city with 218 annual hours lost per driver (see Figure 1-4). In Germany the INRIX study reveals a €1,052 financial burden for each German driver and a total national congestion cost of over €5.1 billion in 2018 [RK19].

2018 IMPACT RANK (2017)	URBAN AREA	COUNTRY	REGION	HOURS LOST IN CONGESTION (RANK 2018)	YEAR OVER YEAR CHANGE	INNER CITY LAST MILE TRAVEL TIME (MINUTES)	INNER CITY LAST MILE SPEED (MPH)
1 (1)	Moscow	Russia	Europe	210 (10)	-12%	5	11
2 (3)	Istanbul	Turkey	Europe	157 (32)	6%	6	10
3 (2)	Bogota	Colombia	South America	272 (1)	-5%	8	7
4 (4)	Mexico City	Mexico	North America	218 (9)	3%	7	9
5 (5)	São Paulo	Brazil	South America	154 (39)	-1%	6	10

Figure 1-4: INRIX Top 5 Most Congested Cities in the World [RK19].

According to the World Health Organization (WHO), in 2012 ambient air pollution contributed to 6.7% of all deaths worldwide. In particular, 16% of lung cancer deaths, 11% of chronic obstructive pulmonary disease deaths, and more than 20% of ischaemic heart disease and stroke are associated with ambient fine particulate matter.

Fine Particulate Matter (PM) pollution ($PM_{2.5}$ and PM_{10}), the complex mixture of chemicals that can penetrate deeply into the lungs, main sources are traffic (25%), combustion and agriculture (22%), domestic fuel burning (20%), natural dust and salt (18%), and industrial activities (15%) worldwide. However, there are significant differences between various regions of the world (see Figure 1-5), due to the geographical (dust from arid areas for example) and the domestic heating mechanism (coal or gas) variation [KBD+15].

The Center for Air Quality, Climate, and Energy Solutions (CACES) at Carnegie Mellon University estimates that the number of lives that could be saved by further reduction of air pollution levels is more than 30,000 each year in the USA, which is similar to the number of deaths from car accidents [Car19].

Technical progress in car development, new communication standards and technical improvements of the infrastructure open up many new possibilities to improve traffic flow and increase efficiency. Tremendous research efforts are made in this fields and new technical possibilities such as autonomous cars will further increase the opportunities.

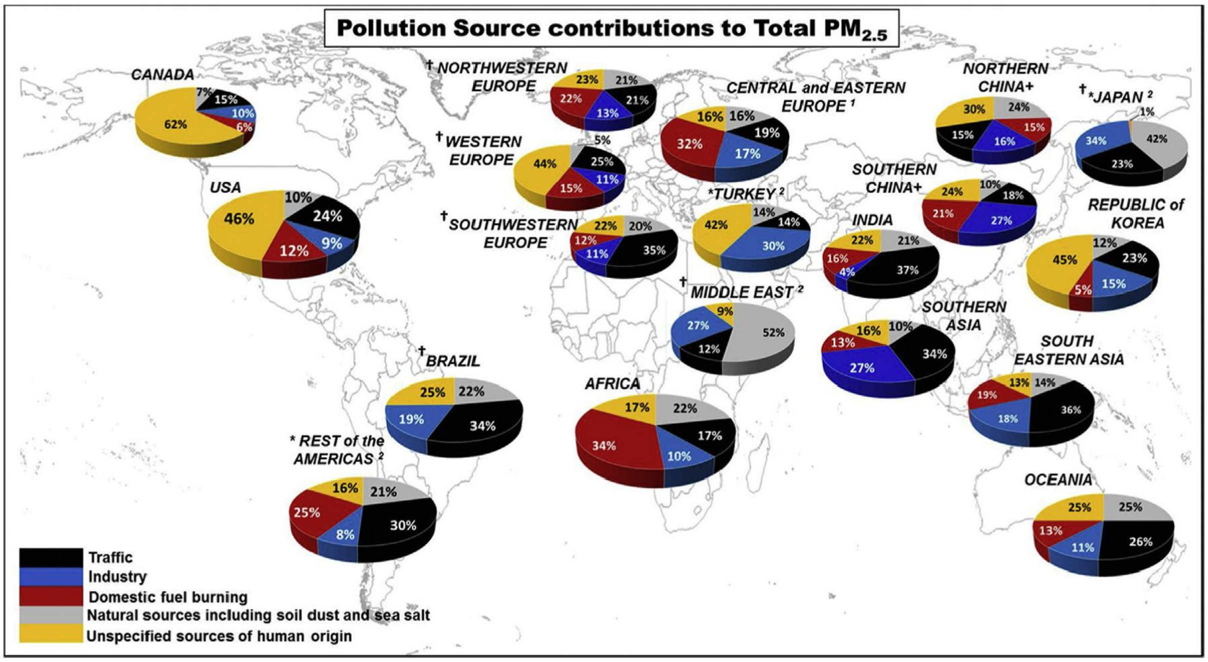


Figure 1-5: Relative source contributions to total $PM_{2.5}$ in urban sites. (*)Regions in which unspecified sources of human origin and (†)regions in which domestic fuel burning sources have not been assessed. [1]Based only on one study including domestic fuel burning, and therefore only provides indicative results. [2]Based only on two studies, and therefore only provides indicative results [KBD+15].

1.4 Objectives

In this section the main objective of the master's thesis is established as well as specific objectives. These objectives are Specific, Measurable, Achievable, Realistic and Time-Bounded, following the SMART criteria.

1.4.1 General Objective

Develop a vehicular system concept to reduce traffic jams and the number of vehicle collisions in the cities. Achieving the objective by using the current emerging vehicular communication technologies, and the factory add-ons to alert the driver from sudden braking vehicles and reduced traffic flow in its current path. The benefits of the system will be measured by simulating the transmission and reception time from a vehicle with the proposed system, and comparing it with an average driver reaction time. The reception time must be lower to show a significant advantage.

1.4.2 Specific Objectives

The specific objectives in chronological order are listed below.

1. **Thesis protocol.** Initial formal thesis definition document.
2. Review of the **state of art, and concept exploration** of commercial products and existent vehicular communication technologies for collision avoidance and traffic congestion in articles, books and internet.
3. Co-write the **concept of operations and high level requirements.**
4. Establish the **fundamental functions and solution principles.**
5. Realize a **concept model design** of the mechatronic system.
6. **Simulation** of the vehicular network system and **establish verifiable parameters** for demonstration of the system benefits.
7. **Thesis manuscript.**
8. **Thesis dissertation.**

1.5 Justification

There is no doubt that traffic jams are manifesting in metropolitan areas worldwide, and are disadvantageous for travel costs and safety. Also, there exist more than the economical and safety consequences of an increasing traffic emergence, such as the environmental aspect. These consequences are pollution, greenhouse emissions and noise. Some previously implemented solutions for this situation was to extend and improve the existing infrastructure for the needed capacities. The last decades, the first reaction was to build roads with higher capacities, due to the lack of knowledge and alternative solutions. This thesis proposes a solution to reduce the current traffic problems produced by the growing vehicular population.

1.6 Scope

The aim of this work is to research and design a concept of a vehicular system using the V-Model for systems engineering, shown in Figure 1-6, this work will reach the concept design part of the system. During the simulation of the system, an urban area will be taken into account with different characteristics, number of lanes and a speed limit of 50 km/h for local streets, suggested by the WHO [WHO18], also the car simulation will be focused into light commercial vehicles which are the largest part of the vehicular collective.

The goal of the system is to:

- Reduce the pollution impact of the urban vehicular collective into the environment.
- Minimize the financial setbacks associated to car accidents and traffic jams.
- Decrease the time consumed during traffic jams and of all the process that implies a vehicle collision.
- Prevent or attenuate the psychological and emotional effects caused by the previously mentioned problems.

1.7 Hypothesis

The project will be developed with a formal hypothesis established.

“Through the use of V2X communication systems, it is possible to decrease the number of vehicular collisions, reduce the traffic flow congestion or mitigate the severity of them. Improving with it the efficiency of resources used while driving, such as time, fuel, and reducing the environmental impact of vehicles."

1.8 Infrastructure

In the master’s thesis project “Vehicular System for Traffic and Collision Avoidance in Urban Areas” several resources are going to be available for its fulfillment, these resources are described in the next subsections.

1.8.1 Human Resources

CIDESI personal involved in the development of this master's thesis are listed below:

- Thesis developer: Eng. Alfonso Ravelo-Hernández
  Born in Tamaulipas, in 1990. He obtained the B.S. degree in Electronic Engineering in 2014 at Instituto Tecnológico Nacional-Campus Ciudad Madero. He has worked as a Commissioning Engineer for 2 years in the offshore platform construction industry as a subcontractor of PEMEX, and 1 year in the chemical industry as a subcontractor of CHEMOURS. Since September 2017 he is doing his double master's degree program at the Center for Engineering and Industrial Development (CIDESI) and the Fachhochschule Aachen (FH Aachen).

- Thesis advisor: Dr. Gengis K. Toledo-Ramírez
  Dr. Eng., 2008 UNAM-Mexico, M.S., 2002 CINVESTAV-Mexico, starts his research career working at the Mechatronics and Micromechanics Lab at the National Autonomous University of Mexico (UNAM) in 2004. He worked as a fellow research scientist at the Institute for Industrial Automation and Software Engineering of the Stuttgart, University, Germany. Since 2012 he has worked at CIDESI-CONACYT, México. Working in fields such as industrial automation, mechatronics, artificial intelligence, automotive, railways and ground based telescopes related projects. He has been reviewer of the Computer Integrated Manufacturing Journal of Thompson and for several projects and studies of Mexico, as well. He has participated in several research papers. His current interests are real-time complex systems, intelligent mechatronics systems and robotics.

1.8.2 Equipment and Materials

For research, simulation and thesis writing a laptop from the brand Lenovo, Ideapad Y700-15ISK model with Windows 10 and Linux, Ubuntu 16.04 LTS was used.

1.8.3 Financial resources

For this thesis project the monetary part was limited to a scholarship from Consejo Nacional de Ciencia y Tecnología (CONACyT) that supports the student program.

1.8.4 Available information and knowledge

All the articles, journals, scientific researches and former works used for this project are obtained thanks to the subscription-based access of the FH Aachen and CIDESI. Also, the open-source community and international organizations free to the public works.

1.9 Methodology

This thesis investigates and evaluates the proposed state of art of vehicle communications (V2X) for real world situations, such as intersections and merging scenarios. Data and channel congestion may be evaluated by finding the maximum rate with which the system can process the messages. Beyond this rate would cause the system to queue the messages and a congestion would be present. This limitation will most likely depend on three bottlenecks: the transfer rate in the physical and the lower layers, the software implementation of the systems and the processing power of the hardware components. By observing and documenting the performance of the vehicle communication, results for the future development of vehicular communications will be obtained.

The activities and work steps will be defined based in the V-Model represented in Figure 1-6. The scope of the project will cover the pre-development (Problem/ Motivation and Concept exploration), and the first stages of the development phase (Concept of operations, System requirements and System concept), which are the definition subphase and the beginning of the design subphase. Due to its emphasize to include as many people as possible for a system design solution, the "Inclusive concept design process" [WGDB+19] shown in Figure 1-7 was selected to complement the main steps taken from the V-Model.

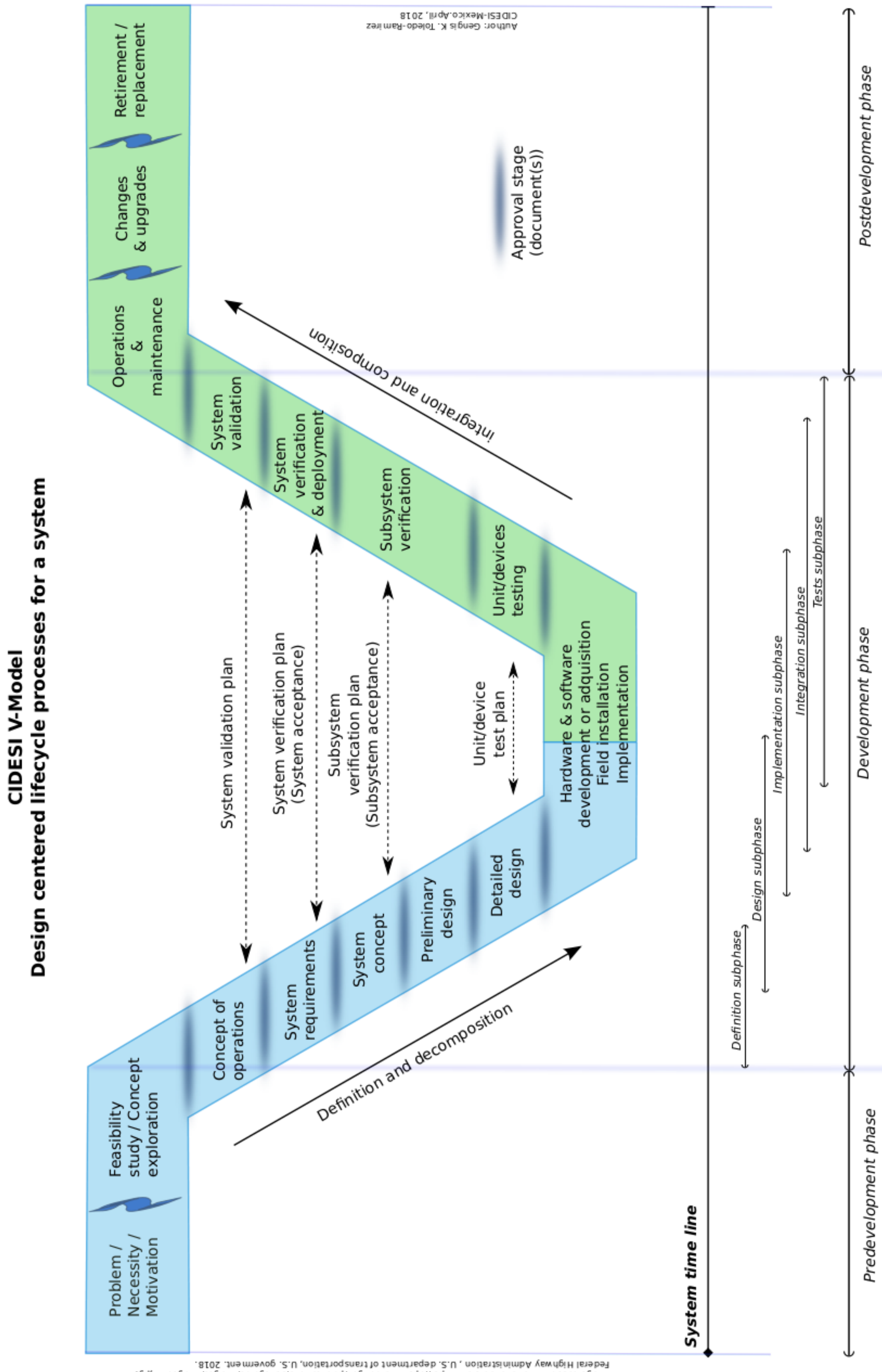


Figure 1-6: CIDESI V-Model for Systems Engineering [Tol18]

Figure 1-7: Inclusive concept design process diagram

The previously shown design cycles were used as reference for the methodology listed below. The performance of these steps is fundamental for a satisfactory result of the proposed system concept model design.

1. Analyze and define the motivation of the project
2. Understand the stakeholders need
3. Define the system
4. Manage the scope of the system
5. Create a list of objectives set in high and low level of priority
6. Decide which use cases and scenarios will drive the development of the architecture
7. Identify the system limits
8. Reconsider use cases and risks
9. Create a preliminary user interface
10. Make a list of essential characteristics or functions for the system
11. Do an initial subsystem partitioning and look at use cases in detail
12. Decide the design of the key scenarios and define formal class interfaces
13. Development of the system concept model
14. Determine the system simulation requirements
15. Simulation of the system
16. Verify the simulation results
17. Identify unexpected cases or risks
18. Write the project documentation
19. Verify the project documentation

2 State of the Art

This section provides a brief review of the assistance systems, the vehicle communication technologies, their applications, relevant projects, papers, and patents to understand the current development state.

2.1 ADAS

Advanced Driver Assistance Systems (ADAS's) are intelligent systems that reside inside the vehicle and assist the main driver in a variety of ways. These systems may be used to provide vital information about traffic, closure and blockage of roads ahead, congestion levels, suggested routes to avoid congestion etc. These systems may also be used to judge the fatigue and distraction of the human driver and thus make precautionary alerts or to assess the driving performance and make suggestions regarding the same. These systems can take over the control from the human on assessing any threat, perform easy tasks (like cruise control) or difficult maneuverings (like overtaking and parking). The greatest advantage of using the assistance systems is that they enable communication between different vehicles, vehicle infrastructure systems and transportation management centers. This enables exchange of information for better vision, localization, planning and decision making of the vehicles [Kal16]. Some applications implemented in the current vehicles are shown in Figure 2-1.

While driving one may be concerned about a variety of things including the route to take, whether one is going on the correct route, the likely congestion levels to expect, whether it is possible to reach the destination on time, whether the current state is safe, and if not what needs to be done, etc. All these questions can concern the mind of the driver which have immense importance in driving. The information based assistance systems take care of all these questions, while enabling the human driver to control the vehicle based on the information provided. These systems do not themselves control the vehicle in any way.

Figure 2-1: Current ADAS applications in vehicles [Men19].

2.2 Current Communication Technologies

In particular, the promise of V2X communications is greater safety and efficient operation. At the present, there are two different technologies enabling V2X (DSRC and C-V2X). Both are rooted from different technologies, leading to fundamentally different operational methods. DSRC, derived from WiFi, is optimized for cost and simplicity, and supports distributed operation. C-V2X, derived from Long Term Evolution (LTE), added new mechanisms to enable distributed operation (V2N).

2.2.1 DSRC

Dedicated Short Range Communications (DSRC) is an open-source protocol for wireless communication, similar in some aspects to WiFi. While WiFi is used mainly for wireless Local Area Networks, DSRC is intended for highly secure, high-speed wireless communication between vehicles and the infrastructure.

The U.S. Federal Communications Commission (FCC) dedicated 75 MHz of spectrum around the 5.9 GHz band (5.850-5.925 GHz) in 1999 to be used for vehicle related safety and mobility systems [Der99]. In August 2008, the European Telecommunications Standards Institute (ETSI) allocated 30 MHz of spectrum for the ITS-G5A for road safety services and 20 MHz for the ITS-G5B for general purposes in the 5.9 GHz band [SL19].

Some DSRC features are:

- A low latency with delays involved in opening and closing a connection close to 0.02 seconds.
- Very robust in the face of radio interference. Its short range (1000 m aprox.) limits the chance of interference from distant sources. Additionally, DSRC is protected by the FCC and ETSI for transportation applications.
- Strong performance during adverse weather conditions.

This communication technology is already accepted and being implemented by the car manufacturers. Nowadays its applications are under test and in process to be part of our daily drive experience. The current price and its future projection for equipping a vehicle with DSRC technology is shown in Figure 2-2.

In-vehicle collision avoidance systems	Year	System Costs
Advanced Emergency Brake System in the UK (2012-00275)	2011	$334 - $1,337
Side collision warning system (Blind Spot Warning) (2013-00287)	2010	$760 - $2,000
Radar-based Truck Collision Avoidance system (2017-00382)	2014	$2,500 - $4,000
Cost to Vehicle Manufacturers for Embedded On-board DSRC equipment (2013-00288)	2017	$175
Cost to Vehicle Manufacturers for Embedded On-board DSRC equipment (2013-00288)	2022	$75
Cost Added to Base Vehicle Price for DSRC equipment (2013-00288)	2017	$350
Cost Added to Base Vehicle Price for DSRC equipment (2013-00288)	2022	$300
Aftermarket DSRC equipment (2013-00288)	2017	$200
Aftermarket DSRC equipment (2013-00288)	2022	$75

Figure 2-2: Cost estimates to equip a car with DSRC technology [HHL+17].

2.2.2 C-V2X

Cellular Vehicle-to-Everything (C-V2X) is a unified connectivity platform developed within the 3rd Generation Partnership Project (3GPP), designed to operate in two transmission modes [PK17]:

1. Direct communication: In this mode C-V2X works independently of cellular networks for scheduling, this mode offers V2V, V2I and V2P.

2. Network communication: It is aimed at leveraging the comprehensive coverage of LTE networks to enable reliable, real-time communication at high speeds and in high-density traffic. This mode offers V2N.

This new technology is the current market competitor of DSRC, proposing a benefit by using the LTE network for a direct V2N communication instead of needing a close Road Side Unit (RSU) for getting the external network information. Some of the major promoters of C-V2X are big companies as Qualcomm, Audi, Ford and Ducati.

Qualcomm is one of the head producers of C-V2X chipsets, field trial validations around the U.S., Europe, and Asia are being held right now with them. The 9150 C-V2X Chipset specifications (see Figure 2-3) show similarities to current market cellphone chipsets or small board computers.

Specifications

CPU	**CPU Clock Speed:** Up to 1.7 GHz **CPU Cores:** ARM Cortex A7
Process	**Process Technology:** 14 nm
PC5 Sidelink	**Sidelink Features:** PC5 Support, 23dBm, 20Mhz Channel BW **C-V2X Direct Communications:** V2V, V2P, V2I, 3GPP R-14 Spec
Location	**Satellite Systems Support:** Beidou, GPS, Galileo, GLONASS
Interface	**Supported Interfaces:** I^2S, PCIe, I^2C, GPIO, SDIO, SPI, UART, USB 2.0, USB 3.0
Navigation Software	**Dead Reckoning:** Qualcomm® Dead Reckoning 3.0

Figure 2-3: Qualcomm 9150 C-V2X Chipset specifications [Qua19].

2.3 Vehicular Network Security and Architecture

To become a real technology that can guarantee public safety on the roads, vehicular networks need an appropriate security architecture that will protect them from different types of security attacks.

2.3.1 Security

Some security mechanism aspects explored are [LQL19] [Ahm15]:

- Event Data Recorder (EDR): EDR will be responsible for recording the vehicles critical data such as position, time, speed, etc. EDR will also record all the received safety messages.
- Tamper Proof Device (TPD): TPD will store all the cryptographic materials and perform cryptographic operations like signing and verifying safety messages.
- Vehicular Public Key Infrastructure (VPKI): In this infrastructure certificate authorities will issue certified public/private key pairs to vehicles.
- Authentication: Vehicles will sign each message with their private key and attach corresponding certificate. Thus, when another vehicle receives the message it verifies the key used to sign the message and then it verifies the message.
- Privacy: To conceal vehicles identity , set of anonymous keys that changes frequently can be used. This keys are preloaded into vehicles TPD for long duration.

2.3.2 Architecture

The Wireless Access in Vehicular Network (WAVE) stack architecture specifies at the bottom a Physical (PHY) and Medium Access Control (MAC) layers as shown in Figure 2-4. The PHY layer uses 10 MHz wide channels to reduce the Doppler spread and the intersymbol interference caused by multipath fading. At the MAC layer, the access rules of the baseline 802.11 standard are used with prioritized channel access, but with simplified setup operations to deal with the short-lived connectivity. No notion of a Basic Service Set (BSS) is considered in VANETs, so a vehicular node is allowed to transmit without becoming a member of a BSS by using a communication mode referred to as Outside the Context of a BSS (OCB), which does not require preliminary authentication and association of the node.
The security layer is specified by the Institute of Electric and Electronics Engineers (IEEE) 1609.2 standard; the addressing, routing, network, and transport issues by 1609.3, the extensions to the MAC layer for multichannel operations and channel coordination by 1609.4 [CM13].

The nodes offering vehicular services are referred to as providers, while other nodes, called users, subscribe to them. Providers advertise their services by broadcasting announcements messages, called WAVE Service Advertisement (WSA). These messages contain information on the offered services and the network parameters necessary for the users to connect to the provider. Interested users simply tune the transceiver to the advertised channel frequency to access the services [CM13].

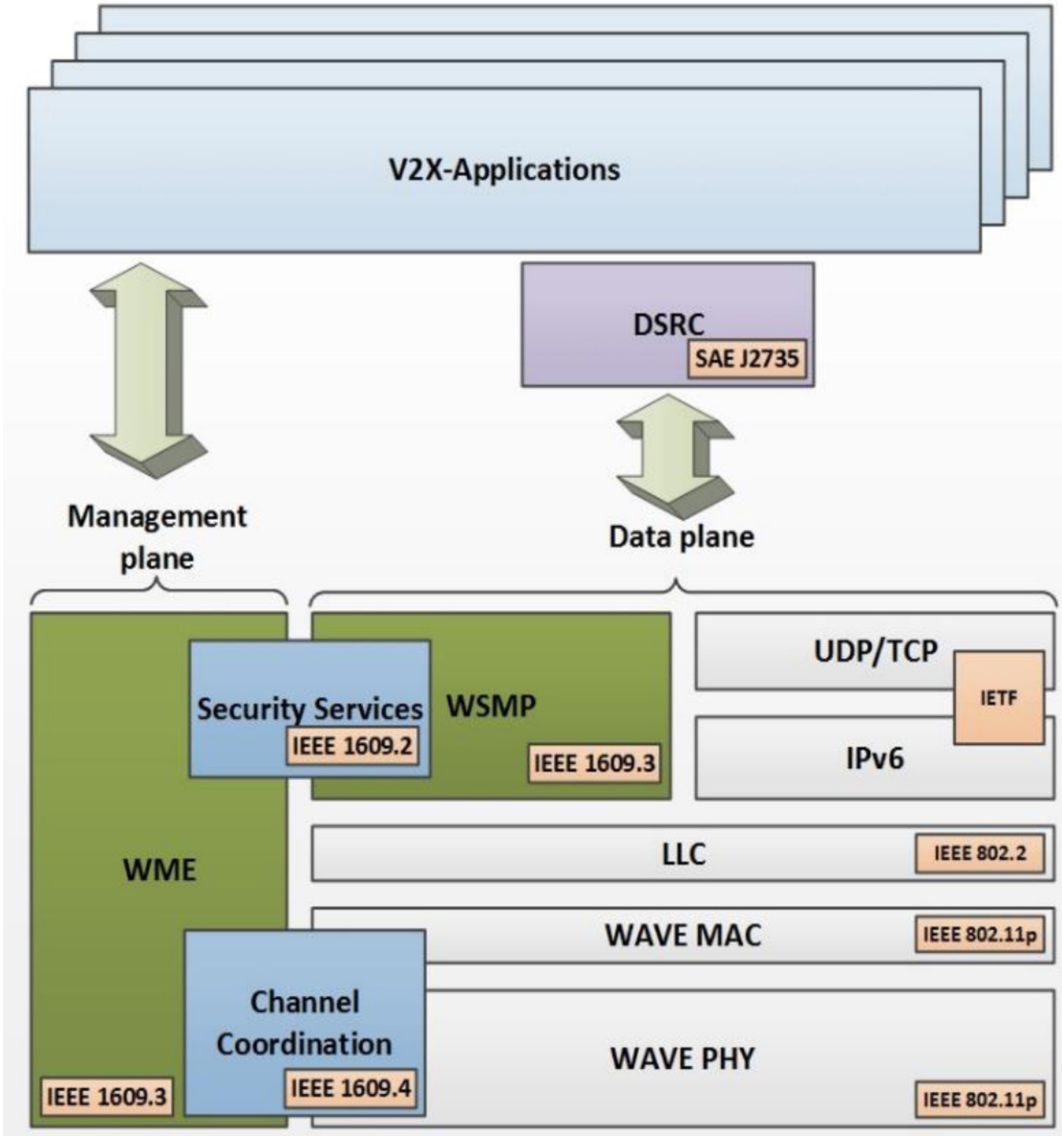


Figure 2-4: IEEE WAVE stack protocol architecture [PLP+16].

2.4 Applications of Vehicular Communication

In recent years, more research works and products have been proposed for V2V or V2I communications for reducing accidents.

Some works and inventions on the vehicle communication field are used to aid other mobile technologies applications, such as DSRC, which can be adapted with a Global Position System

(GPS) module via the same Central Processing Unit (CPU) for a better position detection in areas where GPS is limited or not accessible. The information can be provided by a DSRC base station to the device and then both system data are compared and corrected [HMH03]. The position information is one of the important variables needed for some collision avoidance systems, but the Global Navigation Satellite System (GNSS) limits these applications to open areas. Tunnels or covered ceilings block satellite reception.

Protocols or transmission methods can be implemented in vehicles to broadcast priority messages to surrounding ones in the transmission range. The message can be transmitted by any vehicle detecting a problem in the road or an accident, this message is then re-broadcasted to others during a certain time for a stipulated number of repetitions [LYZ06].

Enhancements to current systems are also part of the goals to improve transport safety, the vehicle warning light system transmits a warning signal to the next rear vehicle and it to the subsequent one. The system activates the rear lights of the vehicles with an intensity proportional to the depression of the brake pedal [Cor06]. This type of system is useful in car platooning, and for car-truck-car scenarios where the field of view is obstructed by the following vehicle.

The transmission method can also be used for warning about other cars that are not in the vision range. For example a first vehicle receives data about a second one within a proximity of an intersection, where both of them are in perpendicular lanes out of their vision due to the presence of a building. The second one is notified too about the presence of the first one [Kel09]. Also, an object data map can be created using this information, and with the addition of a sensor object data map merge into a cumulative object data map. This way a vehicle awareness system can estimate the relative position of remote vehicles and obstacles in the roadway [ZKS12].

2.4.1 Emergency electronic brake light

The Emergency Electronic Brake Light (EEBL) is a safety application in development in the vehicular networks. An application scenario for this technology is shown in Figure 2-5. When the first car hard brakes, the second car can stop without collision based on driver vision, but the third car may not stop fast enough and collide with the second one. Using V2V it is possible to alert the following cars from a sudden hard brake [SXWL12].

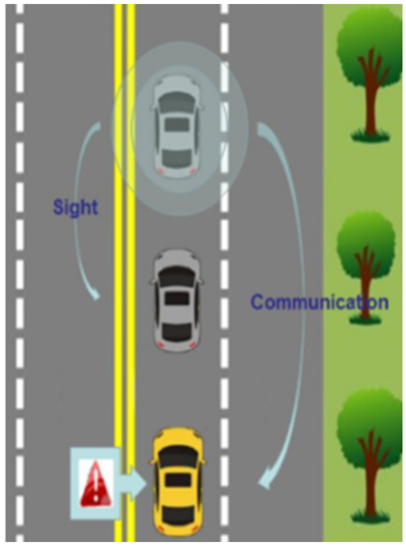
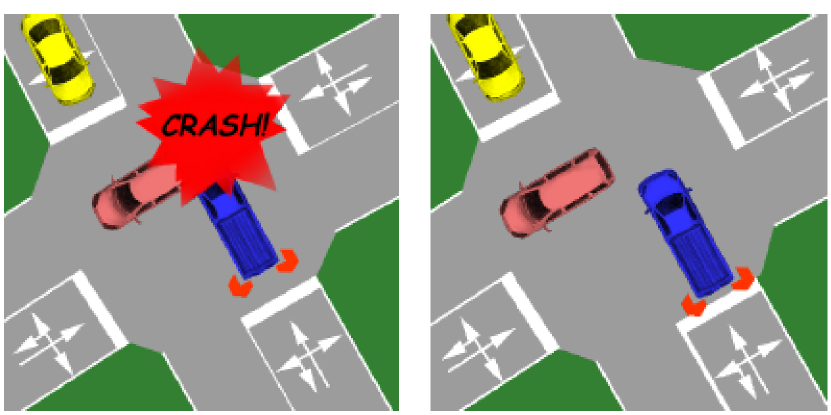


Figure 2-5: Emergency electronic brake light system scenario [TCC+15].

2.4.2 Cooperative intersection collision avoidance

The Cooperative Intersection Collision Avoidance Systems (CICAS) implements critical safety applications combining different ITS technologies to reduce intersection accidents by providing real-time warnings, both in the vehicle and on the infrastructure. The ITS technologies proposed in CICAS include in-vehicle positioning, roadside sensors, intersection maps, and two-way wireless communication. For wireless communication, CICAS uses the DSRC technology. An application scenario is shown in Figure 2-6, where V2V communication enabled vehicles inform others of their presence. The blue vehicle receives the broadcasted message, waits for the fast oncoming red one to pass the intersection and only after that continues its way [LFBZ09].



(a) (b)

Figure 2-6: a) Collision due to non-CICAS warning. b) Collision avoidance due to CICAS implementation in the red and blue vehicle [JBH+14].

2.5 Future Trends

Crash prevention and safety systems detect unsafe conditions and provide warnings to travelers to take action to avoid crashes. These systems provide alerts for traffic approaching dangerous curves, off ramps, restricted overpasses, highway-rail crossings, high-volume intersections, work zones, adverse weather conditions, and also provide warnings of the presence of pedestrians, bicyclists, and even animals on the roadway.

As connected vehicle technologies are just now being developed and tested, few evaluations are available. However, driver acceptance clinics were conducted at six different cities in the United States to assess how motorists respond to connected vehicle technologies and benefit from in-vehicle alerts and warnings. The preliminary findings showed that 91% of volunteer drivers that tested V2V communications safety features indicated they would like to have these technologies on their personal vehicle [Luk12].

The integration of all these systems helps the current market to get used to the autonomous applications. A brief introduction of the stepped integration of automation in vehicles is mentioned in the next subsection.

2.5.1 Autonomous Vehicle

Society of Automotive Engineers (SAE) International describes the “Levels of driving Automation" with its J3016 standard, creating an initial regulatory framework, and guide for manufacturers and clients. A simplified chart of the standard is shown in Figure 2-7. It defines six levels of driving automation in the context of motor vehicles and their operation on roadways [Kel18]:

- Level 0 - No Automation: The driver performs all operating tasks like steering, breaking, accelerating or slowing down. Accounts the majority of vehicles on the road today.
- Level 1 - Driver Assistance: The vehicle has a single aspect of automation, steering, speed or braking, but never simultaneously.
- Level 2 - Partial Automation: The vehicle is able to control two aspects of the car, but the driver still remains in complete control of the vehicle.
- Level 3 - Conditional Automation: The vehicle controls all monitoring of the environment, the driver’s attention is still critical, human interaction can be required to execute some tasks.

- Level 4 - High Automation: The car is able to respond to different situations, human interaction is mostly not required.
- Level 5 - Complete Automation: Human interaction is not required, there is no need for pedals, brakes or steering wheel.

The proposed system of this thesis is intended to initially act as a driver assistance (Level 1) by just alerting the user, but not having a direct action into the vehicle. Nevertheless, its functions can be scaled through all the levels of automation by making the response of the system act directly into it, even they can be part of the highest one (Level 5).

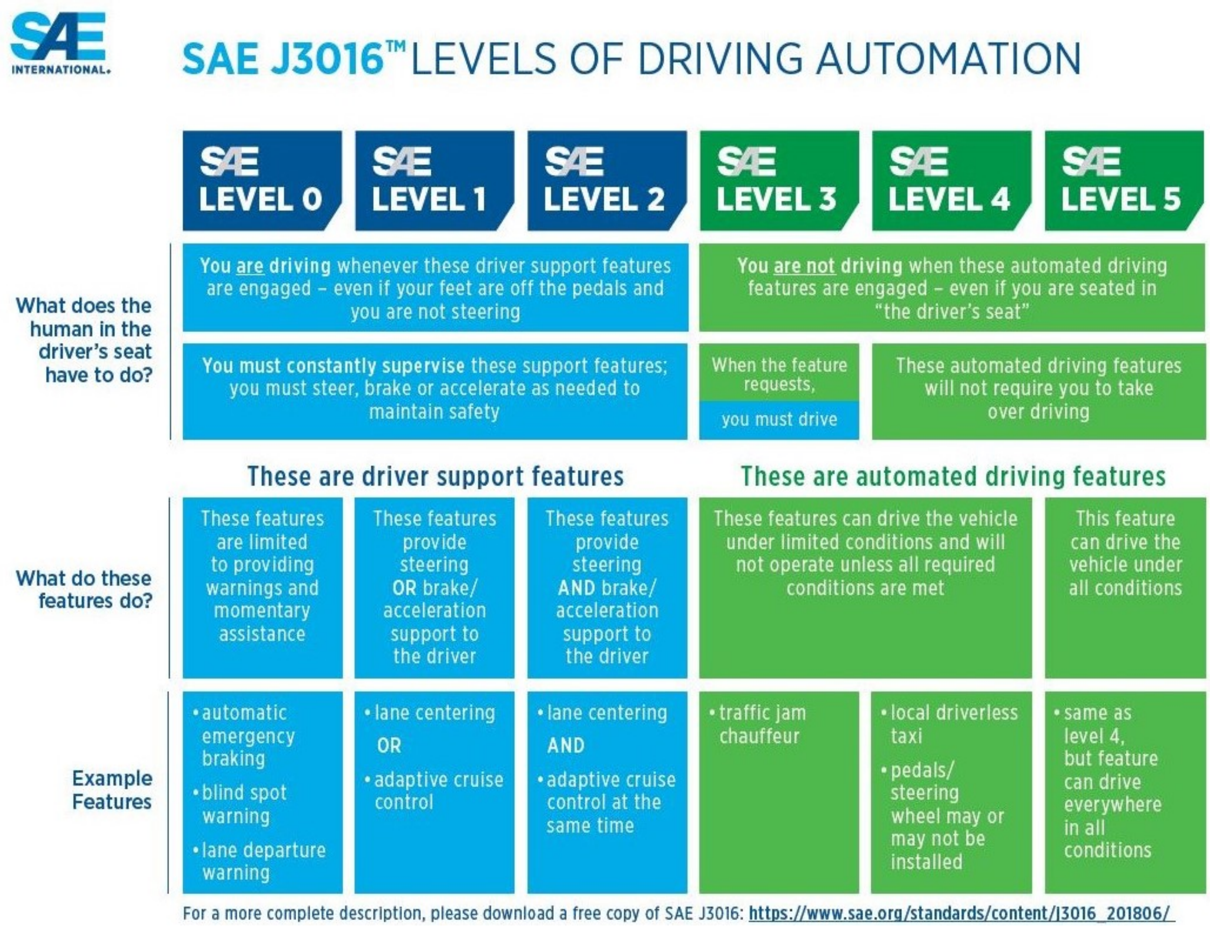


Figure 2-7: Levels of Automated Driving graphic [Shu19].

3 System Approach

An important first step is to make an approach to the system to be developed, to make clear which objectives or functionalities will be satisfied by the system to be designed.

For this, the problem statement and the system objectives for each use case, the concept of operations as a framework of several systems for traffic and collision avoidance, the selection of which functions will be performed by the system to be designed and the high level requirements that should be accomplished by those systems, are presented in the following sections.

3.1 Problem statement

The general problem can be sectioned into particular use cases, which can be solved by different functions that can be performed by the system.

Each problem statement with its corresponding use case is considered in Table 3-1.

Table 3-1: Problem statement for each use case.

Problem statement	**Use case**
A vehicle reduces its velocity abruptly, as a result, another one behind it may not have sufficient time to react and an accident may occur. Drivers sometimes do not react immediately after a deceleration in the leading vehicle occurs due to distraction or they misjudge the situation.	Frontal collision due to driver negligence

Problem statement	Use case
When the driver does not leave enough space between his and the succeeding car, the sum of the distance that will be traveled during the driver reaction time plus the distance traveled while braking is higher than the spacing among them, a collision may occur.	Insufficient spacing between vehicles
A driver may overlook other vehicle when entering or turning at an intersection due to obstacles, distraction or bad weather. During an intersection maneuver a driver may overlook a potential collision risk with other vehicles, negligent drivers or obstacles obstructing the sight at the street corners are not rare cases.	Intersection incident
An accident occurs at an intersection or roadway, therefore, the traffic flow will be reduced or it can cause a new one. Areas susceptible to collisions or accidents may appear into the road without prior warning, this accidents sometimes are caused by external entities such as pedestrians, drivers sometimes do not notice traffic signs or a recent event is held at some point of the roadway.	Emergency situation
Abnormal road conditions or traffic density increased among the roads. Vehicles during traffic jams reduce their speed or stop due to an obstruction in the roadway, other vehicles do not take alternative paths because they are not aware of the situation until they are already into it.	Traffic efficiency

This problem statement will help to identify the gap between the current problem state and the desired developed solution, to have a clear description of the issues that need to be addressed and a vision of them. With the use cases defined, the objectives and the resulting course of action will be determined in the next sections.

3.2 Objectives of the system

In order to clarify the purpose of the system, a list of objectives classified in particular objectives for each of the proposed functions, and general objectives which should be accomplished by any of them is presented in Table 3-2.

Table 3-2: Particular and general objectives of the system for the use cases.

Function	**Particular objectives**	**General objectives**
Prevention of frontal collision due to driver negligence	• Avoid or reduce collision of vehicles • Avoid or minimize congested traffic • Warning for sudden deceleration of succeeding vehicles	• Non-intrusive system • Fast response time • Show clear warning signals • Adequate audible warnings • Automotive environment resistance • Easy to operate • Energy supply from the vehicle connector • To be secure for the driver, other vehicles and pedestrians
Prevention of insufficient spacing between vehicles	• Avoid or reduce collision of vehicles • Avoid or minimize congested traffic • Warning for critical distance between vehicles	
Prevention of intersection incident	• Avoid or reduce collision of vehicles • Avoid or minimize congested traffic	
Alert for emergency situation	• Avoid or reduce collision of vehicles • Avoid or minimize congested traffic • Protection of pedestrians	
Traffic efficiency	• Avoid or minimize congested traffic • Decrease air pollution emissions of vehicles	

After identifying the particular objectives of each function, a broader outlook of the system is established to meet the specific objectives of it, and the functional boundaries between each sub-system becomes more clear.

The particular objectives of each function are compared in Table 3-3 in order to identify common objectives between the use cases besides the general objectives.

Table 3-3: Comparison of particular objectives between main use cases.

Objective	Negligence	Insufficient spacing	Intersection incident	Emergency situation	Traffic efficiency
Reduce collisions	✓	✓	✓	✓	
Minimize congested traffic	✓	✓	✓	✓	✓
Critical distance warning		✓			
Sudden deceleration warning	✓				
Protection of pedestrians				✓	
Decrease air pollution					✓

It can be observed that some objectives from one use case are similar from the other use cases or does not affect their functionality, so it is possible to combine some use cases to form a new system able to perform both of them.

3.3 Concept of Operations

This chapter is aimed to describe the Concept of Operations (ConOps) for a vehicular system for traffic and collision avoidance. Nevertheless, the system development described in this thesis will be up to the concept design phase. The ConOps describe the expected functionality of a future or existence system in terms of its users. It supplies important information for the acquisition or development of the system to develop. It includes the current project situation, system stakeholders, concepts of the required system and important operational procedures for it.

3.3.1 Current system status

V2X communication channels are regulated in the USA by the NHTSA and in Europe by the ETSI, but currently there are no completely functional or commercial systems despite it is already a regulated communication. Automotive companies are developing and testing applications with V2X communication right now, that means that technical information is limited due to commercial confidentiality. Some cities around the world are investing in V2X infrastructure to help achieve a mid-term solution.

It is important to notice how other countries take traffic jams as a serious problem which impacts directly the country economy. Mexico has traffic jam problems in some of its big cities due to its population growth and the expectation is to continue increasing. The benefits of the system proposed by this thesis can help some of the problems generated by the population increase. At the moment, any system or any related subsystem has not been developed in our group or institution.

3.3.2 Stakeholders

A preliminary stakeholders analysis is important in order to consider them during the system development. Within the stakeholders there are those who require the development of the system or at least are direct beneficiaries of the existence of such system. In the opposite sense, there are people which the system could generate a negative impact to them, and so, they are potential detractors of the proposed system.

The current envisioned stakeholders for the system which is required to be developed are listed as follows:

1. **Vehicle drivers.** Urban drivers are interested in having safety add-ons in their vehicles to reduce the possibility of an accident or minimize its consequence. Also, reducing the time spent in traffic jams means less wasted time.

2. **Vehicle passengers.** Every person inside a vehicle that is not necessarily driving could benefit from the safety and efficiency of it.

3. **Family of vehicle drivers and passengers.** People related to drivers or passengers prefer safer means to transport their relatives from their home to their jobs or other places. A more efficient transportation helps them to have more time with their relatives.

4. **Pedestrians.** An accident involving a pedestrian and a vehicle could be lethal for the non-driving part, safer intersection systems involving pedestrians would make them less susceptible to accidents.

5. **Automotive suppliers.** Safety add-ons are among the preferred features of clients purchasing a vehicle, which implies a more attractive product for the customers. The priority of the product that they are selling must be to transport people in the safest way possible.

6. **Insurance companies.** The cost of a vehicle insurance depends on the probability of an

accident involving a monetary loss and how big that loss is. A reduction in the collision probability and its severity implies a reduction on costs to the company.

7. **Government.** Traffic problems in a city have an impact in the resources needed to diminish them for the government. The government is responsible to attend all types of accidents in the road and bring a solution to them.

8. **General population.** The more time a combustion vehicle spends in the road translates into more particles emitted into the environment. This particles reduce the air quality and affect in a negative way the environment. All this affections in the environment have a direct repercussion into the general population of the city. Traffic efficiency reduces the impact that vehicles have into it.

3.3.3 Concepts of the required system

This section is aimed to describe the general concepts for the required system in terms of the users and not from its developers.

3.3.3.1 Operation policies and constraints

The system must comply the international standard for functional safety of electrical and/or electronic systems in production automobiles defined by the International Organization for Standardization (ISO), which is the ISO 26262. Processes within this standard safety life cycle identify and assess hazards (safety risks), establish specific safety requirements to reduce those risks to acceptable levels, and manage and track those safety requirements to produce reasonable assurance that they are accomplished in the delivered product.

The system shall be able to work in an automotive environment, each subsystem must withstand the different conditions of the location in which they are installed or will be working at. Some conditions include a dirty location (dust, water, impact, etc.), magnetic interference from outer sources or even from other internal systems of the vehicle itself, and temperatures proper from their location in the vehicle. This constraints of the system are mentioned in the international standard for electrical and electronic equipment of road vehicles, the ISO 16750 that determines the testing and environmental conditions to which the system will be subjected. This standard also works in accordance with the ISO 20653 that stipulates the degree of protection of electrical equipment against foreign objects, water and access. Another standard linked to it that specifies the relevant protection of an enclosure's resistance to impacts and shocks is the International Electrotechnical Commission (IEC) 62262, and its standardized testing methods.

3.3.3.2 Limits and interfaces

The are few aspects that limit the required system. The first one is the level of integration into the vehicle, some signal variables could be used directly into the vehicle to take an action, but for a system concept this will not be the case and the response of the system will be limited to alerts in a screen or in an audible format. This mean that a non-intrusive system will be the first approach to the development of the project.

The required power supply will be limited to the one provided by a commercial vehicle system, and must not interfere or cause a malfunction on it.

The user system interface shall be intuitive as possible for commodity, also the visual and audible alerts. The Human Machine Interface (HMI) must be functional during normal driving and not interrupt or distract the driver.

3.3.4 Operational concepts

In this last section, the minimal operational concepts are listed for different procedures, including setup, shut down, calibration, diagnostic, maintenance, training and others:

1. **Setup procedures.** Once the system is installed, it must be as fast and easy as possible. Wiring the equipment into the power supply and turning it on with a button must be the only parts of this procedure.
2. **Shut down procedures.** Turning the system off with the same button used to turn it on and as fast as possible.
3. **Calibration procedures.** Should be considered only if it is necessary. The calibration of the sensors and complete system must be done only out of the road in a service workshop or by an authorized technician.
4. **Diagnostic procedures.** Warnings will be displayed during the system operation to notify if a critical event occurs, and if the system encounters a malfunction or anomaly on it, a different warning from the operational ones will be displayed.
5. **Backup procedures.** A backup is not contemplated. When needed the system can be reset to factory configuration.
6. **Maintenance procedures.** Preventive maintenance shall be made during out of service instances. The sensors of the system should be easy to clean or remove obstructions. Corrective maintenance should only be done by an authorized technician.

7. **Training procedures.** The system must include an user manual/guide for a brief explanation of the system functions, how it works, the visual and audible alerts of the system. The operation should be as intuitive as possible for an average driver.

8. **Other procedures.** No additional procedures are envisioned for the system. If other procedure would be required, it must be documented into the user manual.

All the previous conditions shall be met for this system. If they are not met, the system could become useless and may cause damage to the user or external people to it. It is important to analyze, further discuss this ConOps and advance to the system requirements.

3.4 High Level Requirements

This chapter presents the High Level Requirements (HLR) of a vehicular system for traffic and collision avoidance in urban areas based on the V2X service requirements from ETSI and the V2V safety communications requirements from SAE. The proposed requirements of this section are at a conceptual level, the specific values for the applicable standards are not proportioned on it.

The HLR are formal statements that establish the main characteristics of a system that must be accomplished and are divided in functional requirements; behavior, or actions that the system must be able to perform; and non-functional requirements; characteristics, properties, or attributes that the system must posses. These HLR must be clear, ascertainable, verifiable, unambiguous, and must accomplish a series of characteristics that in other way they can induce to problems during the development of the project or afterwards.

In the following sections a description of the required system, the Functional Requirements (FR), Non-Functional Requirements (NFR) and requirements priority classification are presented.

3.4.1 Description of the system

A system that can bring more safety and efficiency in current urban vehicles.

The system to be developed should reduce vehicle collisions, minimize congested traffic flow, warn about a critical distance between two vehicles, warn about a sudden deceleration of the succeeding vehicles, protect pedestrians at intersections, and decrease air pollution emissions.

To achieve this the system should work as an ADAS of the vehicle, by performing alerts of rear-end collisions with other vehicles, alert at intersections about the possible presence of another car or a pedestrian, the presence of an emergency or a possible traffic flow reduction on the remote roadway.

In the next section the functional requirements are formally established, while in Section 3.4.3 the non-functional requirements are stipulated.

3.4.2 Functional Requirements

1. **General**

   FR 1.1 The system must alert of possible dangers in the road, collisions with other vehicles or with a pedestrian at intersections.

   FR 1.2 The system must alert of incoming traffic jams in the current roadway direction.

   FR 1.3 Once the system is installed it should not be intrusive into the vehicle or modify internal parameters of it.

   FR 1.4 The electrical power supply of the system will be provided by a car connector.

   FR 1.5 The communication of the system should have enough range to respond on time.

   FR 1.6 The relative position of the system should be precise enough to not cause a miscalculation.

   FR 1.7 The message exchange between two or more systems should be fast enough to process it and give a response on time.

2. **Interface**

   FR 2.1 The interaction with the system must be as intuitive as possible for the user.

   FR 2.2 The HMI should be easy to read and comprehend.

   FR 2.3 There must be an audible difference between alerts and emergency warnings.

3. **Certification**

   FR 3.1 The system should be certified to withstand the external loads applied into every part of its components.

   FR 3.2 The system communication should be certified to work at a standardized frequency and not invade other frequency bands.

4. Reporting

FR 4.1 Each of the critical events must be saved into a log file with the current parameters at that point in time for further analysis.

3.4.3 Non-Functional Requirements

1. Performance

NFR 1.1 [Communication range] The communication transmit power and its range between systems should be larger than 350 m.

NFR 1.2 [Position resolution] The vehicle positioning may have an average error between 20 and 80 cm.

NFR 1.3 [Latency] The time interval between a message sent and the received confirmation of the system should be less than 50 ms.

2. Constraints

NFR 2.1 [Functional Safety] The life cycle of the system development should follow and be based on the functional safety for automotive equipment of the ISO 26262.

NFR 2.2 [Shock proof] Each subsystem must comply the ISO 16750-3, which corresponds to the mechanical loads requirements for equipment depending on the mounting location.

NFR 2.3 [Climate proof] Each subsystem must comply the ISO 16750-4, which corresponds to the climatic loads requirements for equipment depending on the mounting location.

NFR 2.4 [Dust and water proof] Each subsystem must comply the ISO 20653, which corresponds to the degrees of protection of electrical equipment against foreign objects, water and access. The requirements depending on the mounting location are given by the ISO 16750-4.

NFR 2.5 [Frequency band] The working frequency of the system should be based on the IEEE 802.11p vehicular communication standard, the 5.9 GHz band (5.85 - 5.925 GHz).

NFR 2.6 [Messages] The messages generated and received by the system should comply the SAE J2735 standard. The message set, its data frame and data elements should be specifically aimed for DSRC systems.

NFR 2.7 [Power supply] The power stage of the system must be designed for 12 V, which is the vehicle connector power supply.

3. RAMS

NFR 3.1 [Reliability] The system should achieve a reliability of 99.99%.

NFR 3.2 [Safety] The system should comply a risk classification of Automotive Safety Integrity Level (ASIL) D.

4. Security

NFR 4.1 The communication and system architecture should be designed to prevent external attacks from non-authorized users.

NFR 4.2 The messages sent by the system must be encrypted using the Security Credential Management System specified by the IEEE 1609.2 standard.

NFR 4.3 Only messages authenticated with a digital certificate of a Public Key Infrastructure should be read by the system.

5. Interoperability

NFR 5.1 The system should be able to communicate with other similar systems using the same V2X architecture, for example V2V, V2I and V2N.

NFR 5.2 The exchange of internal information between the subsystems must be fast and compatible among them.

4 Analysis of System Functions

Generating solutions is an essential aspect in design. It is possible to combine a relative small number of elements or basic components in a big number of different shapes.

In order to propose solutions, it was necessary to make an analysis of the system functions and identify the essential ones for the system and after this, make a list of the solutions principles that could be used to perform each function.

4.1 Fundamental Functions

Establishing the functions offers a media to consider the essential ones and the problem level that should be approach to solve.

The starting point consists on focus in what the new design should accomplish. This can be done by expressing the design global function in terms of conversion of inputs to outputs. The global function needs to be decomposed in a set of essential secondary functions. Finally, a block diagram can be used to show the interactions between secondary functions, connected by inputs and outputs and establishing the system limits to satisfy the general function of the design.

For the proposed traffic and collision avoidance system the general function consists on the acquisition of data from the sensors and communication messages from other systems, and process them to generate alerts or broadcast messages to external systems.

For the V2X system model, the following subsystems were established:

- Control
- Communication
- Sensor

- HMI
- Power supply

The secondary functions derived from the general function of the system and the interaction between the subsystems are listed below:

- Vehicle speed estimation
- Deceleration message
- Vehicle direction estimation
- Safe distance determination
- Comparison of vehicles speed
- Determination of corresponding intersection direction
- Determination of heading area
- Determination of situation

The power supply that will feed the system is provided by the cabin outlet of the vehicle. The input data of the system will be acquired by the sensor and communication system, providing the vehicle position, front vehicle distance, the transiting nearby external vehicles messages that come from any direction, and the RSUs messages which correspond to the V2I systems on the roadway (e.g. smart traffic lights, transmission towers and traffic flow systems). The control system analyzes the collected data and decides if an alert must be shown to the driver using the HMI of the system. The system also broadcasts data through the communication system such as position, speed, and direction.

The interactions of the subsystems with the type of information provided and functions realized by each one are represented in Figure 4-1.

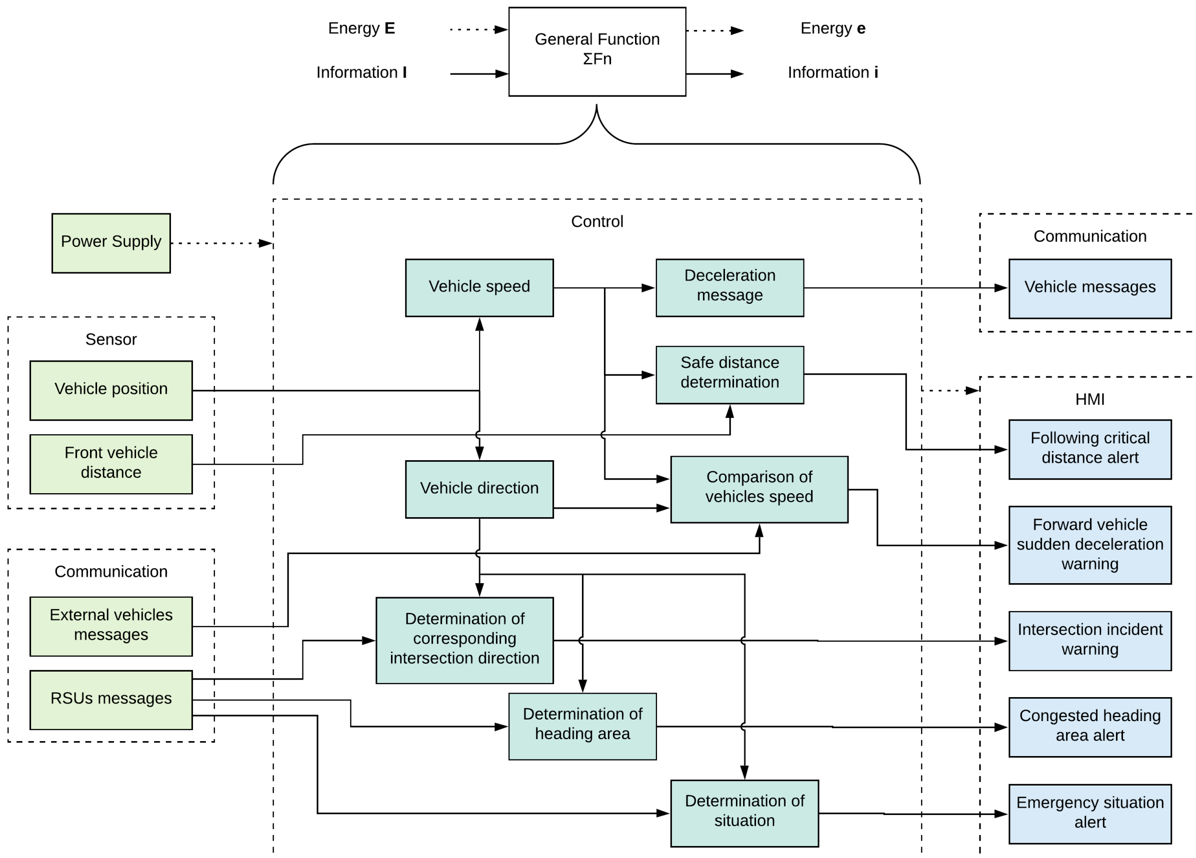


Figure 4-1: Functional relationship diagram of the system.

4.2 Solution Principles

From the establishment of the functions, the essential functions for the system are obtained. The proposed solutions to perform these functions are listed in Table 4-1.

Table 4-1: Proposed solutions for the essential functions of the system.

Functions	Solutions
Position, direction and speed	With an accurate position sensor data it is possible to calculate other variables such as direction and speed, these variables are required by all the functions of the system.

Functions	Solutions
Messages	The messages received by the system must be decrypted and then verified if the situation affects the vehicle. If the vehicle is inside the area of effect an emergency situation alert will be generated.
Detection at intersection	The intersection incident warning is generated when the system determines that the proportioned messages by the RSUs (smart intersections) on the roads are aimed in the same direction of the vehicle.
Traffic flow detection	When a RSU (traffic camera) detects an increment in the number of vehicles transiting on its assigned roadway, a message is broadcasted to the upcoming vehicles and a congested heading area alert is generated.
Following critical distance	The system will generate a following critical distance alert when the space between the vehicle and the leading one is smaller than the suggested distance for the corresponding vehicle speed.
Car following model	The comparison of the vehicle speed, distance and deceleration capability with the succeeding ones using the V2V communication and a mathematical model will allow the generation of a forward vehicle sudden deceleration warning.

A brief explanation of each solution and the proposed media is presented below in order to analyze each option and select the best media for each function based on the system requirements.

4.2.1 Position, direction and speed

The Sensor subsystem shall include a GNSS receiver to obtain the geo-spatial position of the vehicle, in the United States this requires that the GNSS receiver includes GPS. In this section the position reference message and method to obtain the speed will be discussed.

The vehicle position (Position Reference) reported in a Basic Safety Message (BSM) shall be a point (latitude, longitude and elevation) projected onto the surface of the roadway (road plane) with reference to the World Geodetic System 1984 (WGS-84) coordinate system of its reference ellipsoid, and the Coordinated Universal Time (UTC) when at that position. This point is the center of the rectangle on the road plane, oriented about the vehicle that encompasses the farthest forward, rearward, and side-to-side points on the vehicle, including original equipment such as outside side view mirrors, as shown in Figure 4-2. It is important to notice that the GNSS antenna position is not the same as the Position Reference. Also, additional positioning augmentation capabilities can be used, such as Wide Area Augmentation System (WAAS), and for security requirements the complete system shall include a reference clock with an output synchronized to UTC in order to support position and time extrapolation.

The position of the vehicle transmitted shall be accurate within an actual horizontal position reference over 68% under open sky test conditions, this accuracy requirement results in 95% confidence for relative positioning with lane-level granularity, based on testings done by the Federal Highway Administration (FHWA), which recommends a width of 3 meters for any roadway [SAE16b] .

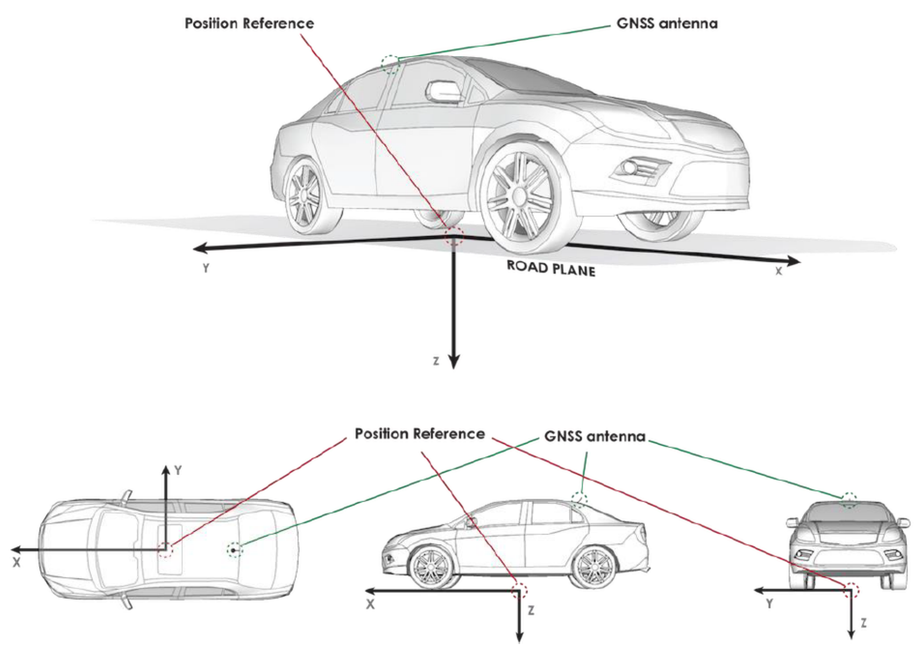


Figure 4-2: Position reference point [SAE16b].

The speed calculation can be obtained by performing a position extrapolation for the moving vehicle (see Figure 4-3), which is an estimation of the vehicle's current position at time T' (current time), based on the vehicle's last known position, heading, and speed at time T (older time). The estimation assumes that the vehicle is moving at a constant speed and constant heading, it is important to mention that the extrapolation will not be performed if there is no update of the position or the new latitude and longitude of the message are the same of the last known position. The difference of the obtained positions at ΔT which is T' − T will give us the estimated vehicle's speed.

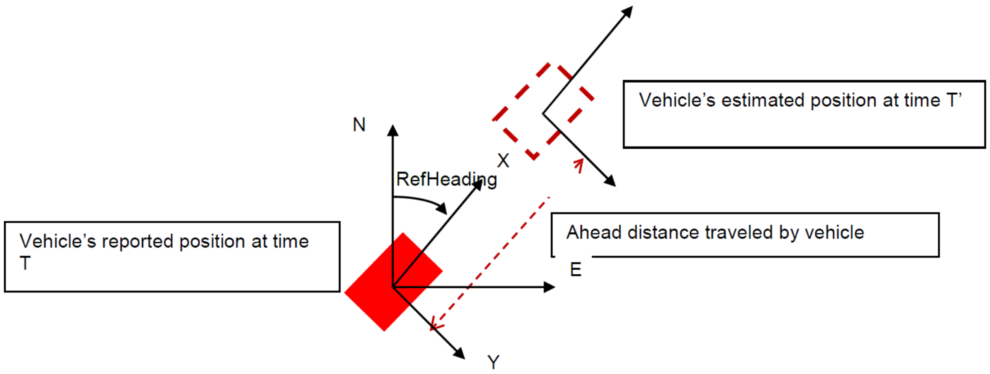


Figure 4-3: GNSS position extrapolation [SAE16b].

4.2.2 Messages

As mentioned in Section 2.2.1 the FCC allocated the spectrum of DSRC in the 5.9 GHz band, thus all the messages sent by the proposed system will be directed to the seven 10 MHz channels as shown in Figure 4-4. Each channel is also designated as either a Service Channel (SCH) or as the Control Channel (CCH), being the CCH a channel that the devices will tune to on a regular basis to hear the announcing availability of any services offered in the other channels.

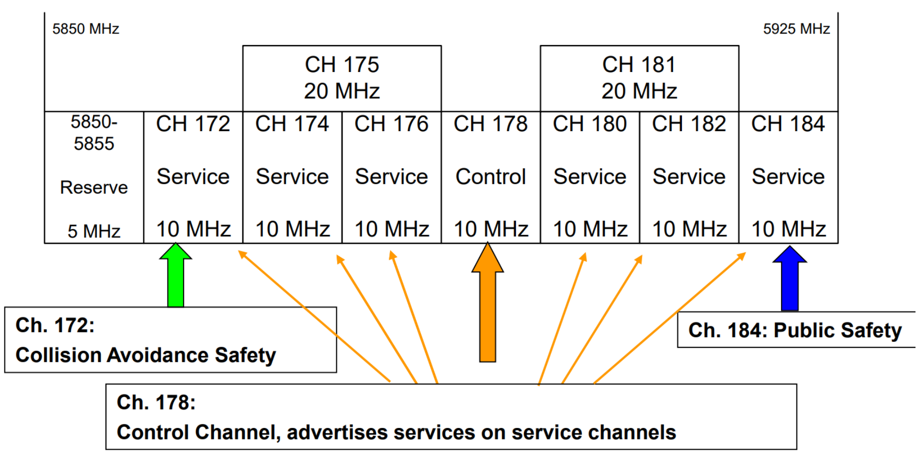


Figure 4-4: DSRC channel spectrum [Ken11].

The message style for this system will be the Abstract Syntax Notation One (ASN.1), using the Unaligned Packed Encoding Rules (UPER) which are a set of encoding rules that specify how to represent a data structure as a series of bytes, this message style was selected due to the standardization proposed by SAE and other ITS standards. This dense encoding uses a three way approach:

- The smallest divisions of information content to be standardized are called Data Elements.
- Data Frames are the next, more complex data structures to be standardized in this dense encoding.
- The top level of complexity in the data structure standardization is called Messages.

Below is an example of a generic signed message with certificate taken from [SAE16a].

```
03 81 00 40 03 80 0F 54 68 69 73 20 69 73 20 61
20 42 53 4D 0D 0A 40 01 20 00 00 0A 35 23 77 2A
85 00 81 01 01 00 03 01 80 00 11 22 33 44 55 66
77 50 80 80 00 C8 00 11 22 33 44 55 66 77 88 56
70 AB 00 11 22 33 44 55 66 77 88 99 00 11 22 00
01 00 11 22 33 84 00 A9 83 01 03 80 00 7C 80 01
E4 80 03 48 01 02 00 01 20 00 01 26 81 82 00 11
22 33 44 55 66 77 88 99 AA BB CC DD EE FF 10 11
12 13 14 15 16 17 18 19 1A 1B 1C 1D 1E 1F 80 82
00 11 22 33 44 55 66 77 88 99 AA BB CC DD EE FF
10 11 12 13 14 15 16 17 18 19 1A 1B 1C 1D 1E 1F
FF 11 22 33 44 55 66 77 88 99 AA BB CC DD EE FF
10 11 12 13 14 15 16 17 18 19 1A 1B 1C 1D 1E 1F
```

The corresponding ASN.1 for the previous message is.

```
value1 TestIeee1609Dot2Data ::= {
   protocolVersion 3,
   content signedData : {
      hashId sha256,
      tbsData {
         payload {
            data {
               protocolVersion 3,
               content unsecuredData : '546869732069732061204253D0D0A'H
            }
         },
         headerInfo {
```

```
        psid 32,
        generationTime {
          time 11223344556677,
          logStdDev 0
        }
      }
    },
    signer certificate : {
      {
        version 3,
        type implicit,
        issuer ecdsaNistP256AndDigest : '0011223344556677'H,
        toBeSigned {
          id linkageData : {
            iCert 200,
            linkage-value '001122334455667788'H,
            group-linkage-value {
              jValue '5670AB'H,
              value '00112233445566778899'H
            }
          },
          cracaId '001122'H,
          crlSeries 1,
          validityPeriod {
            start 1122867,
            duration hours : 169
          },
          region identifiedRegion : {
            countryOnly : 124,
            countryOnly : 484,
            countryOnly : 840
          },
          appPermissions {
            {
              psid 32
            },
            {
              psid 38
```

```
                }
            },
            verifyKeyIndicator reconstructionValue : compressed-y-0 :
'00112233445566778899AABBCCDDEEFF101112131415161718191A1B1C1D1E1F'H
          }
        }
    },
    signature ecdsa256Signature : {
        r compressed-y-0 :
'00112233445566778899AABBCCDDEEFF101112131415161718191A1B1C1D1E1F'H,
        s 'FF112233445566778899AABBCCDDEEFF101112131415161718191A1B1C1D1E1F'H
    }
  }
}
```

4.2.3 Detection at intersection

Currently, some cities are introducing ITS at intersections, specially at intersections which are considered dangerous or are susceptible to accidents due to obstacles or by the street geometry. This solution is named smart intersection technology and is one of the many types of RSUs which can use V2X communication. It expands the use of and creates links between cameras and sensors to allow vehicles the ability to see through and around buildings, walls, weather, and more to detect pedestrians, vehicles, and other significant objects in the area. When an obstacle is present at an intersection or a vehicle breaches a traffic rule such as neglect a stop, a message is sent to the nearby area with the information of the lanes in danger and the direction of it. An example of this solution is shown in Figure 4-5, where the red car is the one trespassing the stop, and the system of the blue one receives the message and determines that a possible collision may occur.

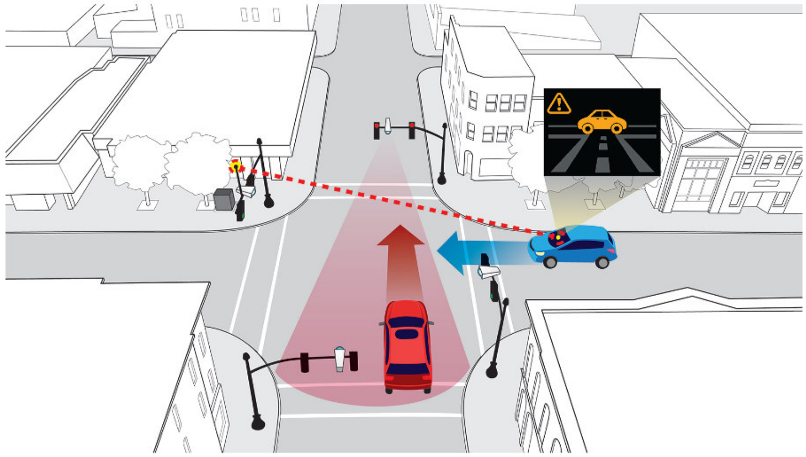


Figure 4-5: Smart intersection with V2X communication [Tre18].

The reflection phenomena is also a problem when using vehicular communications, it is present when an obstruction blocks or reflects the radio signal. To solve this problem all loses between the V2X systems must be taken into account, the Equation 4.1 determines these mentioned loses [EMM+17].

$$P_{RX} = P_{TX} - L_S - i_S L_{SU} - L_P \tag{4.1}$$

The V2X receivers sensitivity is P_{RX}, the transmission power is P_{TX}, the system loss L_S, the path loss L_P, the parameter i_S which is a boolean factor set to 1 for suburban modeling and 0 for urban modeling, and a constant loss L_{SU} is subtracted from the link budget for suburban scenarios due to the higher amount of wood and plants in suburban areas.

The path loss can be calculated with Equation 4.2 and Equation 4.3.

$$L_P = 10log\left(\left(d_t^{E_T}\left(\frac{1}{x_t w_r}\right)^{E_S}\frac{4\pi d_r}{\lambda}\right)^{E_L}\right) \quad \text{for} \quad d_r \leq d_b \tag{4.2}$$

$$L_P = 10log\left(\left(d_t^{E_T}\left(\frac{1}{x_t w_r}\right)^{E_S}\frac{4\pi d_r^2}{\lambda d_b}\right)^{E_L}\right) \quad \text{for} \quad d_r > d_b \tag{4.3}$$

where d_t is the distance between the transmitter and the middle of intersection, d_r is the distance between the receiver and the middle of intersection, w_r is the width of the receiver's street, x_t is the distance between the transmitter and the wall in the direction of the receiver.

The distance of breakpoint d_b (two-ray model) can be obtained with Equation 4.4,

$$d_b = \frac{4h_t h_r}{\lambda} \tag{4.4}$$

where λ is the wave length of the transmitting frequency, h_t is the height of the transmitting car's antenna, and h_r is the height of receiving the car's antenna. The geometric model of the intersection with the previously mentioned parameters of the equations is shown in Figure 4-6.

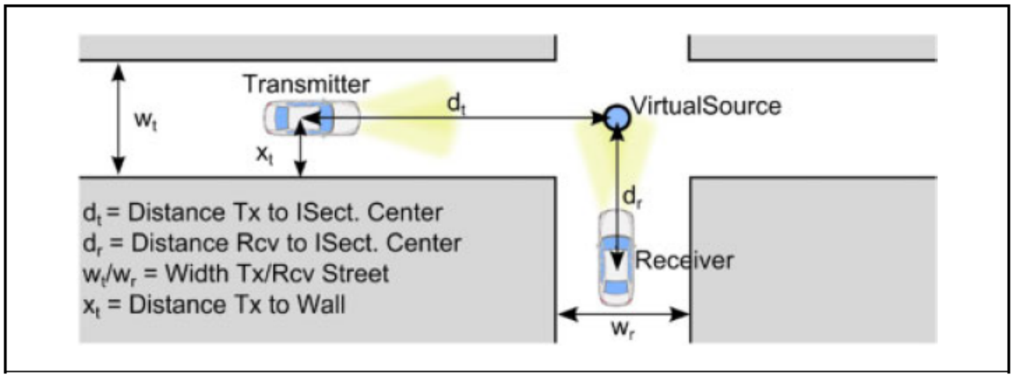


Figure 4-6: Intersection geometric model [EMM+17].

4.2.4 Traffic flow detection

Knowledge about the current traffic flow is used for travel time reduction and proactive jam avoidance by intelligent traffic control mechanisms. This systems are able to find rapid changes in road situations by detecting abnormal driving behavior of running vehicles, and creating information of traffic congestions and required travel time based on data sent by vehicle detection sensors. These sensors can be of loop coil type buried under roadways, ultrasonic sensors installed on roads, and image processing sensors that detect vehicles passing through.

This systems automatically detect abnormal driving behaviors such as stopped, slow or swerving vehicles. The device obtains information on traffic congestion and required travel time by processing sensor data in real time, machine learning algorithms are a plus to improve the accuracy of this type of system. The message of this type of RSU is processed by the vehicle system, and generates a warning to help the driver who passes by to avoid a possible traffic jam. In Figure 4-7 a traffic flow detection system consisting of a camera and a controller for image processing is shown.

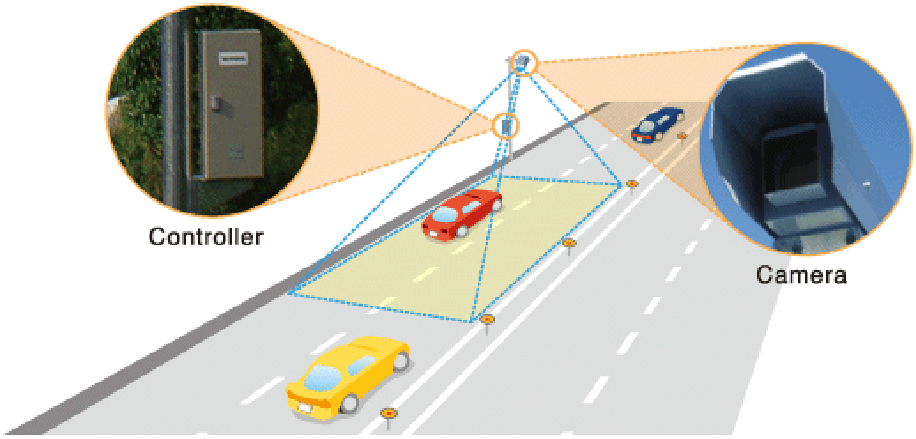


Figure 4-7: Traffic flow detection camera [Sum19].

4.2.5 Following critical distance

To get a better idea of this solution, the concept of stopping distance, the time that it takes to bring a moving car to a complete stop, will be introduced. This concept includes both the time it takes a driver to react to a hazard and the time it takes for the brakes to stop the car. In Figure 4-8 a graph of the typical distances proposed by the United Kingdom (UK) department of transport are shown with the breakdown of its parts, the thinking distance and the braking distance.

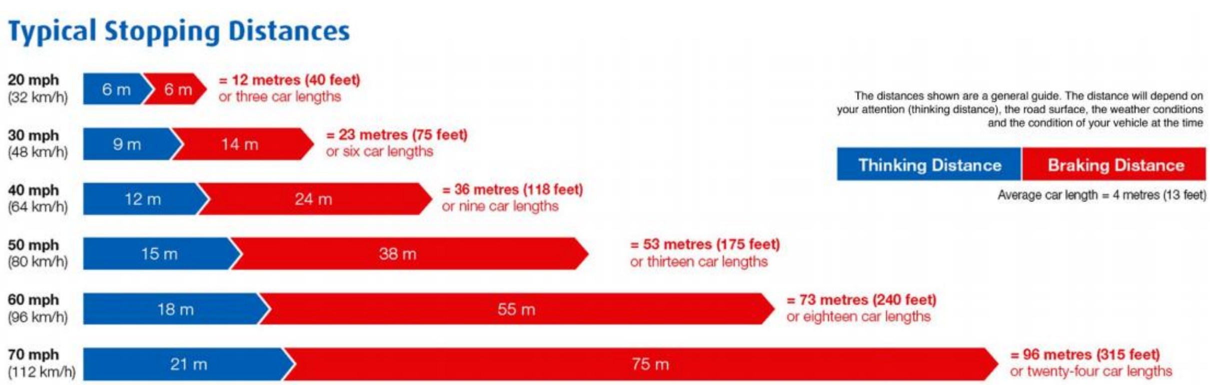


Figure 4-8: Stopping distances [Uni16].

For the proposed system, the thinking distance will be substituted by the distance traveled during the system processing or reaction time. The braking distance will be calculated by deriving the kinetic energy formula

$$E = \frac{1}{2}mv^2 \tag{4.5}$$

into

$$d = \frac{v^2}{2\mu g} \tag{4.6}$$

where d is the stopping distance, v the velocity of the vehicle, μ the coefficient of friction between the tires and the road and g the acceleration due to the Earth's gravity.

The following critical distance will be obtained at every moment by measuring the length to the forward vehicle and comparing the measurement with the stopping distance at that point in time. If the length obtained by the sensor is lower than the stopping distance, an alert will be generated. It is important to notice that this solution has a similar scope to the car following model solution, but this one does not heavily rely on the communication system.

4.2.6 Car following model

As mentioned in Section 1.1, one of the dominant types of vehicle crashes is that the leading vehicle stopped, and the main cause for this issue will probably be due to a recognition error. The proposed solution for this problem is the use of a mathematical model aided by V2X communication to obtain some of the variables needed for it.

Before a car following model is taken into account, a next vehicle's speed model will be introduced, this model is the principle of a car following model when a traveled distance is computed.

First, let us consider a very long road with single lane A with maximum speed of v^A_{max}. A vehicle V that has maximum speed of v_{max} and maximum acceleration of a_{max} is traveling on lane A. The vehicle's speed in the next time step, denoted by v_{next}, is calculated as following:

$$v_{next} = min[v + a_{max} * \Delta t, v_{max}] \tag{4.7}$$

Where v is the current speed and Δt is the time step. The vehicle's speed increases with a_{max} in each time step until it reaches v_{max}. The vehicle's next speed cannot exceed the lane's maximum speed, thus we have:

$$v_{next} \leftarrow min[v_{next}, v^A_{max}] \tag{4.8}$$

By combining Eq. (4.7) and Eq. (4.8), we have:

$$v_{next} \leftarrow min[min[v + a_{max} * \Delta t, v_{max}], v^A_{max}] \tag{4.9}$$

Based on v_{next}, current acceleration *(a)* and current position *(x)* are updated as follows:

$$a_{next} = \frac{v_{next} - v}{\Delta t}, x_{next} = x + v_{next} * \Delta t \tag{4.10}$$

Thus, in the next step we have:

$$v \leftarrow v_{next} \tag{4.11}$$

$$a \leftarrow a_{next} \tag{4.12}$$

$$x \leftarrow x_{next} \tag{4.13}$$

Now with a vehicle's speed model let us assume that a vehicle V_2 is following a vehicle V_1 on a single lane of roadway. The car following model (also known as longitudinal control model) determines the V_2's follow speed in relation to the vehicle ahead of it (V_1). Car following has been successfully described by mathematical models, and is an important facet of driving. Thus, understanding car following contributes significantly to an understanding of traffic flow [Rot92].

Let us consider a road with single lane A with maximum speed of $v^A{}_{max}$. Assume that vehicle V is following vehicle V_l as shown in Figure 4-9. The following vehicle should adapt its speed to the leading vehicle in order to avoid a collision.

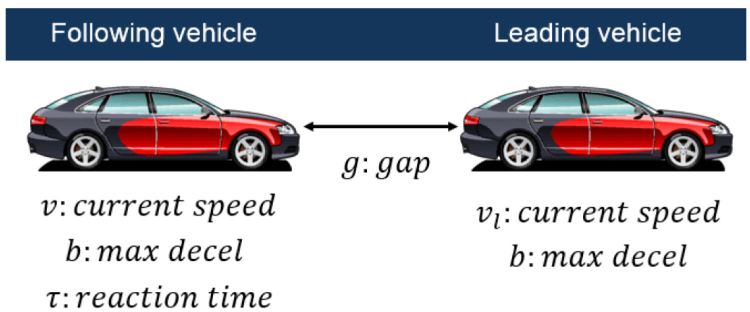


Figure 4-9: Following vehicle example [ADC+15].

The speed of the following vehicle is equal to the following, where v_{next} is the next speed calculated from Equation 4.9 and followSpeed depends on the car following model being used.

$$v_{next} \leftarrow min[v_{next}, followSpeed] \tag{4.14}$$

Krauss car following model which is a simplified version of Gipps car following model and is defined by Stefan Krauss in [Kra98] was the selected mathematical model to solve the V2X system model concept. The principal reason to select this model was the inclusion of variables that other models neglect, the driver imperfection and the difference between braking speeds are some of them.

In this model, the followSpeed, denoted by v_{safe} is calculated as follows:

$$v_{safe}(g, v_l) = -b\tau + \sqrt{(b\tau)^2 + v_l^2 + 2bg} \tag{4.15}$$

Where:
g: Space-gap between following and leading vehicles (m)

v_l: Current speed of the leading vehicle (m/s)
b: Maximum deceleration of the following/leading vehicle (m/s_2)
τ: Reaction time of the following vehicle (s)

Now v_{safe} is calculated considering the worst case scenario where the leading vehicle brakes with maximum deceleration. The braking distance that the leading vehicle needs to come to a complete stop is calculated as follows:

$$\Delta x = -\tfrac{1}{2}bt^2 + v_0 t \tag{4.16}$$

$$v_0 = v \tag{4.17}$$

$$-b = \tfrac{0-v}{t} \rightarrow t = \frac{v}{b} \tag{4.18}$$

we get:

$$\Delta x_l = -\tfrac{v_l^2}{2b} \tag{4.19}$$

The stopping distance for the following vehicle is:

$$\Delta x = v\tau + \tfrac{v^2}{2b} \tag{4.20}$$

Where the first term is the reaction distance and the second term is the braking distance. The space gap, g, should be greater than or equal to $\Delta x - \Delta x_l$ in order to maintain a safe gap and prevent a collision.

$$g \geq \Delta x - \Delta x_l = v\tau + \tfrac{v^2}{2b} - \tfrac{v_l^2}{2b} \tag{4.21}$$

That is equal to the following quadratic equation:

$$v^2 + (2b\tau)v - (v_l^2 + 2bg) \leq 0 \tag{4.22}$$

Solving the above equation for v would be:

$$0 < v \leq v_{safe} = -b\tau + \sqrt{(b\tau)^2 + v_l^2 + 2bg} \tag{4.23}$$

In other words, the maximum safe speed for the following vehicle denoted by v_{safe} is:

$$v_{safe} = -b\tau + \sqrt{(b\tau)^2 + v_l^2 + 2bg} \tag{4.24}$$

Substituting followSpeed Eq. (4.24) into Eq. (4.14) gives us:

$$v_{next} \leftarrow min\left[v_{next}, -b\tau + \sqrt{(b\tau)^2 + v_l^2 + 2bg}\right] \tag{4.25}$$

Substituting v_{next} Equation 4.9 into the above equation gives us:

$$v_{next} \leftarrow min\left[min\left[min\left[v + a_{max} * \Delta t, v_{max}\right], v_{max}^{A}\right], -b\tau + \sqrt{(b\tau)^2 + v_l^2 + 2bg}\right] \tag{4.26}$$

The Krauss model assumes that a driver is not perfect in realizing the v_{next}. Instead, the chosen speed is smaller and is calculated as following, where σ denotes the driver's imperfection between 0 and 1, where 0 means a perfect driver.

$$v_{next} \leftarrow max\left[0, v_{next} - (\sigma * a_{max} * Rnd[0,1]) * \Delta t\right] \tag{4.27}$$

The first part of the Krauss model assumes that following and leading vehicles both have the same maximum deceleration. Which most of the time that is not true. The Krauss model solves this problem by considering the maximum deceleration in both vehicles. In this model, the safe speed is calculated as following where b_f and b_l are maximum deceleration of following and leading vehicle respectively and $b=min(b_f,b_l)$.

$$v_{safe} = -b\tau + \sqrt{(b\tau)^2 + \frac{b}{b_l}v_l^2 + 2bg(g - G_{min})} \tag{4.28}$$

The v_{safe} is calculated as before. Consider the worst case scenario where the leading vehicle brakes with maximum deceleration. The braking distance that the leading vehicle needs to come to a complete stop is calculated as follows:

$$\Delta x_l = -\frac{v_l^2}{2b_l}$$

The stopping distance of the following vehicle is:

$$\Delta x = v\tau + \frac{v^2}{2b} \quad \text{where} \quad b = min(b_f,b_l)$$

The space gap, g, should be greater than or equal to $\Delta x - \Delta x_l + G_{min}$ in order to maintain a safe gap and prevent collision. Adding G_{min} is necessary to ensure an accident free model in the presence of numerical errors arising from discretization.

$$g \geq (\Delta x - \Delta x_l) + G_{min} = v\tau + \frac{v^2}{2b} - \frac{v_l^2}{2b_l} + G_{min} \tag{4.29}$$

For the proposed system, τ which is the driver's reaction time will be substituted by the system reaction time, where 0 represents a perfect system with no delay and an immediate process of the signals. The vehicle's deceleration speed or braking speed (b_f and b_l) will vary among the vehicle models, tires, weather and roadway.

It is proposed that the b_l of the forward vehicle will be obtained using the V2X communication, this means that the messages received and sent by the vehicles will contain the necessary parameters for the gap calculation. The required self vehicle parameters for the mentioned messages are vehicle maximum deceleration, vehicle current velocity, vehicle's dimensions and position. Making a parameterization of the previously mentioned variables is suggested for future works in test vehicles, roads, and with the use of standard components.

The fundamental functions of the system to develop and solution principles for those functions were presented in this Chapter. Then, a general concept idea of the system to be developed was generated from the selected solution principles.

The following chapter contains the conceptual system modeling of the required system generated from the resultant functional relationship diagram (Figure 4-1), as well as an explanation of the components and elements that are part of it.

5 System Model Concept

In the last chapter, the most promising alternatives for those defined essential functions were described and compared. Based on the selected alternatives, the reviewed state of the art for vehicular communications (Section 2.2, Section 2.3 and Section 2.4), and the system approach of Chapter 3, a system conceptual model was generated and is presented at this chapter.

The model reflects the characteristics of the system and how it relates to its environment and to the user, so that anyone can understand its operation more easily. It also represents the internal structure of the system and the possible configuration variants that can be performed on it. For this, an abstract vision of the system was adopted as a system based on the principles of Model Based Systems Engineering (MBSE).

The elected language to realize the modeling was the System Modeling Language (SysML), a high-level graphic language that allows to model the system to study through diagrams, simplifying the reading of the model even in more complex systems. It has a strong system of rules to ensure the readability of the model, while allowing some flexibility when modeling.

The object model of this work aims to explore a new system, describe it and reflect it using a modeling language. In this sense, it is a practical work of applying systems engineering to a specific case. However, during its design, the intention of creating a model applicable to any system with similar characteristics is maintained, so that the generality and the ability to adapt it to particular cases of other similar systems is not lost. With this, the model can be used by students or researchers in the field of ITS as a basis for other related projects, as well as being expanded, modified and adapted with relative ease for other uses.

A representation of the resulting preliminary SysML model is presented in Appendix 7. The SysML is based on the Object Management Group (OMG) specification [Sys17]. The elected software for the creation of it was “Software Ideas Modeler´´ due to its simplicity of use among other modeling software. The system is broken down in its different diagrams, components and elements that conform it. The model presented in this work has a limited scope, given the time constrains, thesis scope, and the size of a system like this one, but it serves for its exploitation in specific uses (simulation) and for its extension by incorporating additional detail.

5.1 SysML model for the development of the system

To structure and organize the model of the system, package diagrams (pkgs) were used to represent the elements. In this case, the types of diagrams that were used for the model are distinguished in Appendix 7, page 95 and page 96. This organization is arbitrary. The use cases of the model and the system, the parametric diagrams, the definition of the types of value, the requirements diagrams, and finally the structural and behavioral ones are distinguished. The V2X system model overview is shown in Figure 5-1.

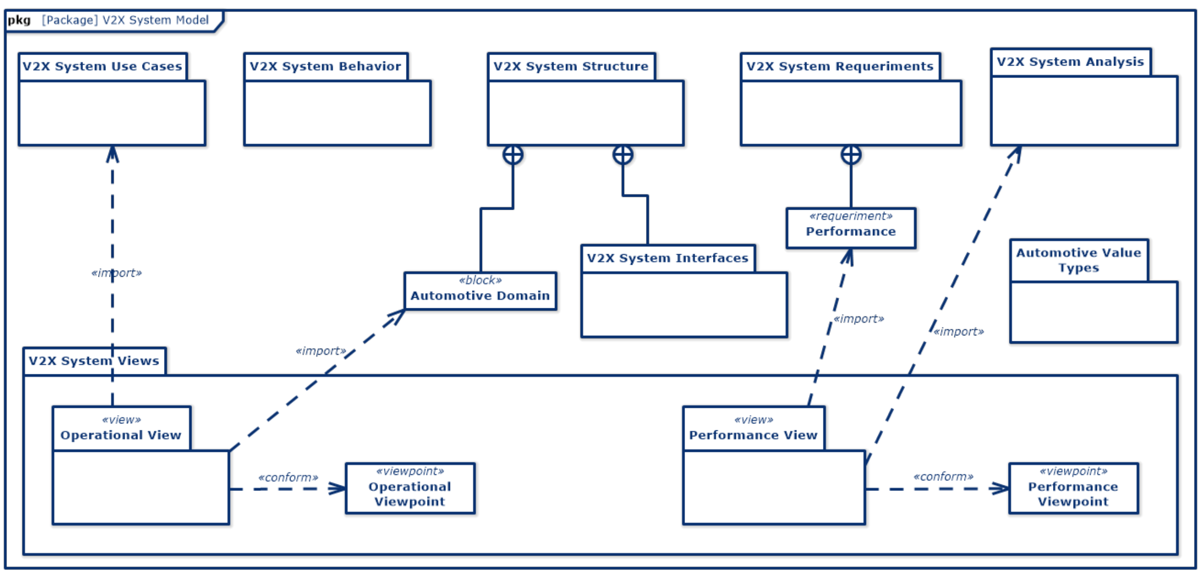


Figure 5-1: SysML package diagram of the V2X system model.

The contained parts of the model are dependent of the previous chapters and sections of this work. The first package to be described will be the requirements analysis of the system.

5.2 Values and Requirements

The structural diagrams allow defining the types of value and the dimensions or units that the model will use. Among the types of value proposed for the model, the units that we will use to express the time (s), the dimensions of the vehicle (cm), its speed (m/s), the battery voltage (V), the current supplied to the system elements (mA) or the frequency to which the components operate (Hz) can be found in the values and units package diagram. The package diagram of the model that shows it can be observed in Figure 5-2.

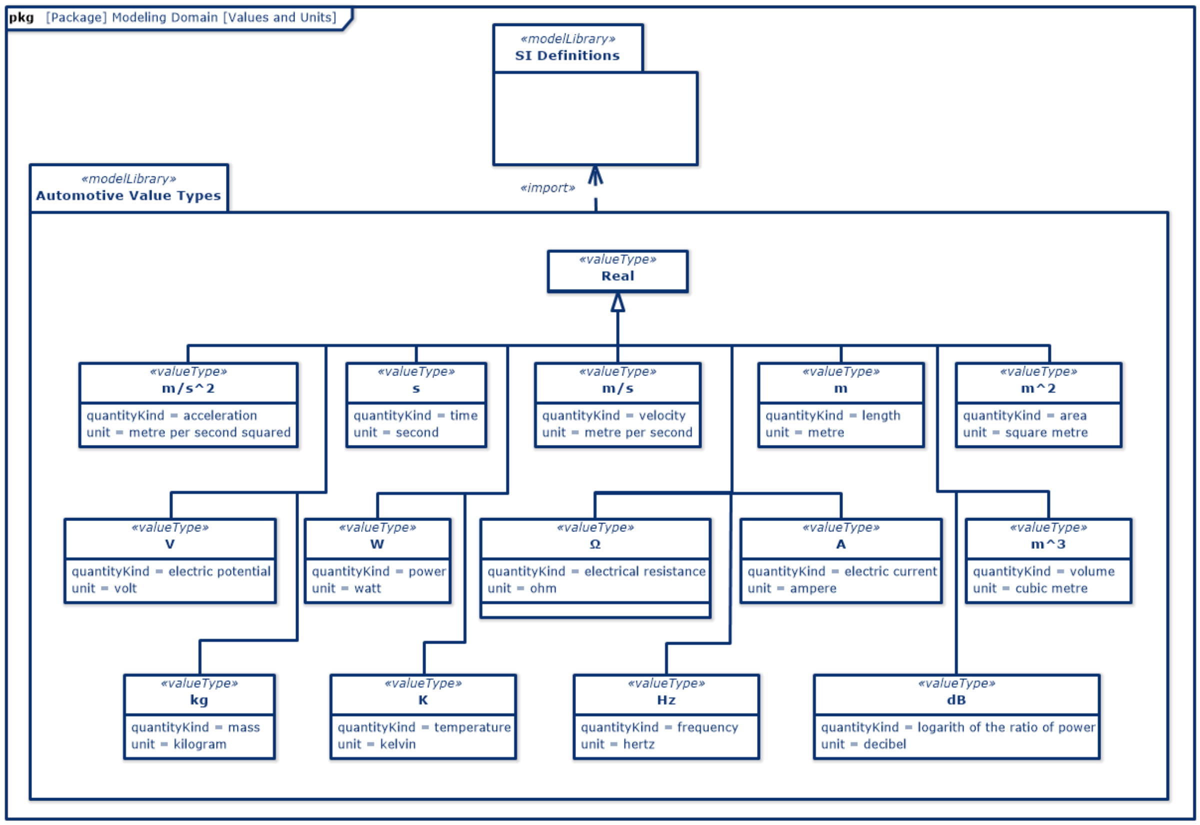


Figure 5-2: SysML package diagram of the values and units from the modeling domain.

The requirements analysis will be limited to determining what requirements both the model and the system must meet. They are based on the objective of the realization of this project, which was discussed earlier in Section 1.4.1.

The requirements applicable to the system are mainly its technical specifications or requirements derived from them, such as the communication range or the latency of the system. The requirements diagram of the system specifications was created based on the high-level requirements of Section 3.4, the id of each requirement of the diagram corresponds to one of the functional and non-functional requirements. The diagram can be consulted in the Appendix 7, page 97. The requirements may be modified or expanded in a future or for other uses.

5.3 System functionality

When describing the functionality of the system, use cases, message sequence, state machine or activity diagrams are used. These diagrams allow to show different perspectives of the system, adding them to the general vision that is the model. First, the use cases of the model and the system, that show how a user could use the system are presented.

The use cases of the system are very simple, its contents are already explained in Chapter 3. The possible action to be performed by the user is the operation of the system, and for the technician is the modification of the system. The use case diagrams of the system (see page 100-101) derive from the automotive domain in which the system will take part, and its shown in the internal block diagram (ibd) of Figure 5-3.

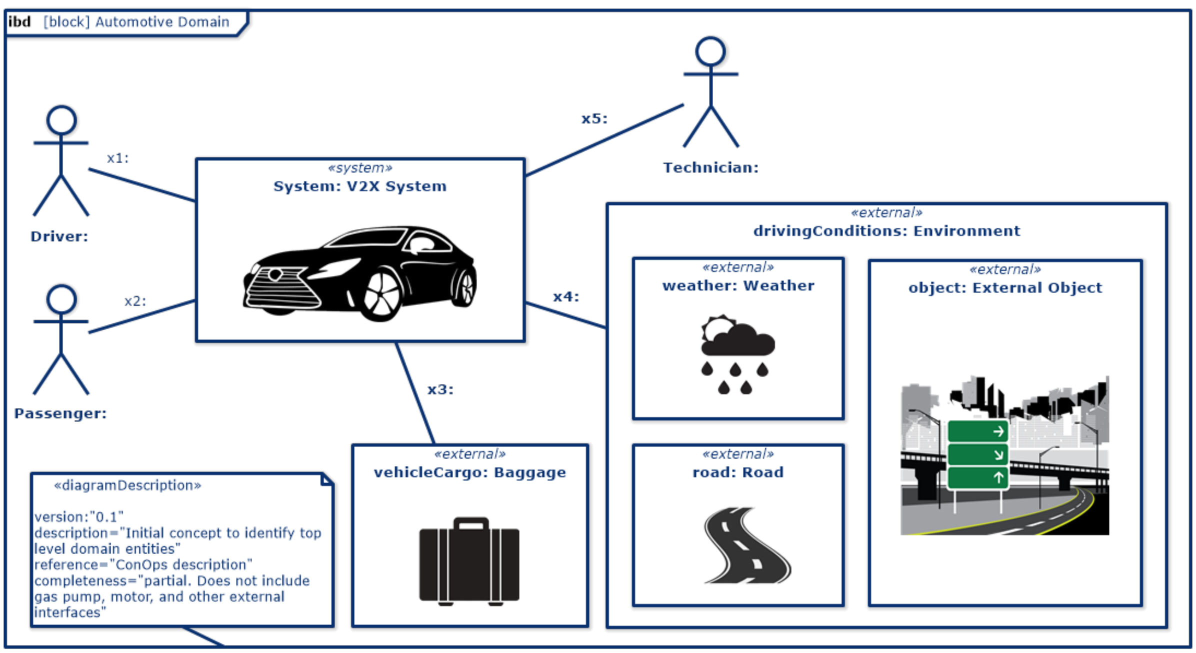


Figure 5-3: SysML block diagram of the Automotive domain.

The sequence diagram shows what actions are carried out within the vehicle operating activity. Sequence partitions separate the actions of an activity based on who will perform them. In this case, the direction, accelerating and braking to be taken will be done by the user, and it will be the system that will alert the driver to take an action on the movement of the vehicle.

The activities are carried out in a loop while the vehicle is operational and the driver receives an alert from the system. The sequence diagram of the vehicle drive black box is shown in Figure 5-4, and a simple state machine with idle, accelerating, alerting and braking states referenced from it is shown in page 103.

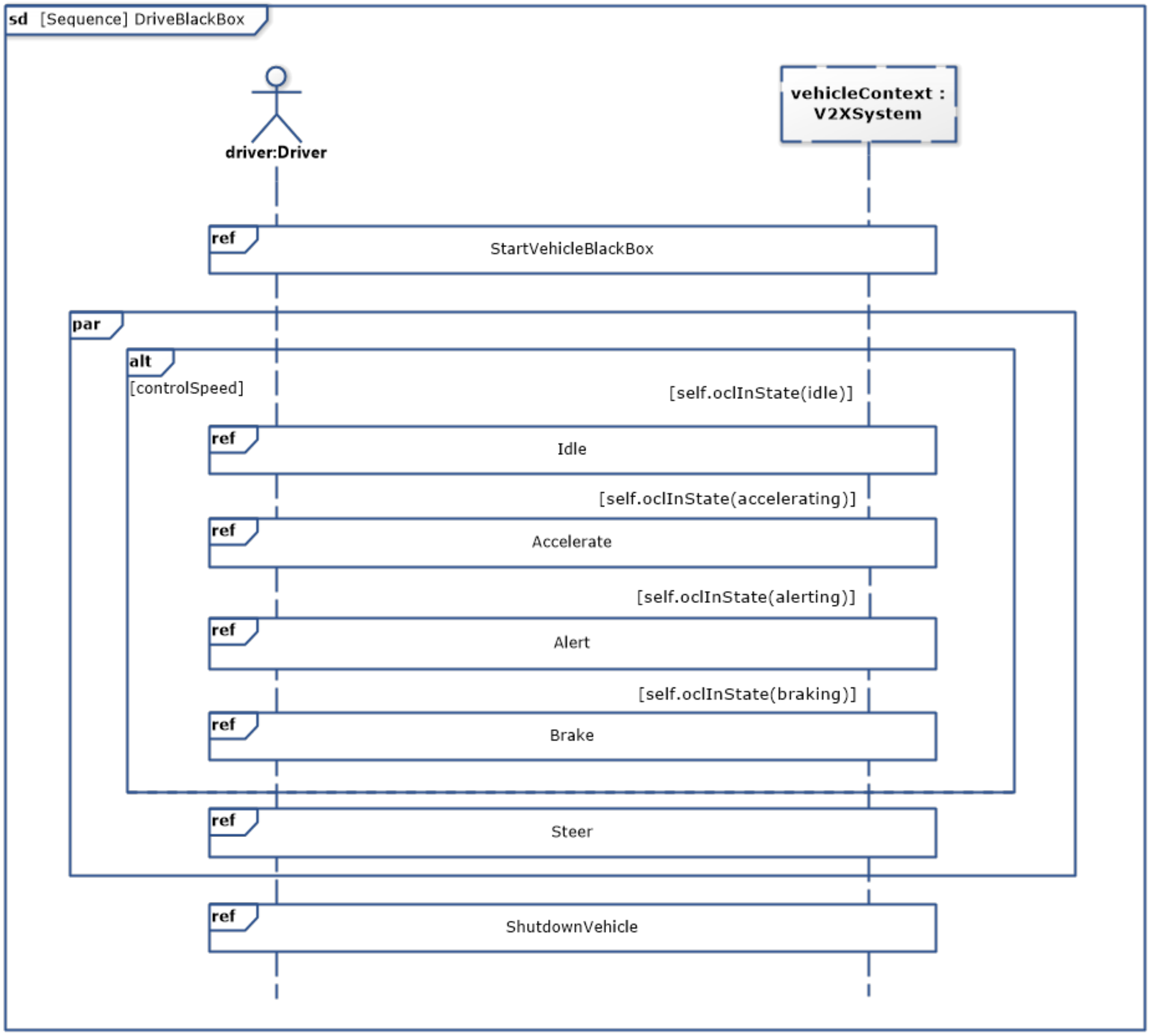


Figure 5-4: SysML sequence diagram of the vehicle drive black box.

5.4 System structure

The system structure (both physically and abstractly) is reflected in the SysML, using for this three types of diagrams: block definition diagram (bdd), internal block diagram (ibd) and pkg. In a first level of structural decomposition, the system domain generally includes everything that surrounds the system, be it its environment or users.

The domain of the vehicle encompasses the system itself, the users and the environment. This environment, in turn, is composed of the road on which the vehicle will move and general situations will occur. Likewise, the road can present differences between cities itself and elements on it, such as RSUs, with which the system can interact. In a second level of decomposition, the system is divided into different subsystems according to the functionalities they perform. The bdd of the system structure from the automotive domain breakdown diagram (see page 104) is represented in Figure 5-5.

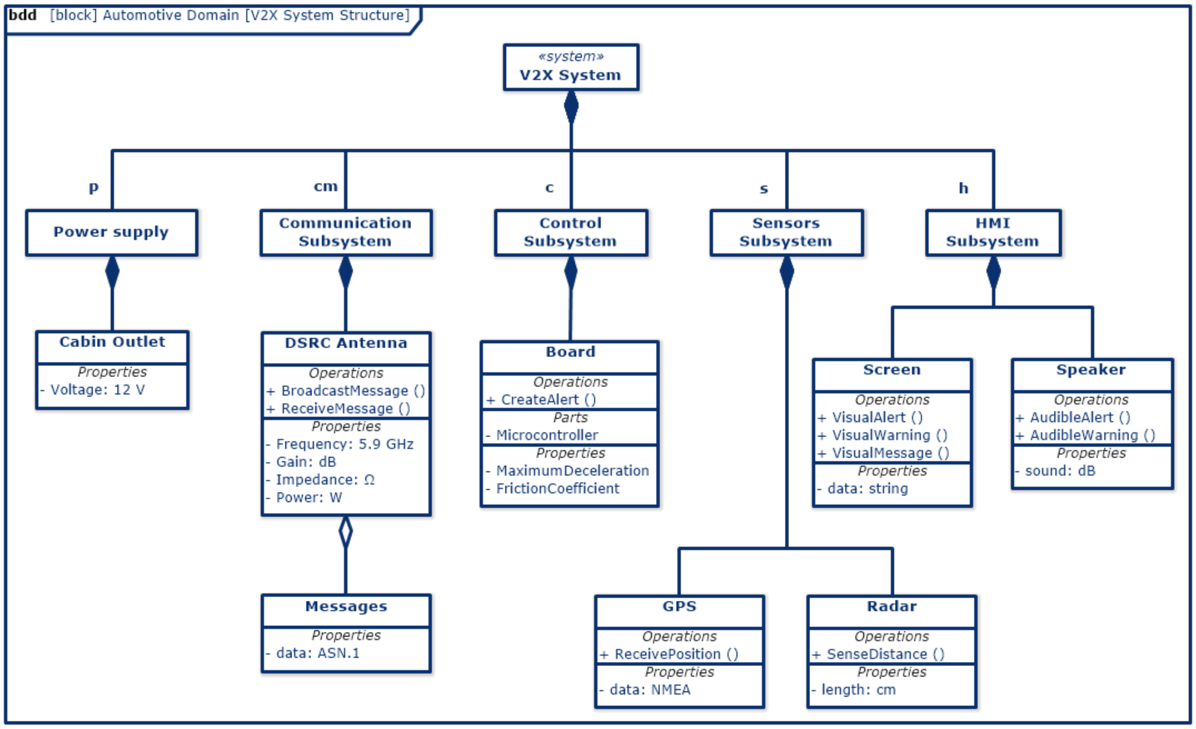


Figure 5-5: SysML block diagram of the V2X System structure.

The V2X system consists of a control subsystem, which contains the electronic board, a communication subsystem, which according to the configuration will be using a DSRC antenna, a sensors subsystem, consisting of a GPS and a radar, a HMI subsystem, composed by a screen and speakers, and the power supply of it. In turn, it is possible to break down the structural diagrams into more specific diagrams, entering each subsystem in greater detail, but for this concept work the structure is only contemplated.

In these block definition diagrams the structure of the system is being described, that is, what elements define and make up which subsystems. The relationships between them are not indicated in the bdd, how they connect or how to exchange information or energy. These relationships are simplified and represented by the ibd shown in page 106.

5.5 Dynamics

The SysML model may be too abstract for many specific uses, but it can be transformed or serve as the basis for more specific models. In this model, some of the system dynamics present on the desired system are stipulated.

The parametric diagram shows the restrictions applicable to the distance traveled, the velocity, the acceleration, the critical distance and the deceleration gap equations, some of them presented in Section 4.2. It shows the inputs and outputs of the block. There is no causality in the equations but a relationship of equality between terms that is verified in both directions. The parametric diagram with the equations that link the variables between them and the subsystems is shown in Figure 5-6.

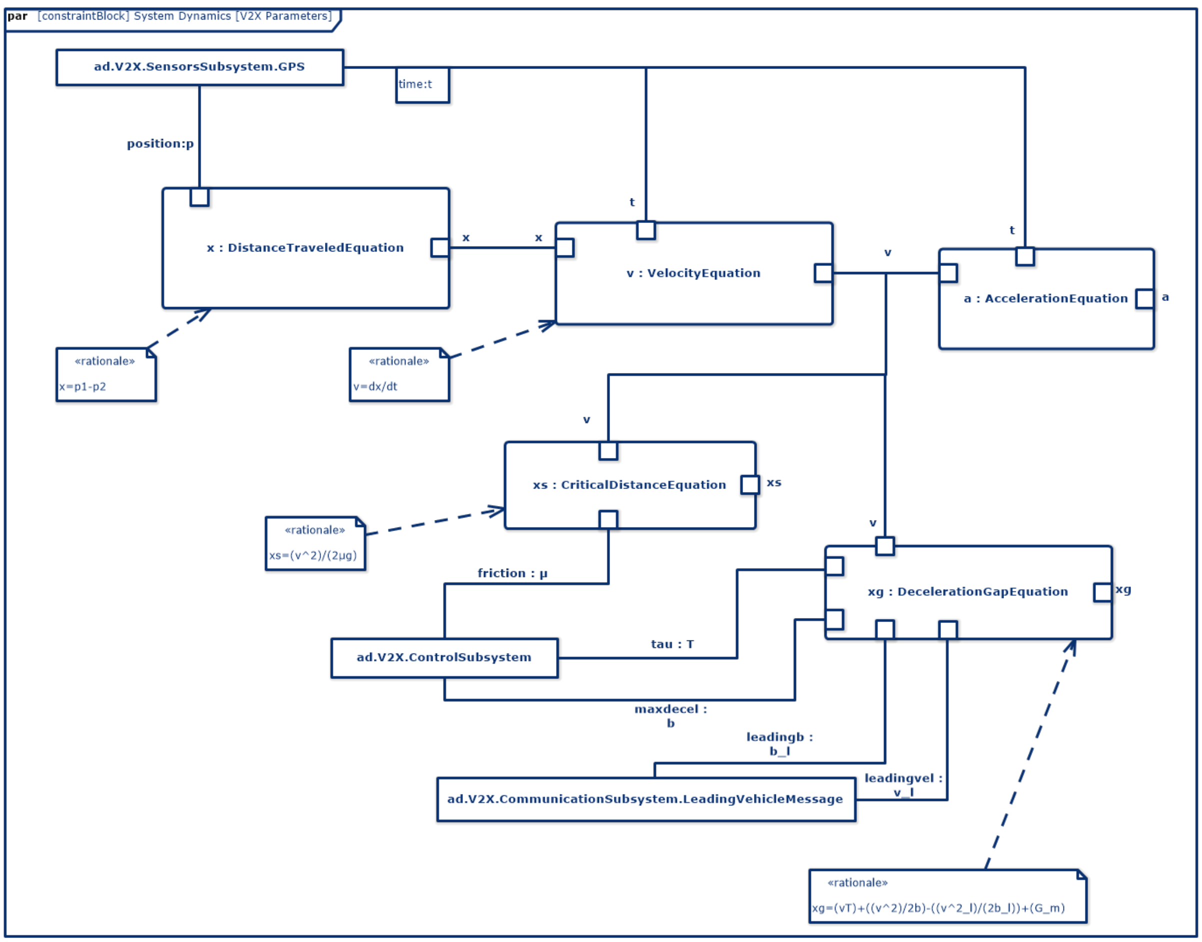


Figure 5-6: SysML parametric diagram of the System dynamics.

The presented SysML diagrams are a simplified structure of the desired system model, this means that it is possible to use them for a similar communication system or to adapt them based on future needs. When modeling with SysML, the limits in terms of depth and detail are completely open to the modeler's choice. It is important to notice that for the subsystems the parts used on them or the properties can be modified depending on the detailed design of the system. In the next chapter a simulation of a vehicular network with vehicles using communication systems, similar to the suggested in previous chapters is presented.

6 System Simulation

In the past chapters a system for a single vehicle was proposed, for the simulation chapter a vehicular network that consists of a city map with a small vehicular traffic of 8 vehicles, with each vehicle using the proposed system is simulated. The resulting variables and data of the simulation are the interactions between the systems. Some of the obtained interactions are the time between a message transmission and its reception, the distance between them, and the propagation delay of the message.

For the system simulation, the so called "microscopic traffic flow model" [SD14] was selected as the main one because it simulates single vehicle driver units, so the dynamic variables of the model represent microscopic properties like the position and velocity of each vehicle. In contrast the macroscopic model formulates the relationships among traffic flow characteristics like density, flow, and mean speed of a traffic stream. Such values can be integrated by the results of a microscopic model.

Currently, the most used open source network simulators by researchers for V2X systems, sorted by number of citations in a descending order are:

1. Veins
2. VENTOS
3. VSimRTI
4. iTetris

The first three simulators have a similar architecture because they are based on another 2 software, so Veins was the first election for the simulation. It is worth to mention that licensed software as V2X Emulator from Spirent and CANoe.Car2x from Vector were not used due to the monetary implication and its limited information from their communities.

Nevertheless, numerous attempts for the installation of Veins on a Linux and Windows environment failed due to bugs and incompatibility among the outdated libraries of the software. This caused the simulator change to VENTOS, which had a successful installation into an Ubuntu 16.04 LTS environment.

6.1 Software elected

Vehicular Network Open Simulator (VENTOS) is an open source integrated VANET C++ simulator for studying vehicular traffic flows, collaborative driving, and interactions between vehicles and infrastructure through DSRC enabled wireless communication capability. It is being developed in the University of California, Davis Rubinet Lab since 2013, and is an useful tool for researchers in transportation engineering, control theory and vehicular networking fields. It supports multi modal traffic simulation of motor vehicles (cars, buses, trucks, motorcycles, etc.), bikes and pedestrians. It is possible to design and verify many DSRC applications and monitor the message exchange between On-Board Units (OBUs) installed on motor vehicles or bikes, RSUs and pedestrians. It supports all types of V2X wireless communications such as V2V, V2I and V2P.

VENTOS is an integrated simulator based on two well-known simulators: SUMO and OMNET++.

- Simulation of Urban Mobility (SUMO) is an open-source, microscopic, continuous-space, discrete-time C++ road traffic simulator, developed by the Institute of Transportation Systems at the German Aerospace Center (Deutsches Zentrum für Luft-und Raumfahrt). VENTOS is closely coupled with SUMO through Traffic Control Interface (TraCI) and uses the mobility information of cars, bikes and pedestrians to perform realistic simulation.

- Objective Modular Network Testbed in C++ (OMNeT++) is an open-source, extensible, modular, component-based C++ simulation package and captures the wireless communication simulation. IEEE 802.11p physical layer modeling and IEEE 1609.4 are implemented in the Vehicles in Network Simulation (Veins) framework. They are used for wireless V2X communication between different modules.

Many V2X communication scenarios need to dynamically change the behavior of microscopic traffic simulation. SUMO provides the TraCI which allows an external application to retrieve information from the traffic simulation or to influence the simulation behavior. TraCI uses a Transmission Control Protocol (TCP) based client/server architecture to provide access to SUMO where the TCP server is listening on a specific port. SUMO, when started in TraCI mode, only prepares the simulation and waits for an external application to take over the control.

The simulation is performed by running the OMNeT++ network simulation and SUMO road traffic simulation in parallel. OMNeT++ and SUMO are connected using the TraCI. Movement of nodes (vehicles) in SUMO is reflected as movements of nodes in OMNeT++ simulation. Nodes in OMNeT++ can interact with each other using V2X wireless communication and their behavior in SUMO is changed through TraCI, the architecture of the interaction between them is shown in Figure 6-1.

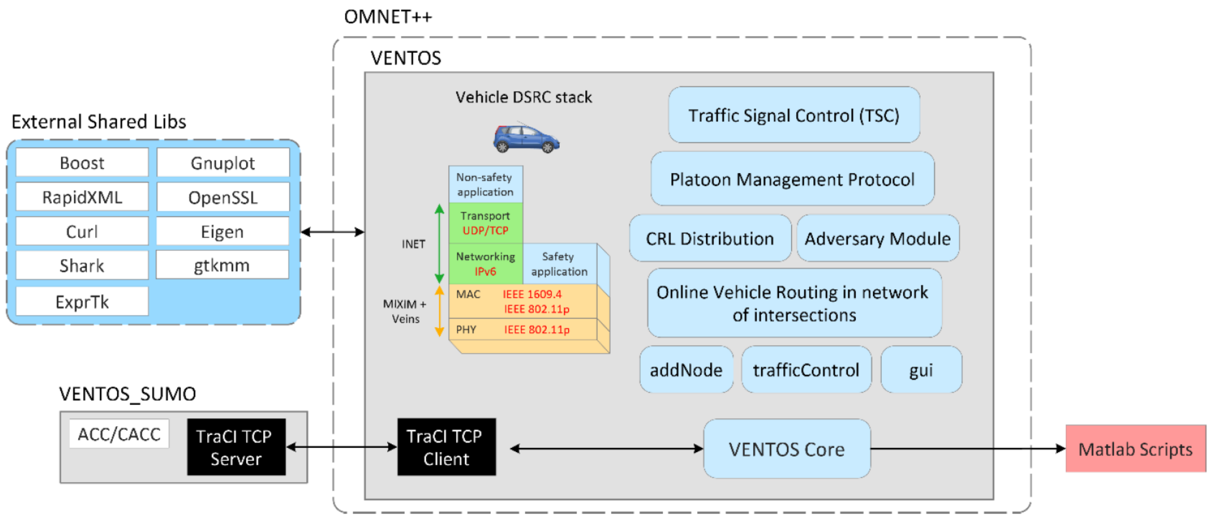


Figure 6-1: VENTOS architecture [ADC+15].

The step-by-step simulation procedure is described as follows:

1. VENTOS starts running.
2. VENTOS uses fork to create a new process and then starts an instance of SUMO in TraCI mode.
3. SUMO prepares the simulation by loading the SUMO configuration file (.sumocfg). It then starts a TCP server and waits for an incoming connection from VENTOS to take over the control.
4. VENTOS connects to the TCP server in SUMO.
5. VENTOS performs network simulations for one time step and then forces SUMO to perform simulation for the same time step. For each node inserted into SUMO, a node is mirrored in OMNeT++.

The procedure for the creation of the V2X system simulation is described in detail in the next subsections with the corresponding concepts and learning steps for each of the different software.

6.2 Road network generation

The first step for the simulation is to create a road network file for SUMO, this file contains the parameters of the physical road in which the simulation is going to be held. The methods to generate SUMO network files are shown in Figure 6-2.

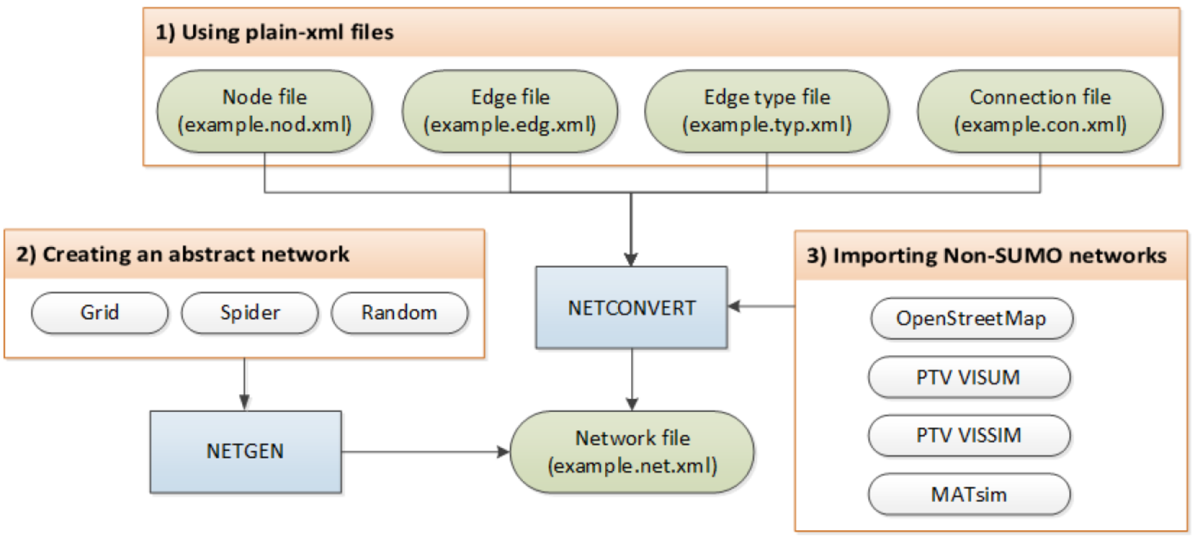


Figure 6-2: Methods for generating SUMO network files [LBBW$^+$18].

It is important to comprehend the structure of the first method (plain xml file) because the second one (import non-SUMO network) is nothing more than an automated way of the first one.

For the first method a set of plain xml files (node file, edge file, edge type file and connection file) which describe the network topology and geometry to generate the SUMO network file are defined by hand. To generate streets in a file, nodes (junctions) and edges (streets connecting the junctions) are required as basic elements. A node has an id for reference, specifies x and y coordinates that show the distance to the origin in meters, and have a nod.xml suffix. A simple code example of a node file is shown below.

```
<nodes>
   <node id="1" x="-200.0" y="0.0" />
   <node id="2" x="0.0" y="0.0" />
   <node id="3" x="+200.0" y="0.0" />
```

```
</nodes>
```

An edge is unidirectional and starts from a source node id and ends at a target node id. The length of this edge will be computed as the distance between the starting and the end point. It is needed to specify a unique id for each edge for reference. Optionally for each edge, it is specified the number of lanes using 'numLanes' and maximum speed in all lanes using 'speed'. Lanes of edge "X" are named X_0, X_1, X_2, etc. where X_0 is the right most lane. The corresponding edge file code of 2 lanes for the previous node file is shown below.

```
<edges>
   <edge id="street1" from="1" to="2" numLanes="2" speed="30" />
   <edge id="street2" from="2" to="3" numLanes="2" speed="30" />
</edges>
```

Then, using the NETCONVERT script on the Ubuntu terminal the street is generated, the resulting xml file is shown in Figure 6-3.

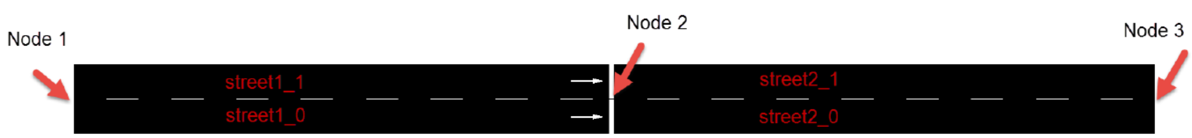


Figure 6-3: Visualization of a simple network file in SUMO.

When an intersection needs to be represented, NETCONVERT can automatically compute the lane to lane connection or for a better result, it can be specified with a connection file. The edge ids and lanes to be connected are specified on it, also the left turn, prohibited maneuvers or u-turn are declared. An example code of an intersection is presented below.

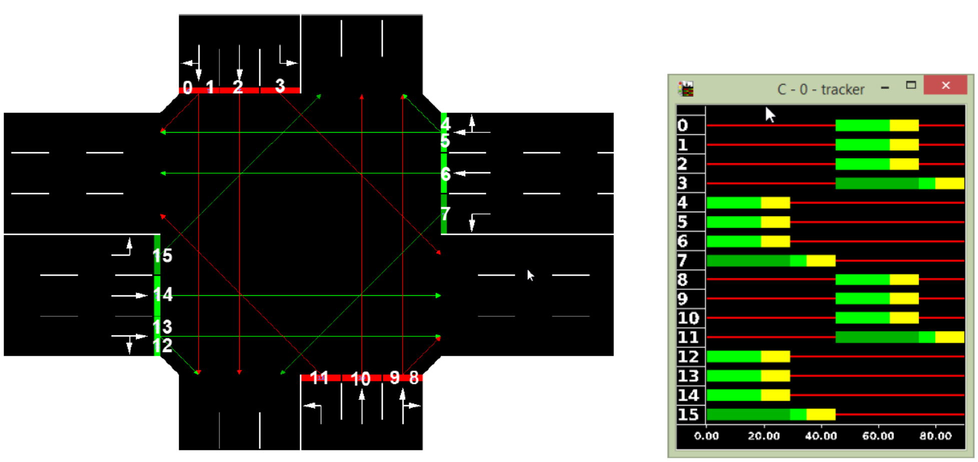
```
<connections>
   <connection from="EC" to="CW" fromLane="0" toLane="0" />
   <connection from="EC" to="CN" fromLane="0" toLane="0" />
   <connection from="EC" to="CW" fromLane="1" toLane="1" />
   <connection from="EC" to="CS" fromLane="2" toLane="2" />

   <connection from="WC" to="CS" fromLane="0" toLane="0" />
   ...

   <connection from="NC" to="CW" fromLane="0" toLane="0" />
   ...
```

```
    <connection from="SC" to="CE" fromLane="0" toLane="0" />
    ...
</connections>
```

Optionally, the traffic light phase durations can be created in an additional file. The traffic lights have default values, but for a better city simulation the phases could be provided by the city road office. An example of an additional file code for the previous connection file is presented below.

```
<tlLogic id="C" type="static" programID="0" offset="0">
    <phase duration="19" state="rrrrGGGgrrrrGGGg"/>
    <phase duration="10" state="rrrryyygrrrryyyg"/>
    <phase duration="6" state="rrrrrrrGrrrrrrrG"/>
    <phase duration="10" state="rrrrrrryrrrrrrry"/>
    <phase duration="19" state="GGGgrrrrGGGgrrrr"/>
    <phase duration="10" state="yyygrrrryyygrrrr"/>
    <phase duration="6" state="rrrGrrrrrrrGrrrr"/>
    <phase duration="10" state="rrryrrrrrrryrrrr"/>
</tlLogic>
```

The result of the previous 2 codes is shown in Figure 6-4, let us notice that the u-turn was not specified in the code and the traffic phase can be observed by double clicking the edge of the lane at the intersection.



(a) (b)

Figure 6-4: a) Visualization of connections at an intersection. b) Visualization of the traffic light phase.

As the traffic light phase, other parameters can be added to the simulation, such as pedestrian crossings and bike lanes. Now that the basic elements of a network file were described, the non-SUMO network way will be explained.

For a non-SUMO network generation, OpenStreetMap was used to import a free editable map from the cities of Aachen and Queretaro (shown in Figure 6-5). The process was to access the webpage and export the selected area of the city into an osm file.

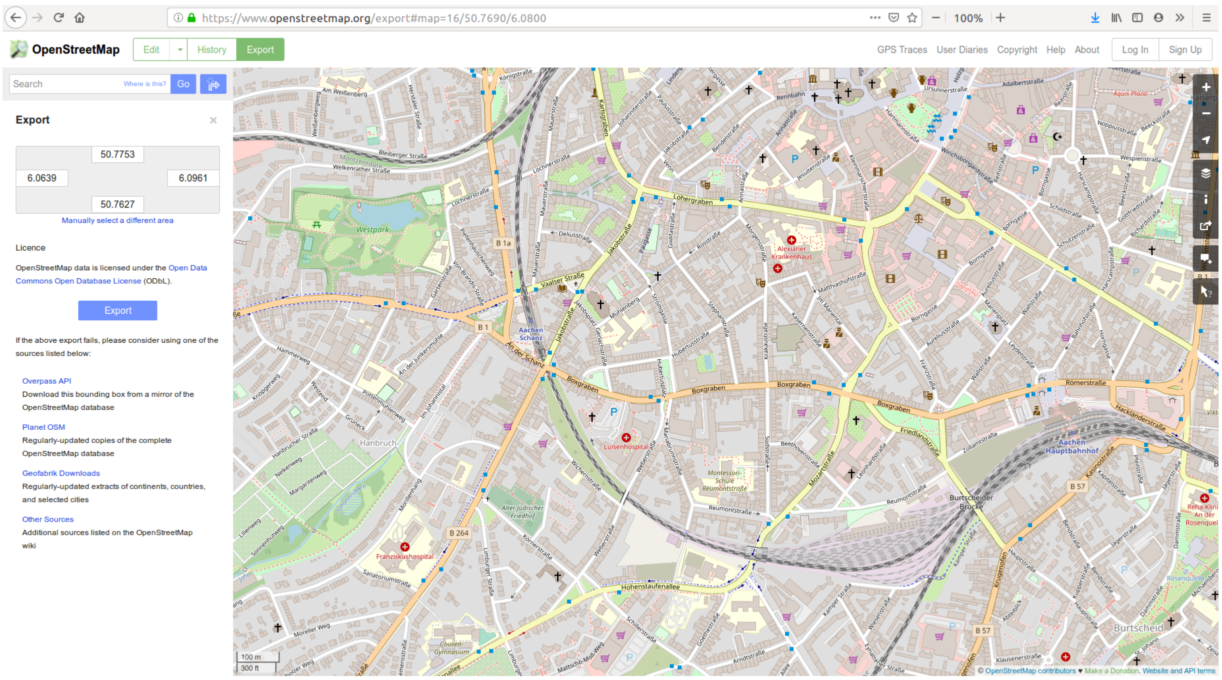
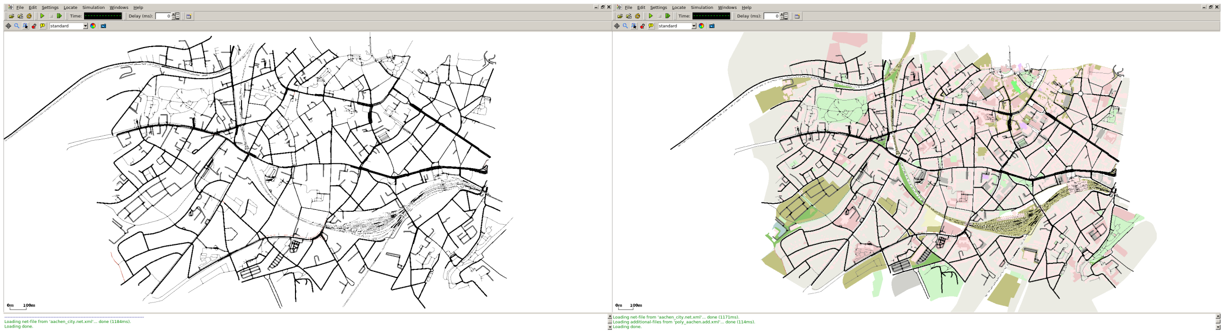


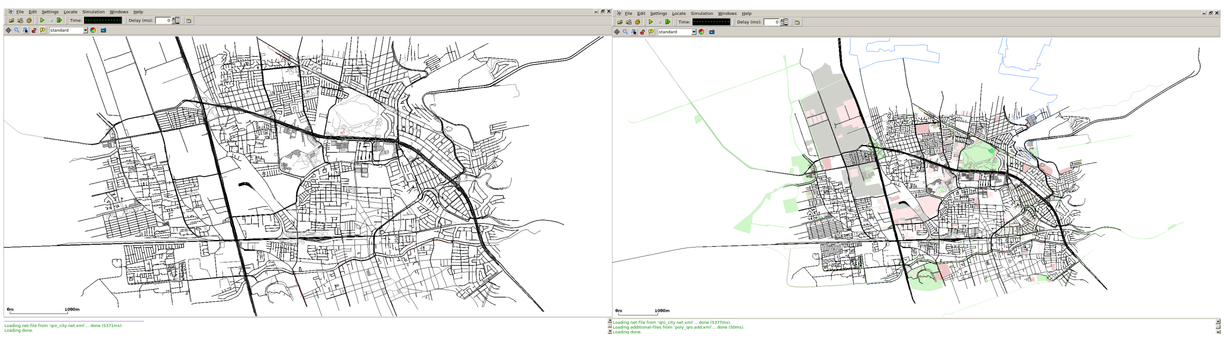
Figure 6-5: Section of Aachen from OpenStreetMap to export.

Using the NETCONVERT script on the terminal, it is possible to convert the osm file of the city into a xml file for the network file of the simulation, the generation of nodes, edges, connections, etc. is done automatically by the script, and can lead to problems on the generated map. Also, the polygons of the buildings, parks and other non-road elements can be added using the POLY-CONVERT script. The results of converting the cities of Aachen (see Figure 6-6), Queretaro (see Figure 6-7), and visualizing them in SUMO-GUI for a preview of the desired maps to use are shown below.



(a) (b)

Figure 6-6: a) Aachen xml file visualization with no polygons. b) Aachen xml file visualization with polygons.



(a) (b)

Figure 6-7: a) Queretaro xml file visualization with no polygons. b) Queretaro xml file visualization with polygons.

After generating the road network file, the vehicles that will transit into it must be created. The next subsection describes the different forms of creating the vehicle definitions (nodes) of the simulation.

6.3 V2X nodes generation

The nodes that correspond to the vehicles, RSUs, and other elements with V2X communication technology need to be generated for a vehicular simulation. The SUMO software can only create nodes of the vehicle type and its behavior, it calls this method the traffic demand file. This generated nodes may have 2 different behaviors as shown in Figure 6-8.

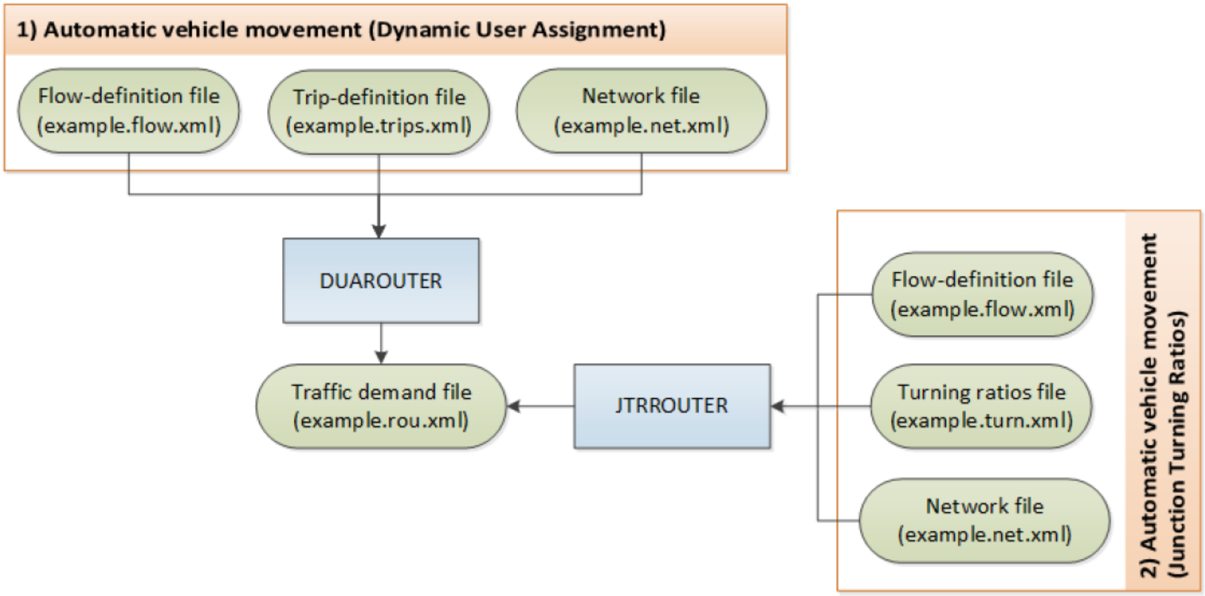


Figure 6-8: Methods for generating SUMO traffic demand files [LBBW$^+$18].

To define a traffic demand file that describes the vehicle type as well as the routes, the following model, and the characteristics, a code is generated. Below is shown an example of a traffic demand file.

```
<routes>
   <!-- passenger vehicle type -->
   <vType id="passenger" length="5.0" minGap="2.0" maxSpeed="30.0"
   vClass="passenger" >
      <carFollowing-Krauss accel="3.0" decel="5.0" sigma="0" tau="1.64"
      />
   </vType>

   <!-- bus vehicle type -->
   <vType id="bus" length="10.0" minGap="4.0" maxSpeed="15.0"
   vClass="bus" >
      <carFollowing-Krauss accel="2.0" decel="3.0" sigma="0" tau="2.0"
      />
   </vType>

   <!-- route definition -->
   <route id="route0" edges="street1 street2" />

   <vehicle id="veh0" type="passenger" color="1,0,0" route="route0"
```

```
    depart="0" departSpeed="0" departPos="0" departLane="first" />
    <vehicle id="veh1" type="passenger" color="1,0,0" route="route0"
    depart="8" departSpeed="0" departPos="0" departLane="first" />
    <vehicle id="veh2" type="passenger" color="1,0,0" route="route0"
    depart="16" departSpeed="0" departPos="0" departLane="first" />
</routes>
```

At the end, these parameters will be represented in the simulation, as in Figure 6-9 were the vehicles with the previously defined characteristics are shown.

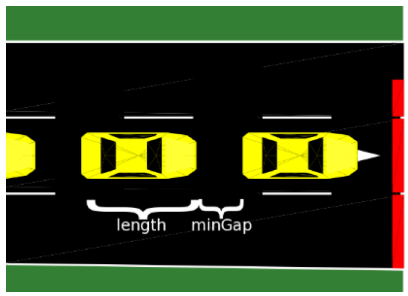


Figure 6-9: Length and minGap for a vehicle.

Other method, which can generate a more variety of node types is the VENTOS method. It provides the addNode module to add different node types into the simulation easily. Adding fix nodes such as RSUs, obstacles, etc. is possible, as well as mobile nodes such as motor vehicles, bikes and person. All nodes are defined in the addNode.xml file located in the omnetpp.ini configuration file folder. The addNode module reads this file and decides which nodes should be inserted at the beginning of the simulation. The addNode module for the simulation test of this theses is presented in Figure 6-10.

```
-<addNode id="add_0">
   <rsu id="RSU0" pos="403.30,1271.46,0"/>
   <rsu id="RSU1" pos="1778.41,2223.92,0"/>
   <rsu id="RSU2" pos="2888.35,2219.63,0"/>
   <rsu id="RSU3" pos="1963.90,1463.26,0"/>
   <rsu id="RSU4" pos="3201.40,916.57,0"/>
   <rsu id="RSU5" pos="4927.74,639.66,0"/>
   <vehicle id="veh0" type="TypePassenger" from="5788351#0" to="-23981217#2" color="red" depart="0"/>
   <vehicle id="veh1" type="TypePassenger" from="5788351#0" to="-23981217#2" color="red" via="41514575#1" depart="5"/>
   <vehicle id="veh2" type="TypePassenger" from="5788351#0" to="-23981217#2" color="red" via="41514575#1,4742027#1-AddedOnRampEdge" depart="10"/>
   <vehicle_flow id="flow1" type="TypePassenger" from="45049317" to="-149621929" color="green" begin="0" number="5" distribution="deterministic" period="10"/>
 </addNode>
```

Figure 6-10: VENTOS addNode module for V2X test simulation.

The addNode.xml file is not a replacement for SUMO traffic demand file and can still define nodes in that file. In fact, addNode.xml complements the SUMO traffic demand file by allowing to add more node types. Defining the SUMO traffic demand file is still necessary (to define vehicle type, route type, etc.).

In the addNode module definition each node has its own default module type, name and display string in OMNeT++. If a vehicle is added into the simulation, then VENTOS uses the vehicle module type defined in it.

6.4 Simulation algorithm

Once a road network is generated and nodes are added into the simulation, the simulation algorithm can start to be written. The input parameters to simulate and the ones to be registered into output files are specified on it.

The algorithm code is written into the omnetpp.ini file, TraCI is activated here for SUMO-OMNET communication, the record of statistics is stipulated and the emulation of the DSRC architecture set. On Figure 6-11 the code for the V2X end simulation is presented with the corresponding values for the test. It is important to notice that VENTOS opens the TraCI interface automatically and controls the simulation under the hood. A maximum time for the simulation is established to avoid infinite loops created by errors.

```
include ../omnetpp_general.ini

[Config V2X_Simulation]
description = "V2V and V2I communication in VANET"

Network.TraCI.active = true
Network.TraCI.SUMOconfig = "sumocfg/stock.sumo.cfg"
Network.TraCI.terminateTime = 800s

Network.addNode.id = "add_0"

# turn on beaconing in vehicles
Network.V[*].appl.sendBeacons = true
Network.V[*].appl.beaconInterval = 0.1s

# turn on beaconing in RSUs
Network.RSU[*].appl.sendBeacons = true
Network.RSU[*].appl.beaconInterval = 1s

Network.V[*].record_stat = true
Network.V[*].record_list = "vehId | lanePos | speed | accel"

Network.V[*].nic.phy80211p.emulationActive = true
Network.RSU[*].nic.phy80211p.emulationActive = true

Network.V[*].nic.phy80211p.record_frameTxRx = true
Network.RSU[*].nic.phy80211p.record_frameTxRx = true
```

Figure 6-11: VENTOS simulation algorithm for test simulation.

To run the algorithm it is necessary to execute first the OMNeT++ application, and configure the simulation with the run parameters. The Run Configuration parameters for the test simulation of the project are shown in Figure 6-12.

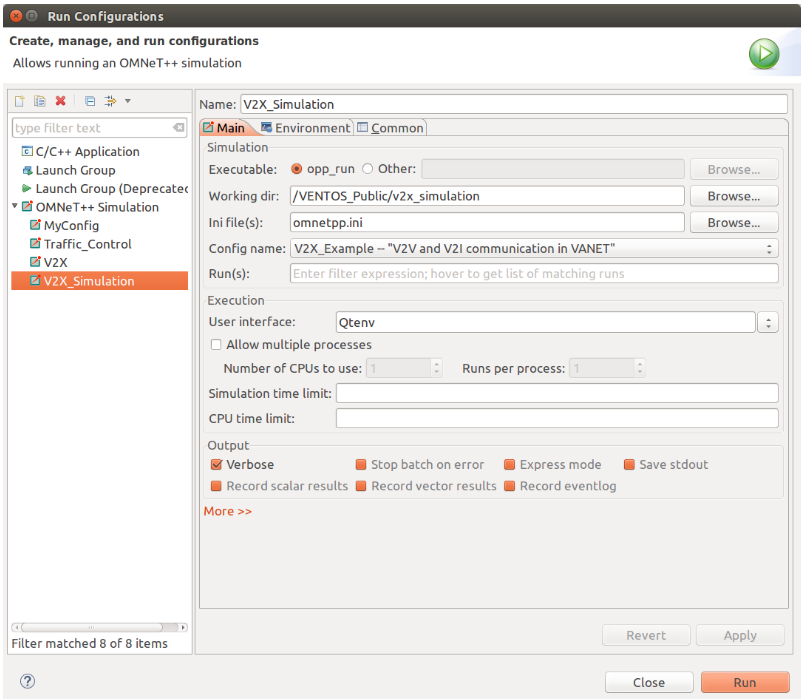


Figure 6-12: VENTOS run configuration of the simulation.

For the test of the system, a OMNeT++ simulation configuration type was used and called V2X_Simulation, the executable was set to opp_run, the working directory of the algorithm selected, the omnetpp.ini containing the algorithm of the simulation was picked, the V2V and V2I communication in VANET was used as sample for the preconfigured files, and the following parameters were left by default.

6.5 Simulation results

Finally, after the algorithm was created and configured into the OMNeT++ software, the simulation test run was done.

After some unsuccessful attempts with the Aachen and Queretaro city maps, the network file of the city of Stockholm was used. The errors encountered on the city maps were caused by miss matches in their junctions and edges, which probably are part of a conversion failure from an osm file into a xml file. The errors persisted even after some attempts with different conversion parameters. For this reason the main map of the VENTOS community (Stockholm) was used. The generated map with 4 distributed RSUs which are represented with green circles is shown in Figure 6-13.

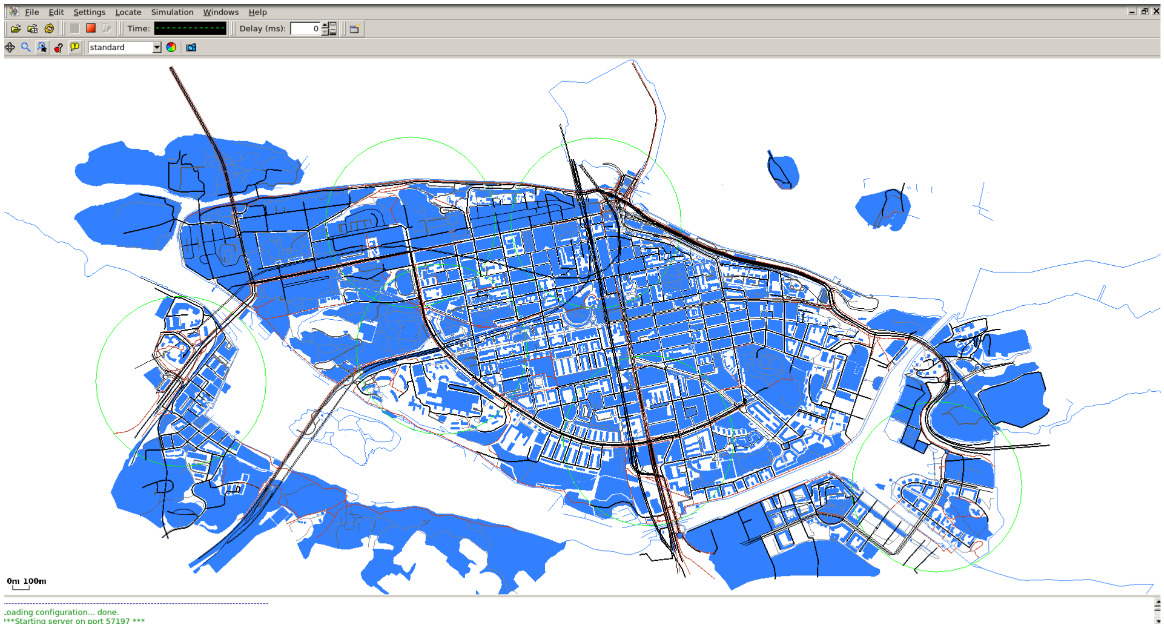


Figure 6-13: Stockholm map used for the test simulation with 4 RSUs (circles on green).

The visualization of the vehicle #2 with the node parameters described in Section 6.3 is shown in Figure 6-14 of the SUMO-GUI.

The communication events from OMNeT++ can be observed in Figure 6-15, the transmission and reception of a message from V[1] to the RSU[2] is colored in yellow. The connections and communication process from the DSRC architecture described in Section 2.3.2 is also part of the events from the simulation.

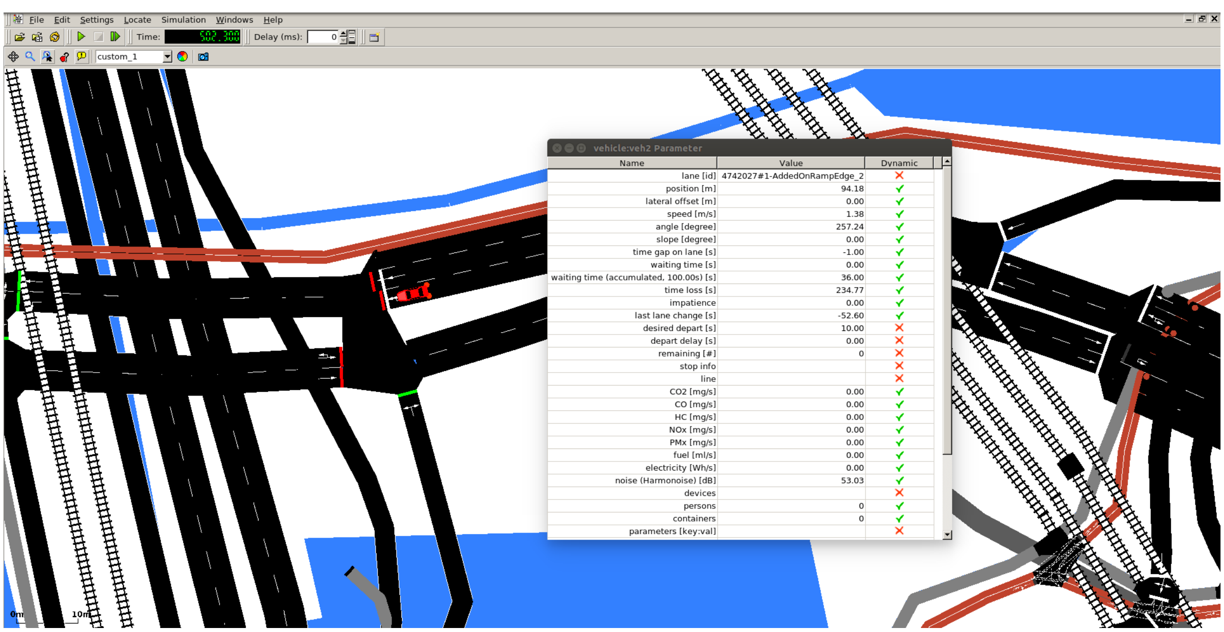


Figure 6-14: Visualization of node parameters of the test simulation in SUMO.

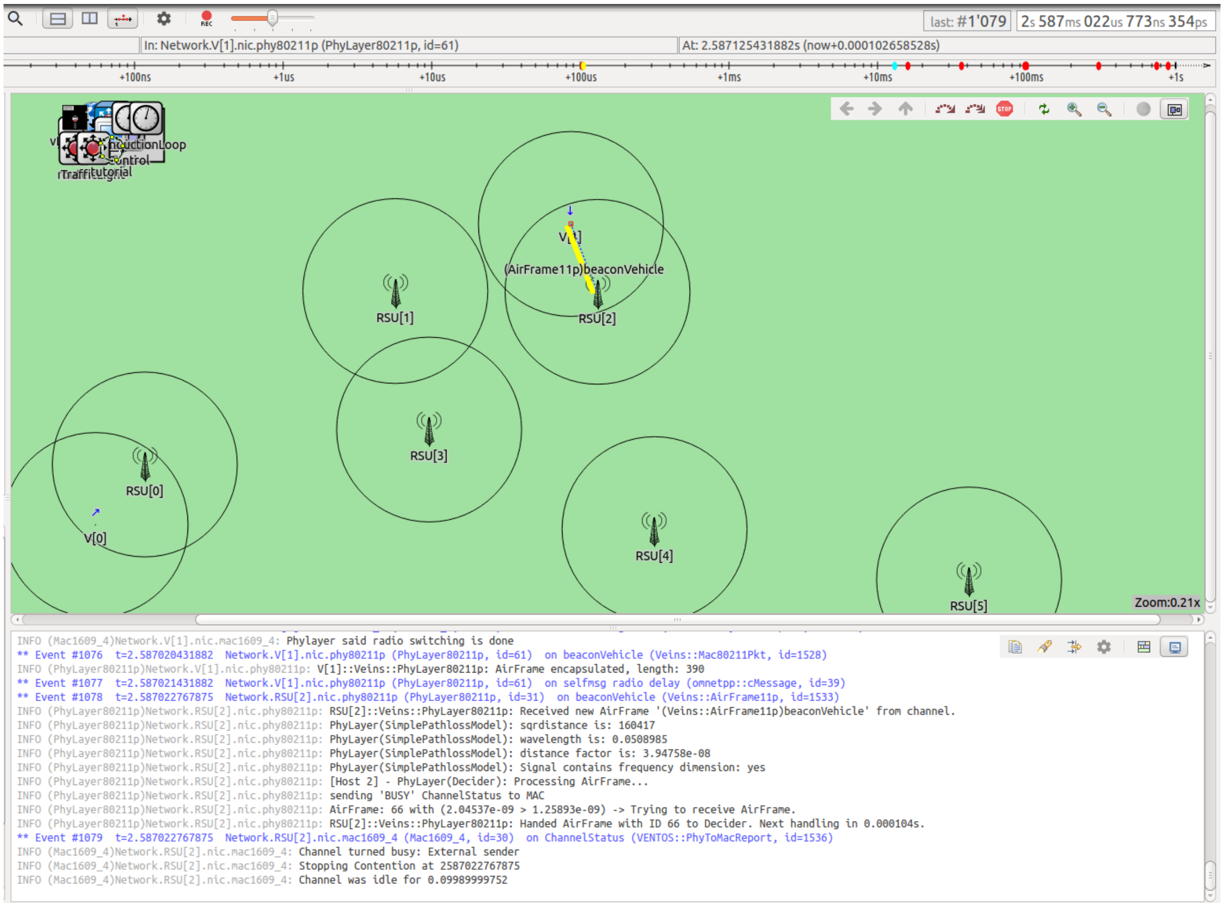


Figure 6-15: Visualization of the communication process of the test simulation in OMNeT++.

The observed parameters are during 502.3 seconds of the system simulated. The dynamic variables such as waiting time, noise, and speed will vary during the whole simulation.

After the simulation finished, the FrameTxRxdata file is created as an output, on it all the communication events of the simulation are registered (see Figure 6-16). When a vehicle sends a message or creates a connection with other V2X system, a message id is assigned to that event and recorded with all the other respective values. It is important to notice that in the simulation results the time between the sending of the message and the reception is less than 0.0002 s. This occurs because the obstacles and noise in the environment are neglected in the simulation. Nevertheless, the margin between the transmission time and an average driver recognition time (0.6 s) is still huge, so it is viable to consider further tests for the processing time of the system.

```
configName      V2X_Simulation
iniFile         omnetpp.ini
processID       6780
runID           V2X_Simulation-0-20191017-00:03:57-6780
totalRun        1
currentRun      0
currentConfig   V2X_Simulation
sim timeStep    100 ms
startDateTime   2019-10-17 00:03:57.720
endDateTime     2019-10-17 00:05:56.720
duration        0 hour, 1 minute, 59 second

MsgId              MsgName              SenderNode           ReceiverNode         ReceiverGateId       SendingStartAt       FrameSize
ChannelNum         TransmissionPower    TransmissionSpeed    TransmissionTime     DistanceToReceiver   PropagationDelay
ReceptionEndAt     FrameRxStatus


48                 beaconVehicle        V[0]                 RSU[0]               16                   0.08327300           390
178                20.00                6.00                 0.00010400           438.04152052         0.0000014611490
0.08337846         HEALTHY

72                 beaconVehicle        V[1]                 RSU[2]               28                   0.08701700           390
178                20.00                6.00                 0.00010400           410.18871962         0.0000013682420
0.08712237         HEALTHY

96                 beaconVehicle        V[0]                 RSU[0]               16                   0.18326400           390
178                20.00                6.00                 0.00010400           438.01170134         0.0000014610500
0.18336946         HEALTHY

120                beaconVehicle        V[1]                 RSU[2]               28                   0.18702100           390
178                20.00                6.00                 0.00010400           410.15896538         0.0000013681430
0.18712637         HEALTHY

144                beaconVehicle        V[0]                 RSU[0]               16                   0.28326800           390
178                20.00                6.00                 0.00010400           437.95206304         0.0000014608510
0.28337346         HEALTHY

168                beaconVehicle        V[1]                 RSU[2]               28                   0.28701200           390
178                20.00                6.00                 0.00010400           410.09945702         0.0000013679450
0.28711737         HEALTHY

192                beaconRSU            RSU[5]               -                    -                    0.33741000           390
178                20.00                6.00
0.00010400         -                    -                     -                    -
```

Figure 6-16: Frame data output file for the communication events.

Also, the record_stat output was created containing the vehicle id, speed and acceleration values collected from the simulation. The output data for that set of values is written into the vehicle-Data.txt file. The graph generated with the registered values is shown in Figure 6-17.

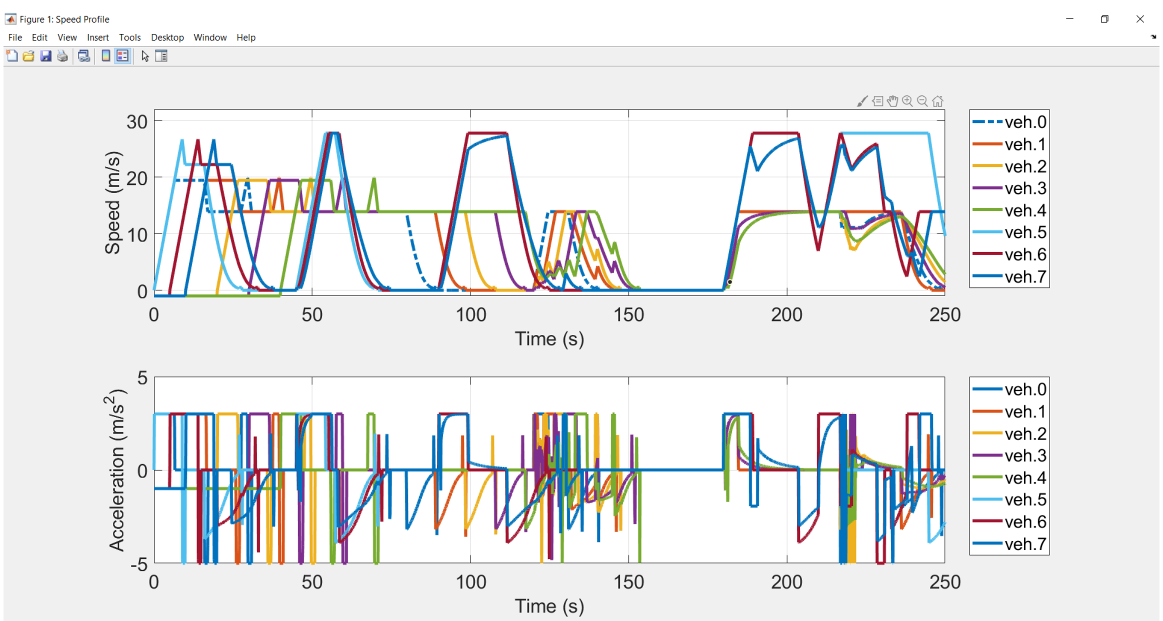


Figure 6-17: Graphs of speed and acceleration, comparison from the 8 vehicles of the simulation.

The previous graph was generated with a MATLAB script provided by VENTOS, it helps to read the output text file and plot the graph of the speed and acceleration of the simulated vehicle. The shown values come from all the vehicles that took part in the test simulation.

The V2X system simulation was built using the following steps:

1. Generating a road network consisting of junctions (nodes) and roads (edges) in SUMO, by importing a non-SUMO network with Open Street Map.
2. Generating a multi-modal DSRC enabled traffic including motor vehicles and RSUs, using the addNode module from VENTOS to add different node types into the simulation.
3. Writing the algorithm that uses the simulation data and affects the simulation behavior.
4. Running the simulation and collecting data for post-processing.

7 Conclusion and Further work

The vehicular systems introduced to today's market are becoming more refined and sophisticated than ever. As technology advances towards to a driverless solution, data gathering plays an important role in developing such systems. Vehicular communication is one way of receiving information from the surrounding Intelligent Transport Systems (ITS) and transmitting to them.

The presented work consisted in the definition and conceptualization of a vehicular system for traffic and collision avoidance. Also, the creation of a model that reflects the characteristics and functionality of a Vehicle-to-Everything (V2X) system to be applied. In this regard, it is concluded that the model satisfactorily reflects the characteristics of the system proposed and has potential utility. Also, its system structure contributes to the the growing V2X technology by proposing functions and applications for real world issues. For the simulation, the interaction between different system types (Road Side Unit (RSU) and Dedicated Short Range Communications (DSRC) enhanced vehicles) was tested and gave positive results for the transmission and reception time, concluding that further developments and tests are viable. It can be said that the initially set specific objectives in Section 1.4.2 have been satisfactorily met. The realization of the work was carried out according to the planned time, although there were certain scheduled issues. In general, it can be said that the thesis work was completed within the agreed deadline.

For future work, the continuation of the next stages from the methodology established in section 1.9 is intended, going from the preliminary and detailed design of the system to the implementation of a functional alpha prototype that allows to test and prove concrete achievements is intended. A possible way of further development is the adaptation of the model to other similar vehicular systems. Thus, another way of extension would be to address the software modeling in depth, taking as a model of interest not only the single system but also the RSUs with which it is connected, and thus model the complete network from which the system would form part. Finally, for the simulation part it is recommended to add the noise and the path obstruction equations into the communication signals. Also, the generation of real life events such as vehicle collisions and roadway closures will help to achieve a more realistic simulation of the intended system.

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Acronyms

3GPP 3rd Generation Partnership Project

ADAS Advanced Driver Assistance System

ASIL Automotive Safety Integrity Level

ASN.1 Abstract Syntax Notation One

bdd block definition diagram

BSM Basic Safety Message

BSS Basic Service Set

CAN Controller Area Network

CCH Control Channel

CICAS Cooperative Intersection Collision Avoidance Systems

ConOps Concept of Operations

CPU Central Processing Unit

C-V2X Cellular Vehicle-to-Everything

DSRC Dedicated Short Range Communications

ECU Electronic Control Unit

EDR Event Data Recorder

EEBL Emergency Electronic Brake Light

ETSI European Telecommunications Standards Institute

FCC Federal Communications Commission

FHWA Federal Highway Administration

FR Functional Requirements

GNSS Global Navigation Satellite System

GPS Global Position System

HLR High Level Requirements

HMI Human Machine Interface

ibd internal block diagram

IEC International Electrotechnical Commission

IEEE Institute of Electric and Electronics Engineers

ISO International Organization for Standardization

ITS Intelligent Transport Systems

LiDAR Light Detection and Ranging

LIN Local Interconnect Network

LTE Long Term Evolution

MAC Medium Access Control

MANET Mobile Ad Hoc Network

MBSE Model Based Systems Engineering

NFR Non-Functional Requirements

NHTSA National Highway Traffic Safety Administration

OBU On Board Unit

OCB Outside the Context of a BSS

OMG Object Management Group

OMNeT++ Objective Modular Network Testbed in C++

PHY Physical

pkg package diagram

PM Particulate Matter

RSU Road Side Unit

SAE Society of Automotive Engineers

SCH Service Channel

SUMO Simulation of Urban Mobility

SysML System Modeling Language

TCP Transmission Control Protocol

TPD Tamper Proof Device

TraCI Traffic Control Interface

UK United Kingdom

UPER Unaligned Packed Encoding Rules

USA United States of America

UTC Coordinated Universal Time

V2I Vehicle-to-Infrastructure

V2N Vehicle-to-Network

V2P Vehicle-to-Pedestrian

V2R Vehicle-to-Roadside Unit

V2S Vehicle-to-Sensor

V2V Vehicle-to-Vehicle

V2X Vehicle-to-Everything

VANET Vehicle Ad Hoc Network

Veins Vehicles in Network Simulation

VENTOS Vehicular Network Open Simulator

VPKI Vehicular Public Key Infrastructure

WAAS Wide Area Augmentation System

WAVE Wireless Access in Vehicular Network

WGS-84 World Geodetic System 1984

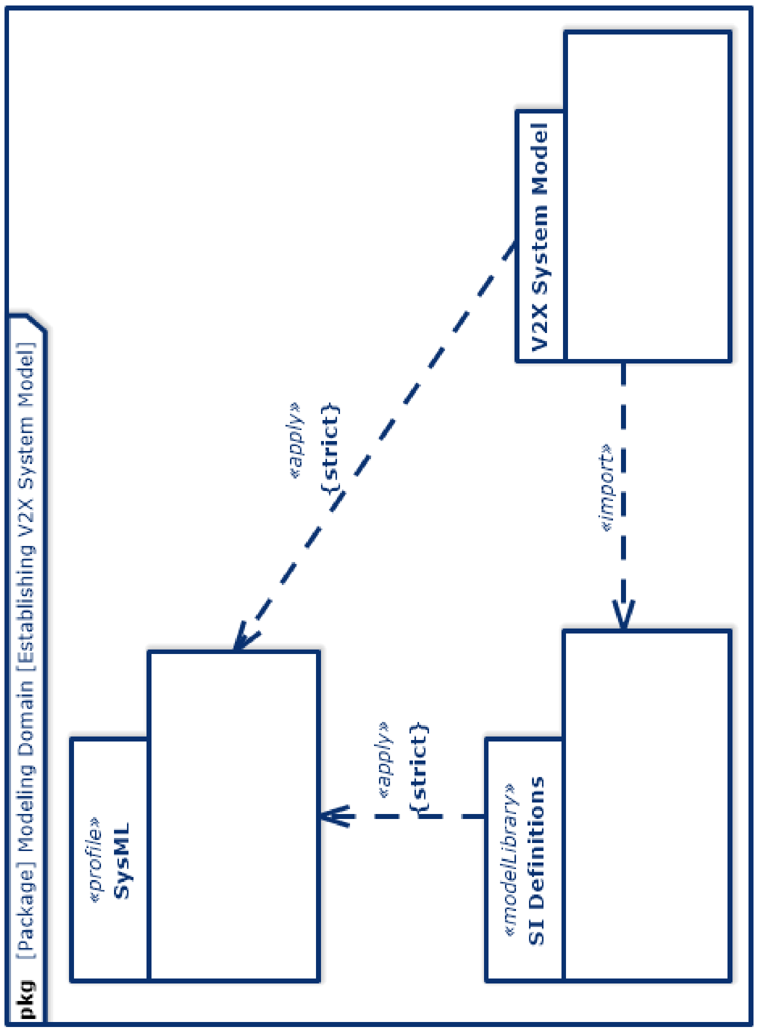
WHO World Health Organization

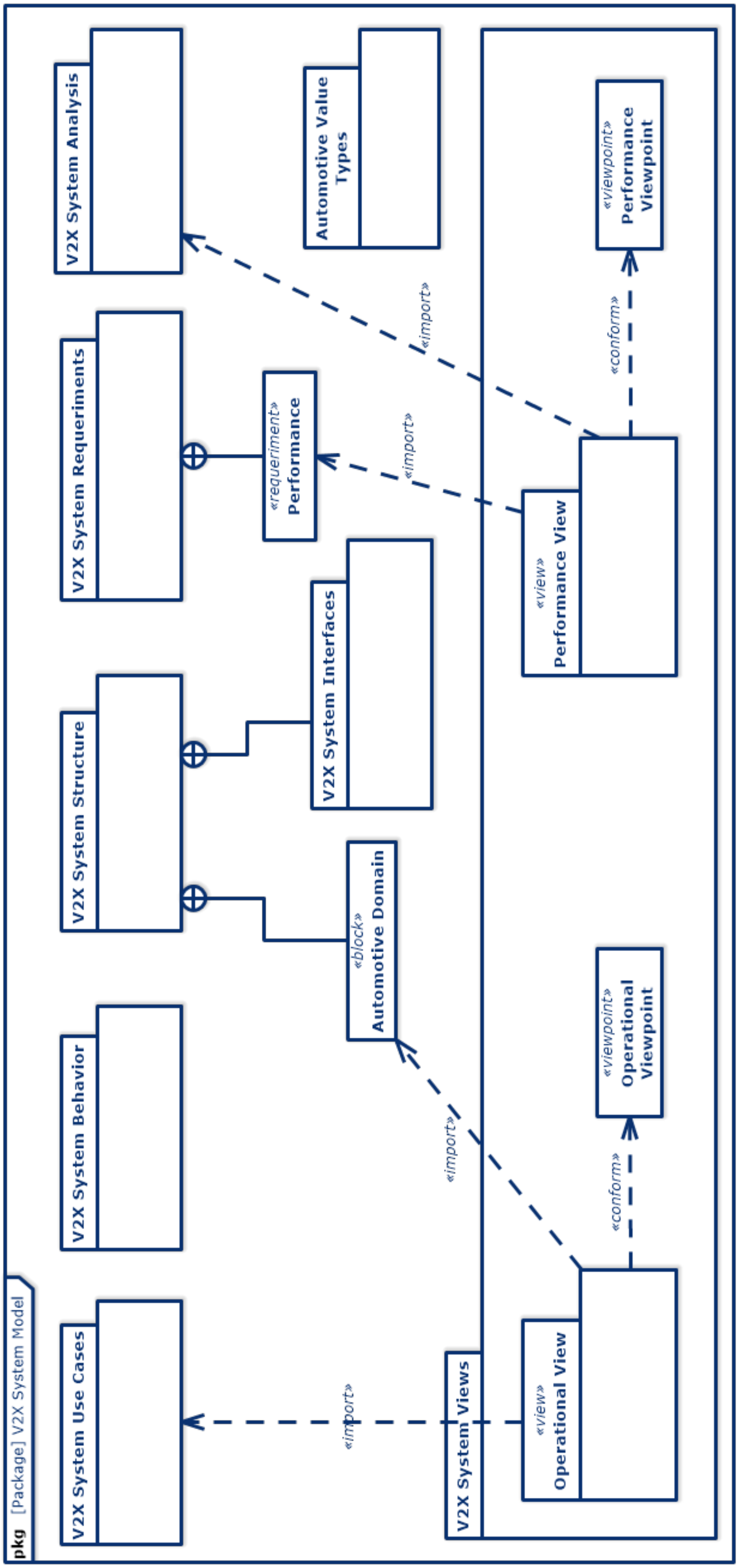
WSA WAVE Service Advertisement

List of Figures

List of Tables

Appendix A: SysML

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V2X System Use Cases
V2X System Behavior
V2X System Structure
V2X System Requeriments
V2X System Analysis
Automotive Value Types
V2X System Interfaces
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Automotive Domain
«requeriment»
Performance
«import»
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«import»
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V2X System Views
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Operational View
«view»
Performance View
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Operational Viewpoint
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Performance Viewpoint
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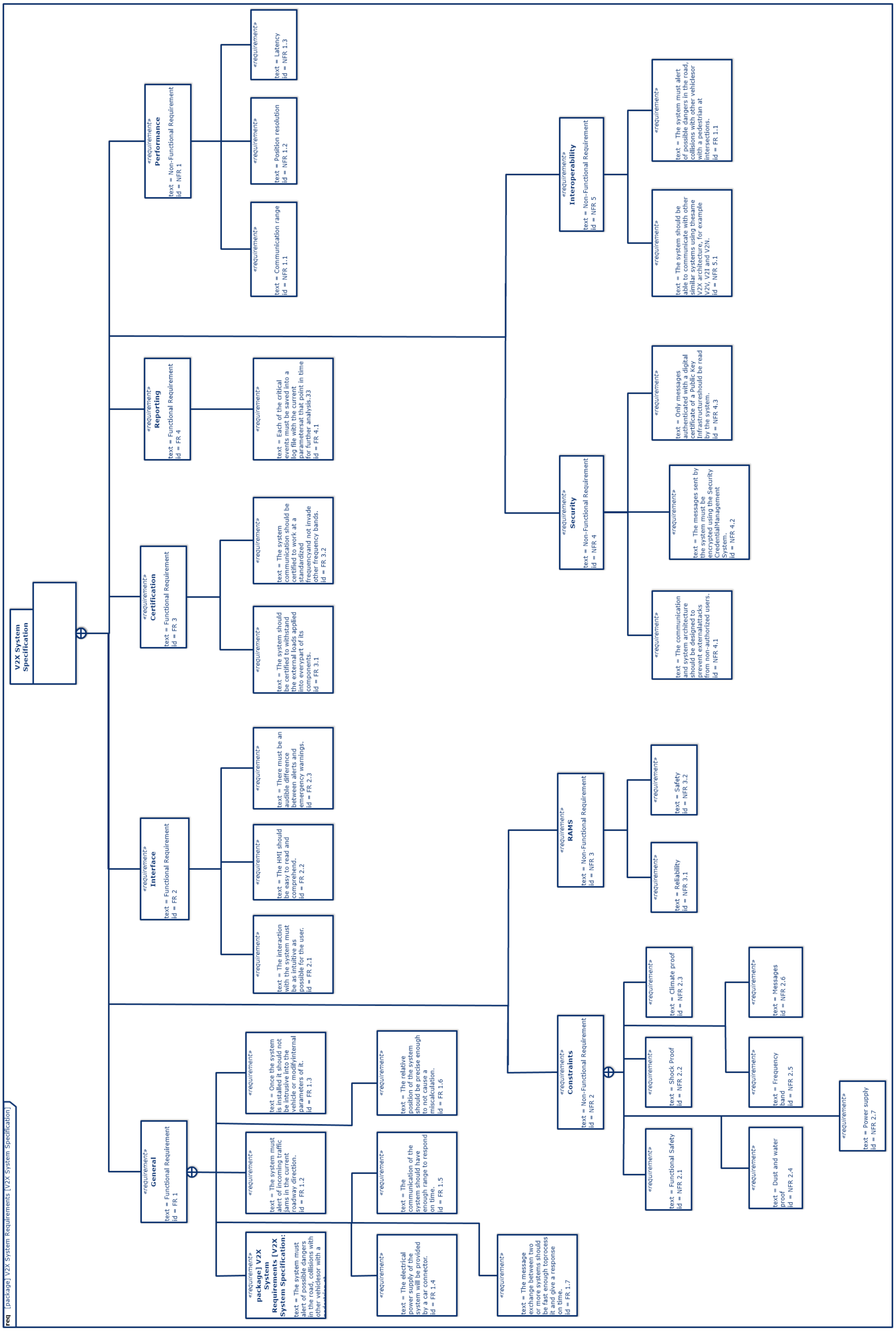
«conform»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text = Communication range
id = NFR 1.1
«requirement»
text = Position resolution
id = NFR 1.2
«requirement»
text = Latency
id = NFR 1.3
«requirement» Reporting
text = Functional Requirement
id = FR 4
«requirement»
text = Each of the critical events must be saved into a log file with the current parametersat that point in time for further analysis.33
id = FR 4.1
«requirement» Certification
text = Functional Requirement
id = FR 3
«requirement»
text = The system should be certified to withstand the external loads applied into everypart of its components.
id = FR 3.1
«requirement»
text = The system communication should be certified to work at a standardized frequencyand not invade other frequency bands.
id = FR 3.2
«requirement» Interface
text = Functional Requirement
id = FR 2
«requirement»
text = The interaction with the system must be as intuitive as possible for the user.
id = FR 2.1
«requirement»
text = The HMI should be easy to read and comprehend.
id = FR 2.2
«requirement»
text = There must be an audible difference between alerts and emergency warnings.
id = FR 2.3
«requirement» General
text = Functional Requirement
id = FR 1
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text = The system must alert of possible dangers in the road, collisions with other vehiclesor with a
«requirement»
text = The system must alert of incoming traffic jams in the current roadway direction.
id = FR 1.2
«requirement»
text = Once the system is installed it should not be intrusive into the vehicle or modifyinternal parameters of it.
id = FR 1.3
«requirement»
text = The electrical power supply of the system will be provided by a car connector.
id = FR 1.4
«requirement»
text = The communication of the system should have enough range to respond on time.
id = FR 1.5
«requirement»
text = The relative position of the system should be precise enough to not cause a miscalculation.
id = FR 1.6
«requirement»
text = The message exchange between two or more systems should be fast enough toprocess it and give a response on time.
id = FR 1.7
«requirement» Interoperability
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text = The system should be able to communicate with other similar systems using thesame V2X architecture, for example V2V, V2I and V2N.
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text = The system must alert of possible dangers in the road, collisions with other vehiclesor with a pedestrian at intersections.
id = FR 1.1
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id = NFR 4
«requirement»
text = The communication and system architecture should be designed to prevent externalattacks from non-authorized users.
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«requirement»
text = The messages sent by the system must be encrypted using the Security CredentialManagement System.
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«requirement»
text = Only messages authenticated with a digital certificate of a Public Key Infrastructureshould be read by the system.
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id = NFR 3.1
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text = Safety
id = NFR 3.2
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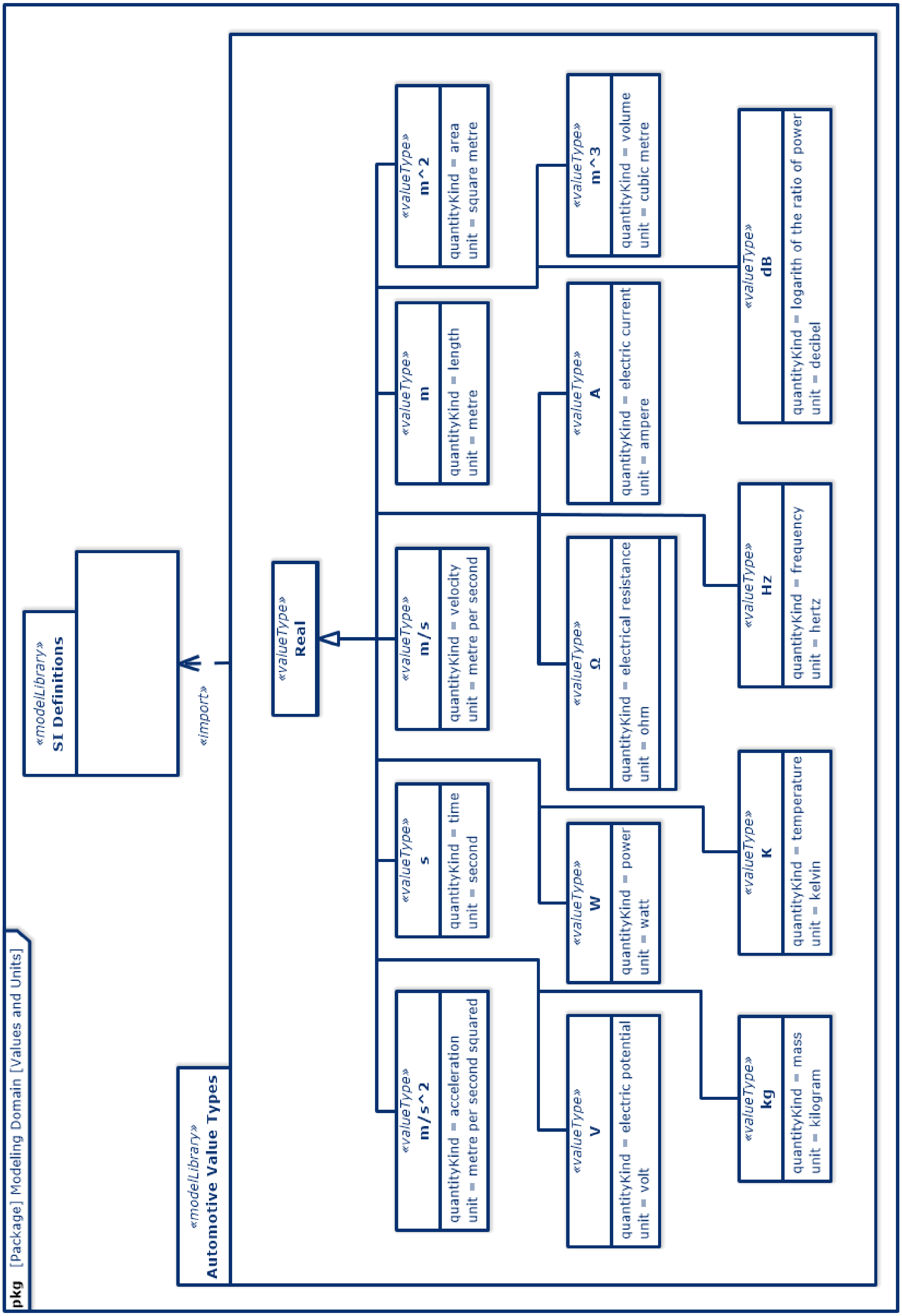
text = Functional Safety
id = NFR 2.1
«requirement»
text = Shock Proof
id = NFR 2.2
«requirement»
text = Climate proof
id = NFR 2.3
«requirement»
text = Dust and water proof
id = NFR 2.4
«requirement»
text = Frequency band
id = NFR 2.5
«requirement»
text = Messages
id = NFR 2.6
«requirement»
text = Power supply
id = NFR 2.7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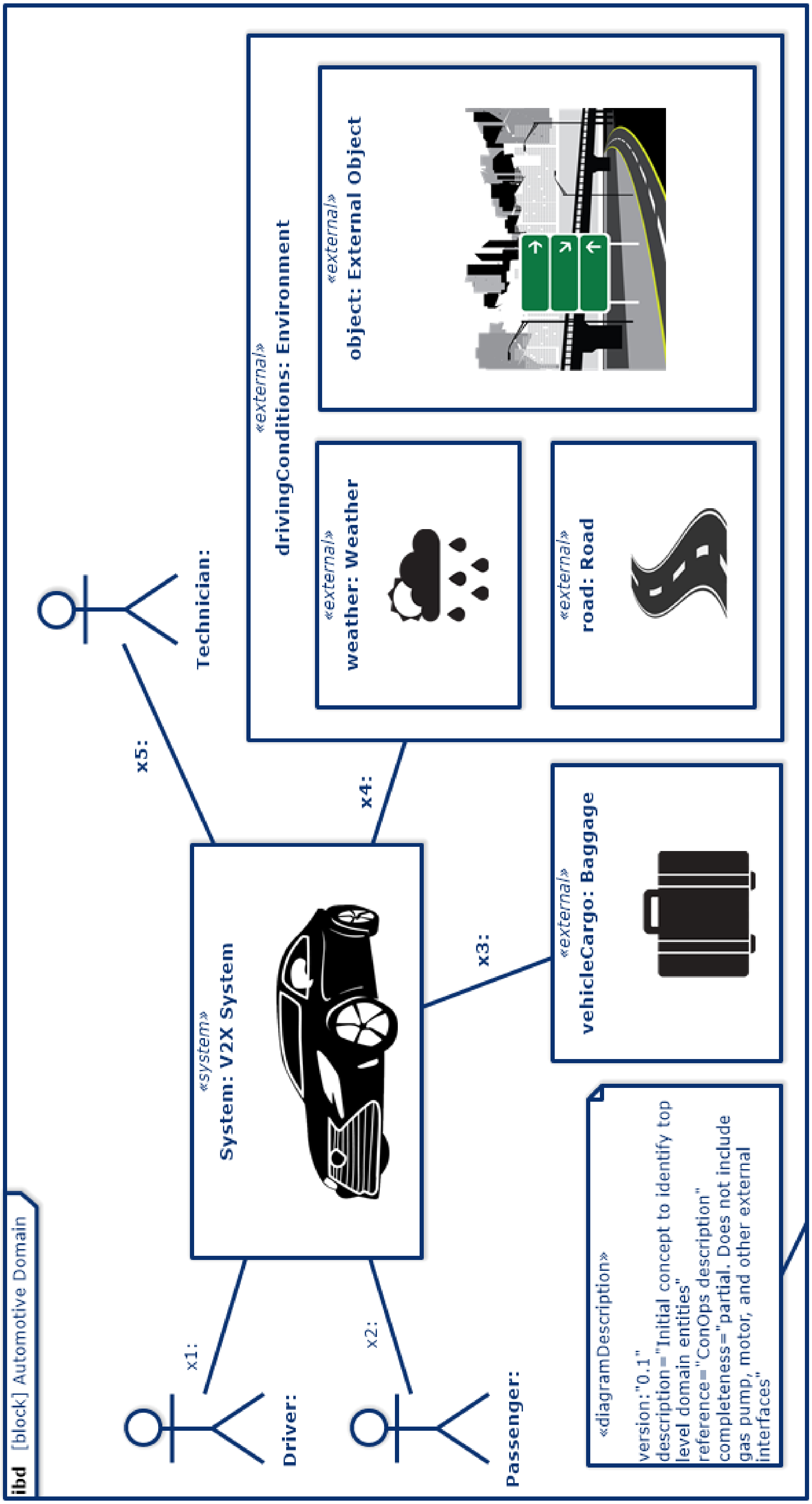
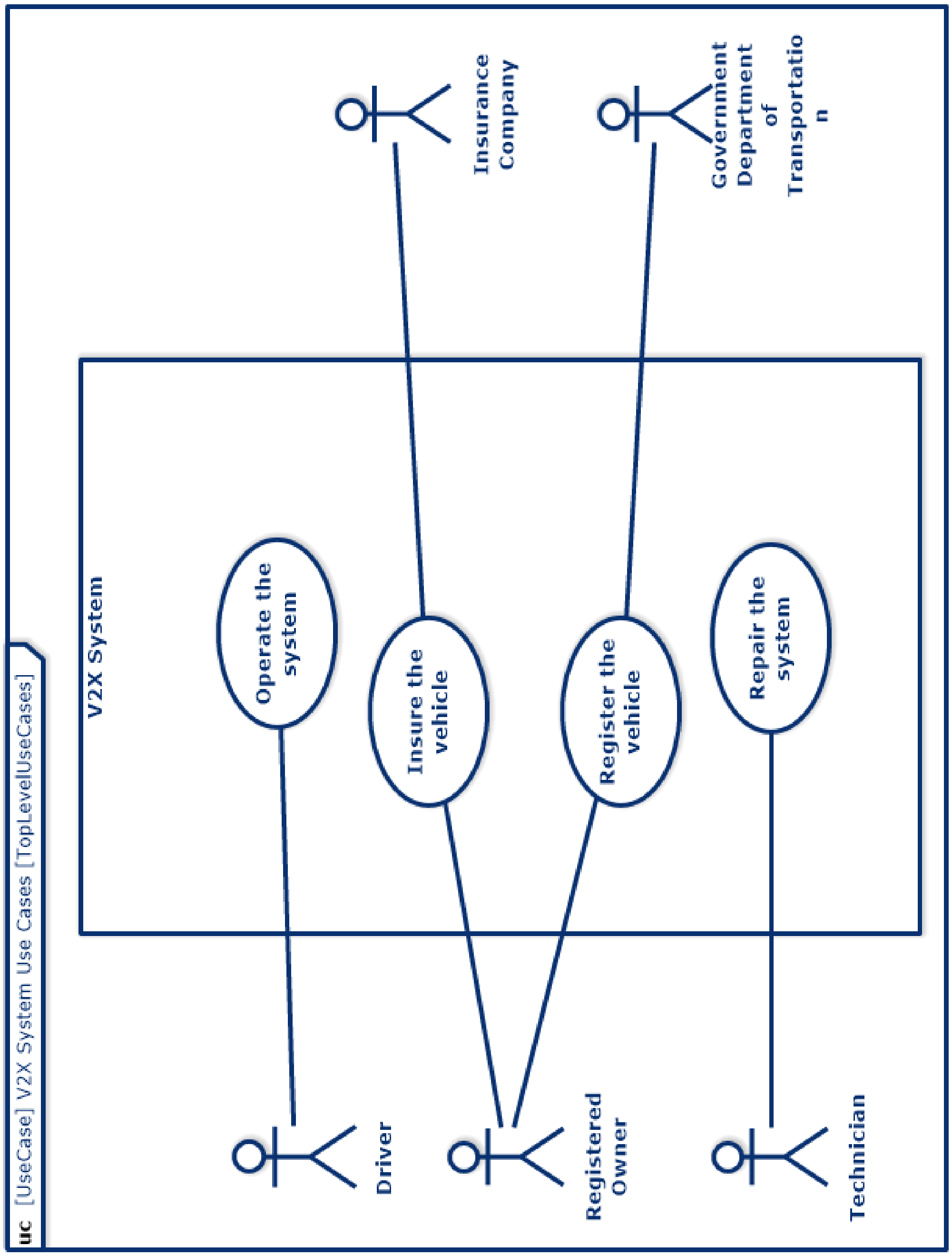
SI Definitions
«import»
«modelLibrary»
Automotive Value Types
«valueType»
Real
«valueType»
m/s^2
quantityKind = acceleration
unit = metre per second squared
«valueType»
s
quantityKind = time
unit = second
«valueType»
m/s
quantityKind = velocity
unit = metre per second
«valueType»
m
quantityKind = length
unit = metre
«valueType»
m^2
quantityKind = area
unit = square metre
«valueType»
V
quantityKind = electric potential
unit = volt
«valueType»
W
quantityKind = power
unit = watt
«valueType»
Ω
quantityKind = electrical resistance
unit = ohm
«valueType»
A
quantityKind = electric current
unit = ampere
«valueType»
m^3
quantityKind = volume
unit = cubic metre
«valueType»
kg
quantityKind = mass
unit = kilogram
«valueType»
K
quantityKind = temperature
unit = kelvin
«valueType»
Hz
quantityKind = frequency
unit = hertz
«valueType»
dB
quantityKind = logarith of the ratio of power
unit = decibel


ibd [block] Automotive Domain
«system»
System: V2X System
Driver:
Passenger:
Technician:
x1:
x2:
x3:
x4:
x5:
«external»
vehicleCargo: Baggage
«external»
drivingConditions: Environment
«external»
weather: Weather
«external»
road: Road
«external»
object: External Object
«diagramDescription»
version:"0.1"
description="Initial concept to identify top level domain entities"
reference="ConOps description"
completeness="partial. Does not include gas pump, motor, and other external interfaces"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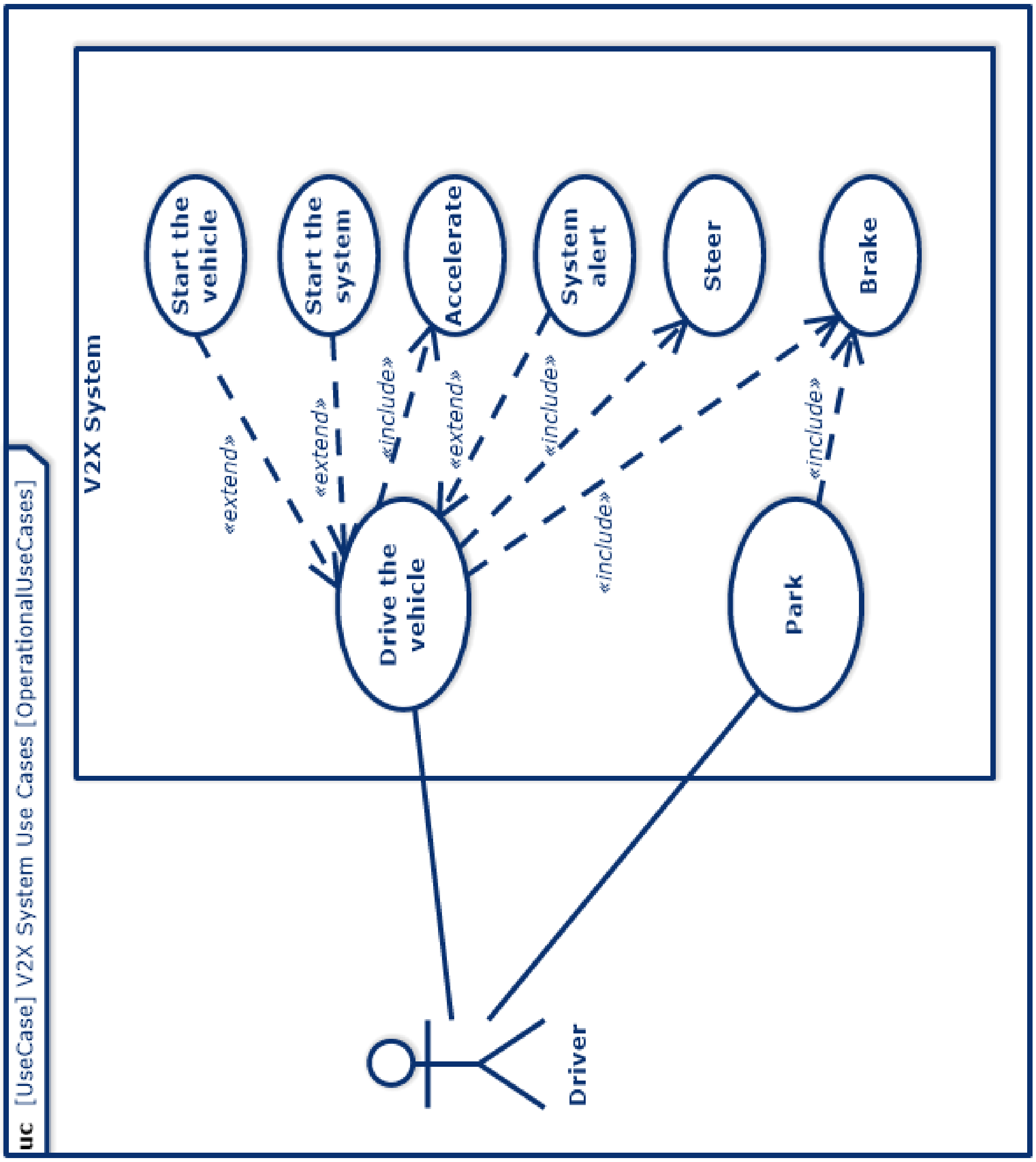
V2X System
Operate the system
Insure the vehicle
Register the vehicle
Repair the system
Driver
Registered Owner
Technician
Insurance Company
Government Department of Transportatio n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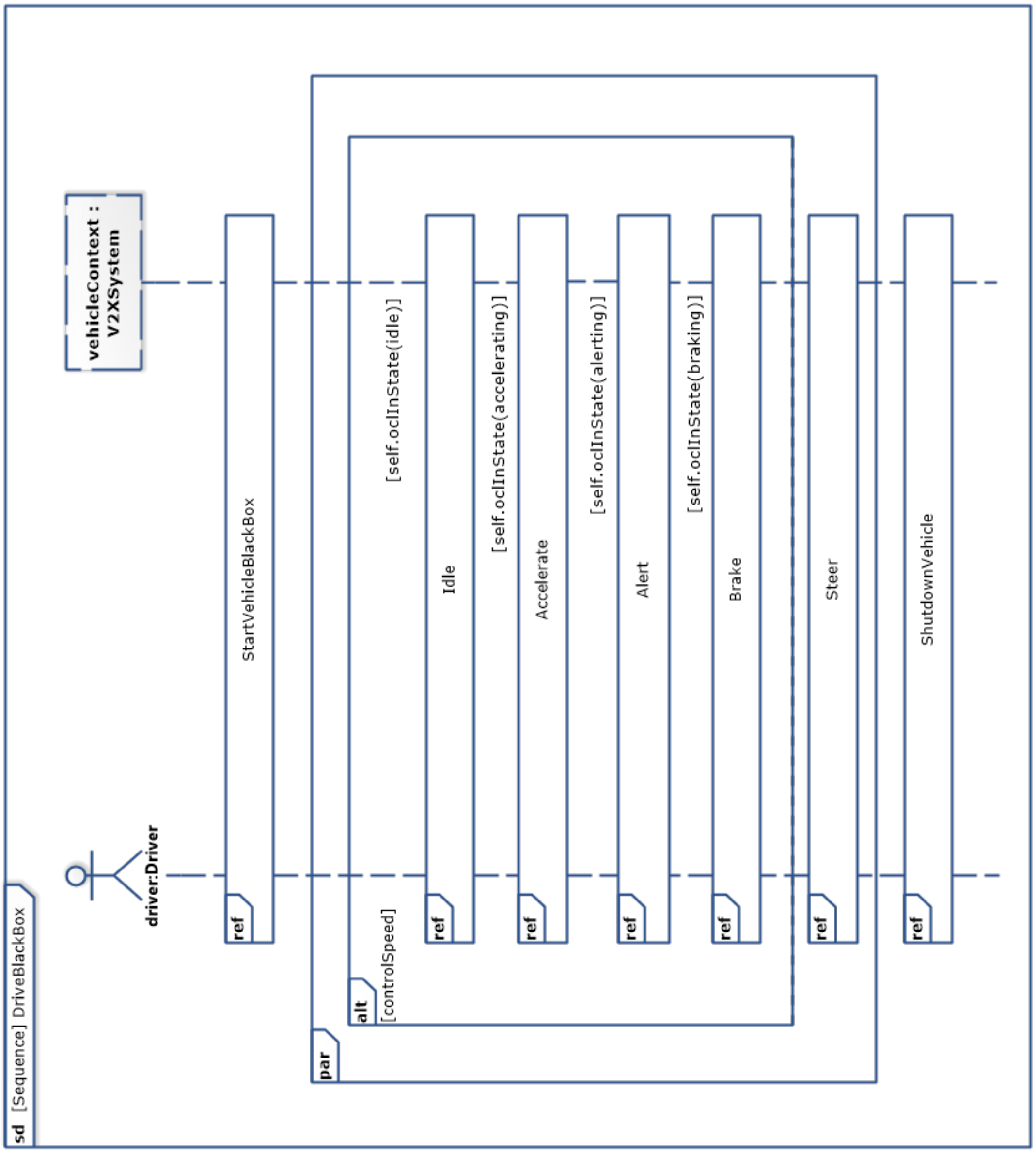
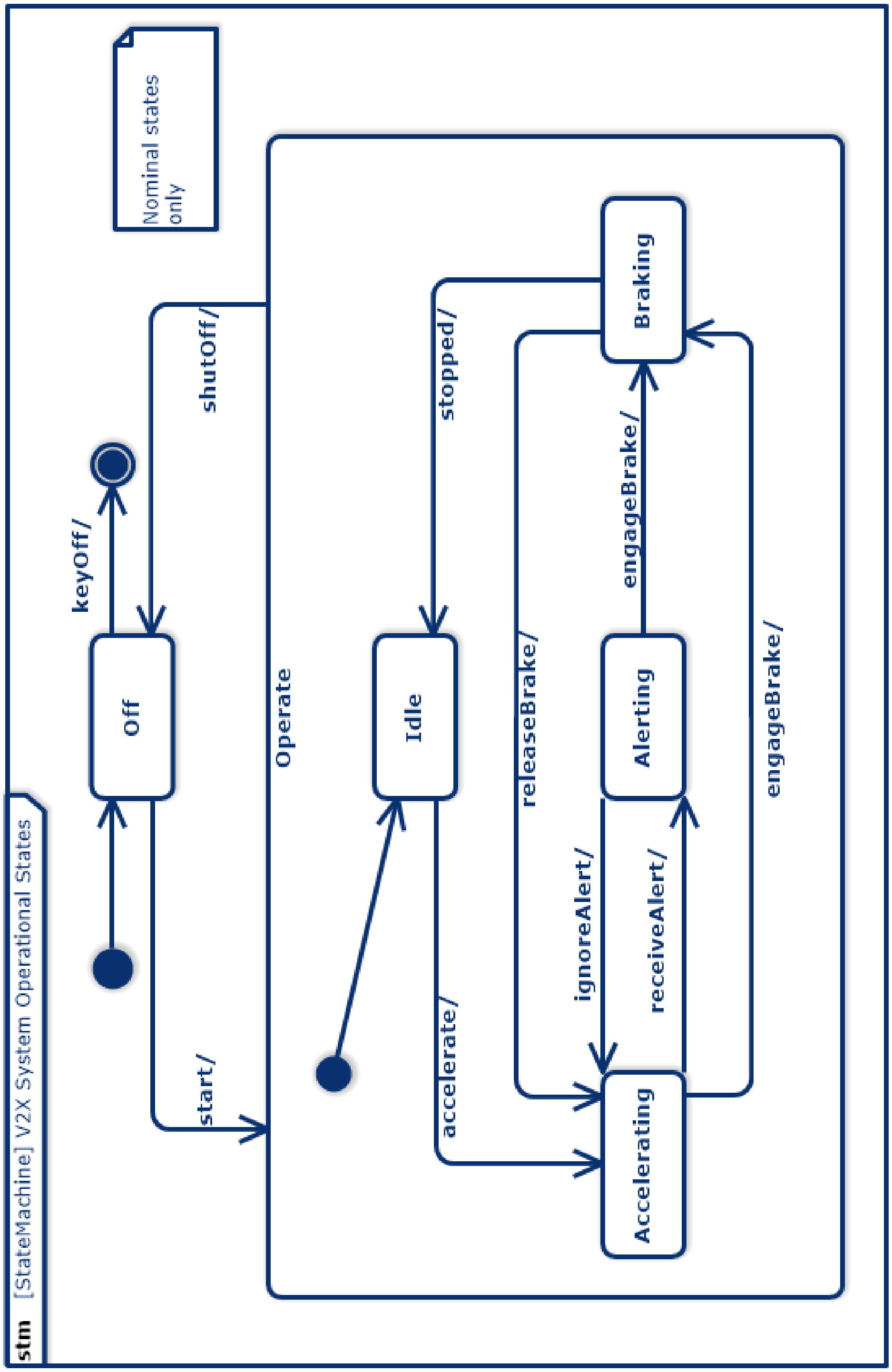
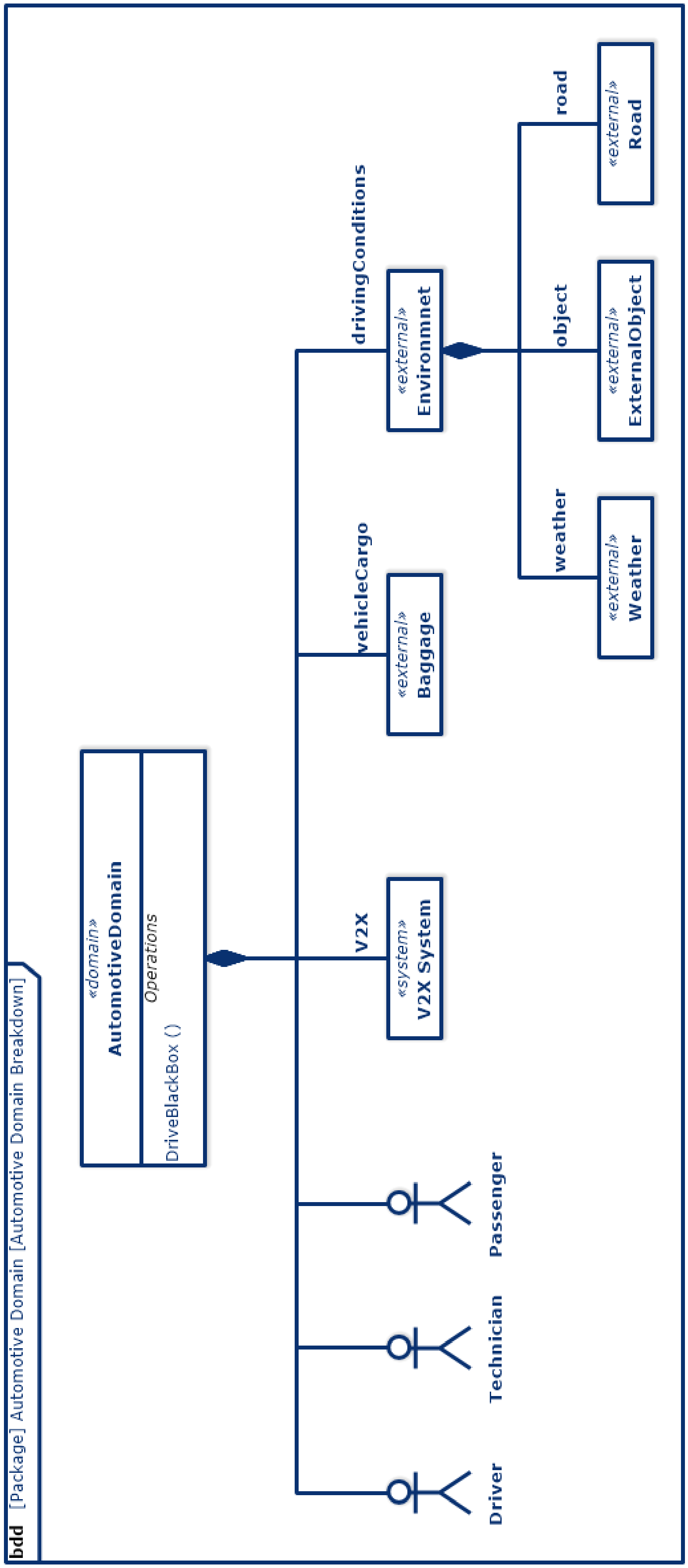
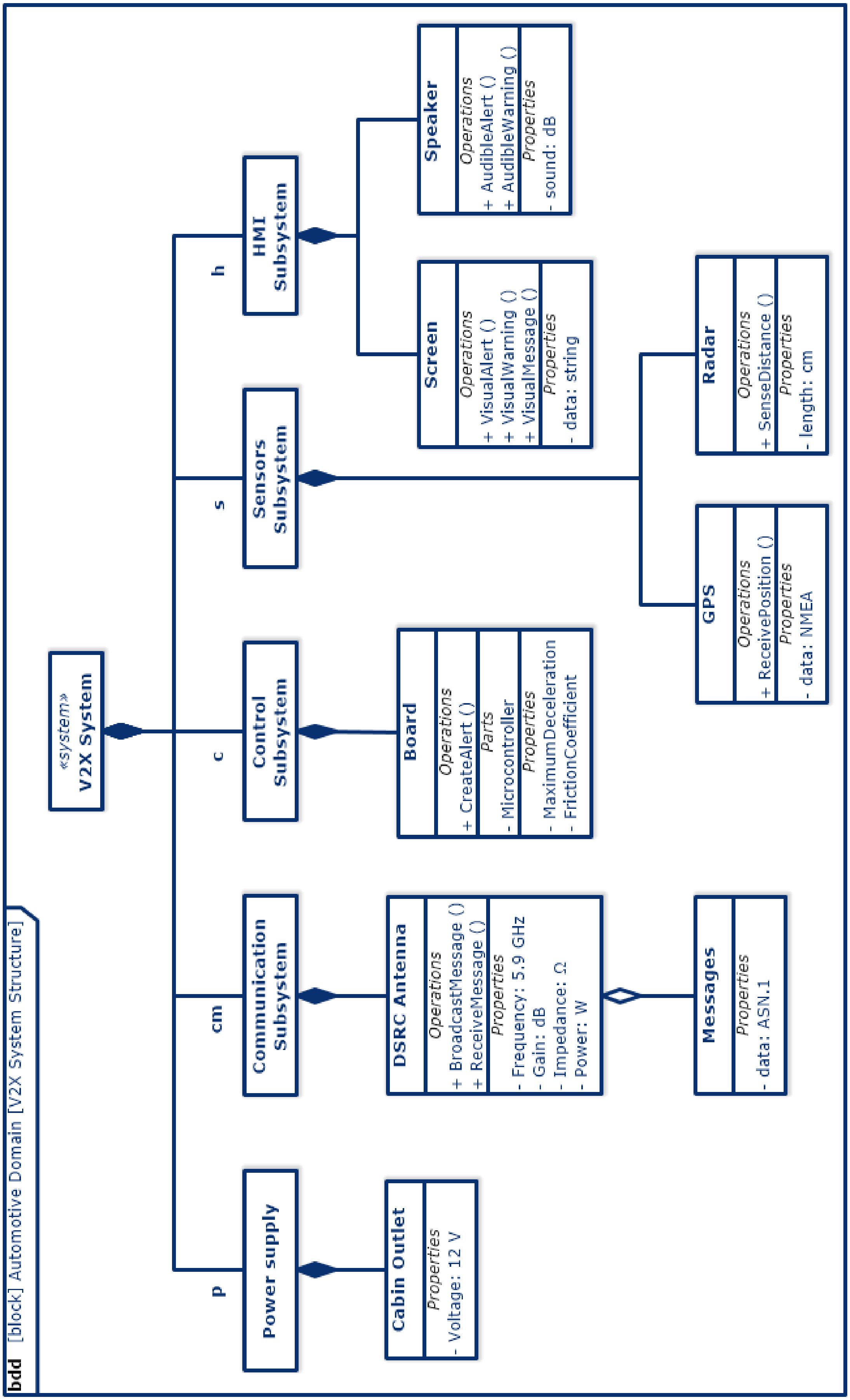
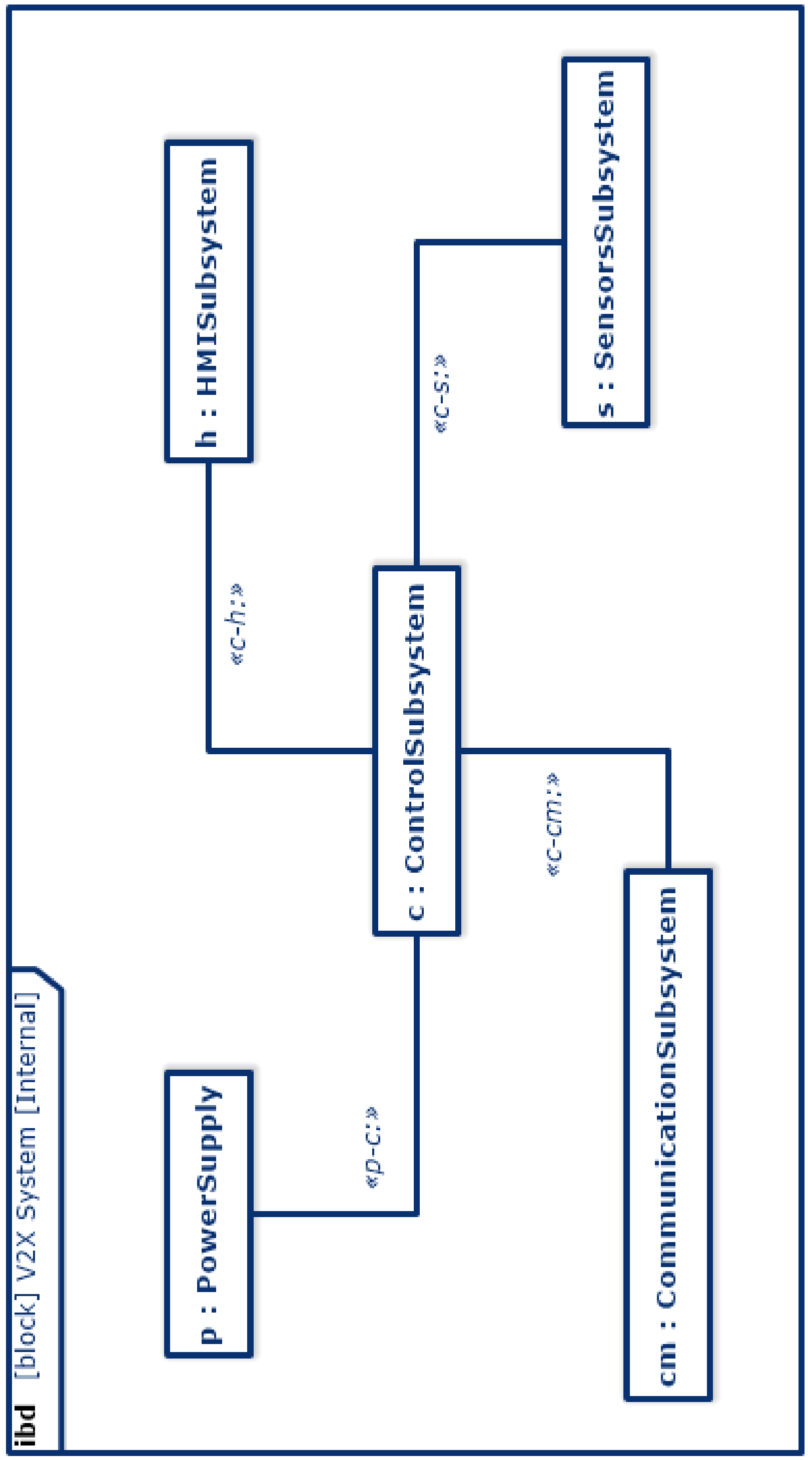
V2X System
Start the vehicle
Start the system
Accelerate
System alert
Steer
Brake
«extend»
«extend»
«include»
«extend»
«include»
«include»
«include»
Drive the vehicle
Park
Driver

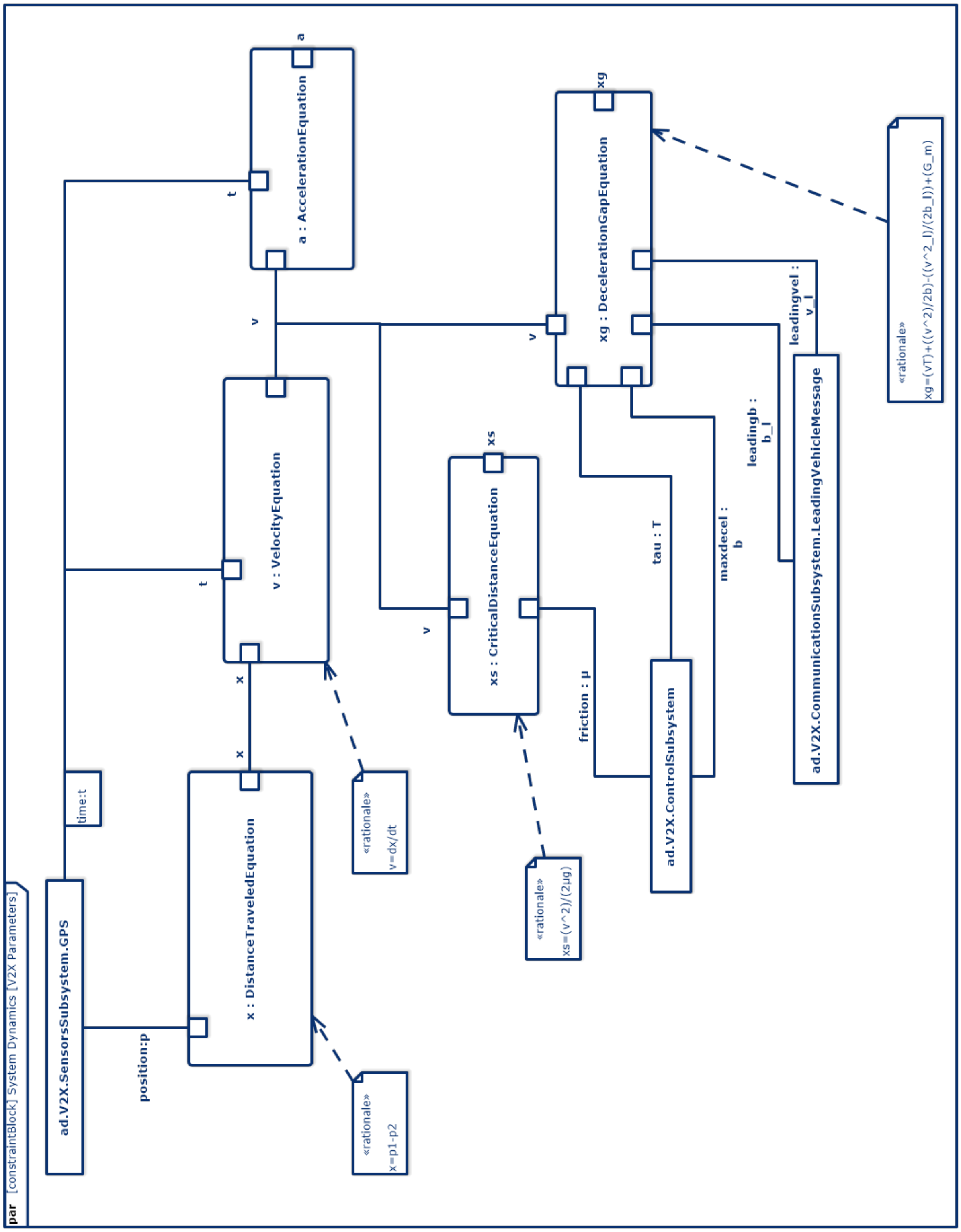

sd [Sequence] DriveBlackBox
driver:Driver
vehicleContext : V2XSystem
ref
StartVehicleBlackBox
par
alt
[controlSpeed]
[self.oclInState(idle)]
ref
Idle
[self.oclInState(accelerating)]
ref
Accelerate
[self.oclInState(alerting)]
ref
Alert
[self.oclInState(braking)]
ref
Brake
ref
Steer
ref
ShutdownVehicle


stm [StateMachine] V2X System Operational States
Nominal states only
Off
keyOff/
shutOff/
start/
Operate
Idle
stopped/
accelerate/
releaseBrake/
ignoreAlert/
receiveAlert/
engageBrake/
engageBrake/
Alerting
Braking
Accelerating


bdd [Package] Automotive Domain [Automotive Domain Breakdown]
«domain»
AutomotiveDomain
Operations
DriveBlackBox ()
V2X
«system»
V2X System
vehicleCargo
«external»
Baggage
drivingConditions
«external»
Environmnet
weather
«external»
Weather
object
«external»
ExternalObject
road
«external»
Road
Driver
Technician
Passenger

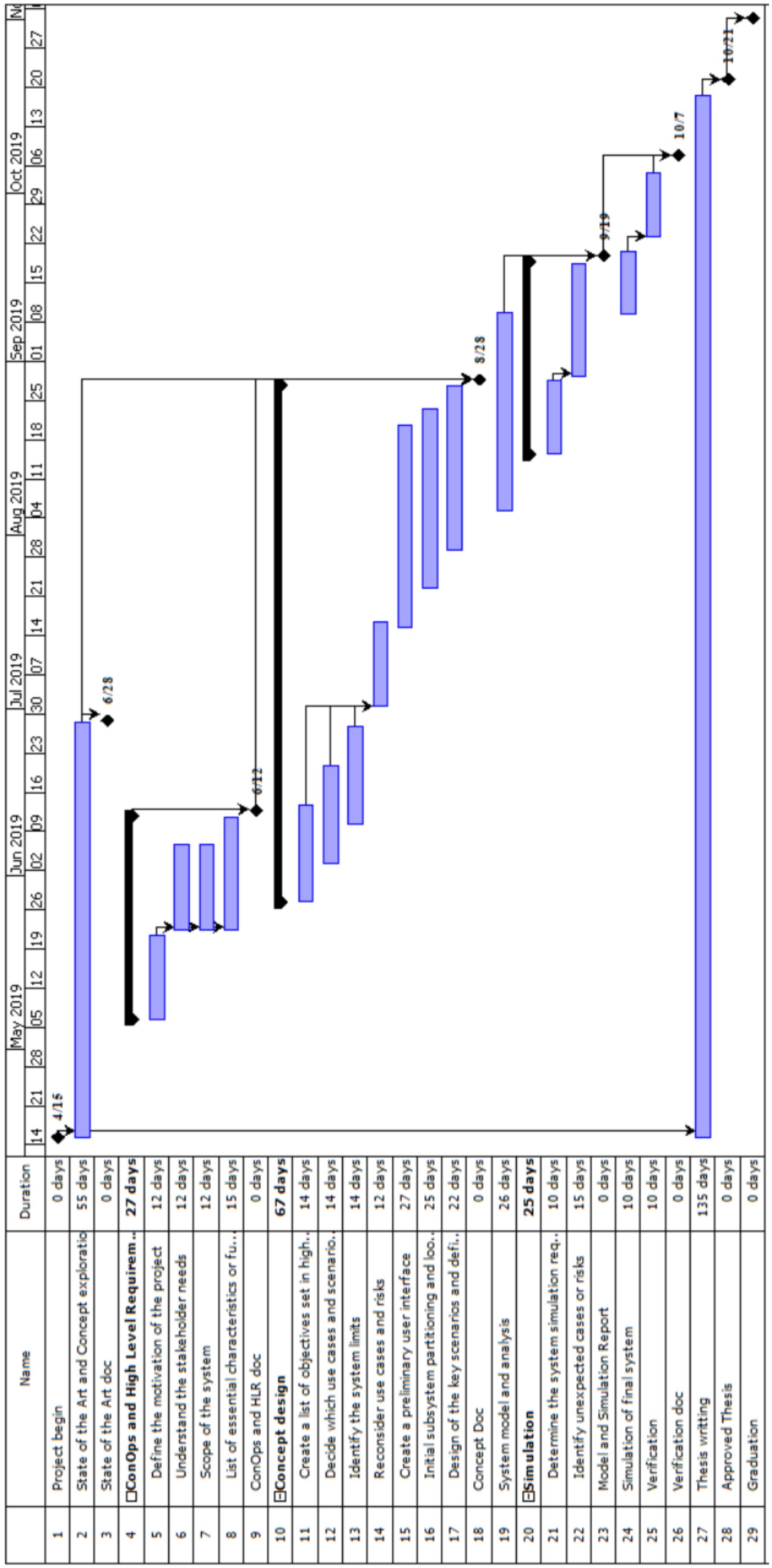

bdd [block] Automotive Domain [V2X System Structure]
«system»
V2X System
p
Power supply
cm
Communication Subsystem
c
Control Subsystem
s
Sensors Subsystem
h
HMI Subsystem
Cabin Outlet
Properties
- Voltage: 12 V
DSRC Antenna
Operations
+ BroadcastMessage ()
+ ReceiveMessage ()
Properties
- Frequency: 5.9 GHz
- Gain: dB
- Impedance: Ω
- Power: W
Messages
Properties
- data: ASN.1
Board
Operations
+ CreateAlert ()
Parts
- Microcontroller
Properties
- MaximumDeceleration
- FrictionCoefficient
GPS
Operations
+ ReceivePosition ()
Properties
- data: NMEA
Radar
Operations
+ SenseDistance ()
Properties
- length: cm
Screen
Operations
+ VisualAlert ()
+ VisualWarning ()
+ VisualMessage ()
Properties
- data: string
Speaker
Operations
+ AudibleAlert ()
+ AudibleWarning ()
Properties
- sound: dB


ibd [block] V2X System [Internal]
h : HMISubsystem
s : SensorsSubsystem
c : ControlSubsystem
p : PowerSupply
cm : CommunicationSubsystem
«c-h:»
«c-s:»
«c-cm:»
«p-c:»


par [constraintBlock] System Dynamics [V2X Parameters]
ad.V2X.SensorsSubsystem.GPS
time:t
position:p
x : DistanceTraveledEquation
«rationale»
x=p1-p2
v : VelocityEquation
«rationale»
v=dx/dt
a : AccelerationEquation
xs : CriticalDistanceEquation
«rationale»
xs=(v^2)/(2μg)
xg : DecelerationGapEquation
«rationale»
xg=(vT)+((v^2)/2b)-((v^2_l)/(2b_l))+(G_m)
ad.V2X.ControlSubsystem
ad.V2X.CommunicationSubsystem.LeadingVehicleMessage
friction : μ
tau : T
maxdecel : b
leadingb : b_l
leadingvel : v_l
t
x
v
a
xs
xg

Appendix B: Thesis Chronogram

The main activities required from the start to the finish, or completion of this thesis are represented in the Gantt chart shown in the next page. Each activity has a proportional length to the time required for its completion in a time scale of 5 months. The project management of the presented thesis work was created with the free licensed software “ProjectLibre" [Pro19].


Name
Duration
1 Project begin 0 days
2 State of the Art and Concept exploratio 55 days
3 State of the Art doc 0 days
4 ConOps and High Level Requirem... 27 days
5 Define the motivation of the project 12 days
6 Understand the stakeholder needs 12 days
7 Scope of the system 12 days
8 List of essential characteristics or fu... 15 days
9 ConOps and HLR doc 0 days
10 Concept design 67 days
11 Create a list of objectives set in high... 14 days
12 Decide which use cases and scenario... 14 days
13 Identify the system limits 14 days
14 Reconsider use cases and risks 12 days
15 Create a preliminary user interface 27 days
16 Initial subsystem partitioning and loo... 25 days
17 Design of the key scenarios and defi... 22 days
18 Concept Doc 0 days
19 System model and analysis 26 days
20 Simulation 25 days
21 Determine the system simulation req... 10 days
22 Identify unexpected cases or risks 15 days
23 Model and Simulation Report 0 days
24 Simulation of final system 10 days
25 Verification 10 days
26 Verification doc 0 days
27 Thesis writting 135 days
28 Approved Thesis 0 days
29 Graduation 0 days
May 2019
Jun 2019
Jul 2019
Aug 2019
Sep 2019
Oct 2019
14 21 28 05 12 19 26 02 09 16 23 30 07 14 21 28 04 11 18 25 01 08 15 22 29 06 13 20 27
4/15
6/28
6/12
8/28
9/19
10/7
10/21