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Performance evaluation of vehicular networks in urban environments

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Advisor:

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Title of the thesis: Performance evaluation of vehicular networks in urban environments

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Abstract

With the development of all kinds of science and technology nowadays, people are paying more attention to the various aspects of smart cities, especially vehicular networks. Based on the increase in traffic demand, people's dependence on vehicles is also growing gradually, which leads to an intelligent social transportation system being crucial. However, inevitably, there will always be some unexpected car accidents in the urban traffic environment. In this paper, we would mainly focus on the performance evaluation of vehicular networks with a car accident in the urban centre of Barcelona. And we will start from different angles for a multi-dimensional analysis of the impact of different vehicles and environmental factors on urban traffic.

In this project, the performance of the vehicular network in the Eixample district would be evaluated from the following four perspectives:1. The configuration of the vehicles 2. The nominal road speed around accident 3. The transmission range 4. The rebroadcasting scheme of the accident message.

Through the data analysis of the packet delay, the percentage of warned vehicles, and the warning distance respectively, to explore the impact of diverse factors on the vehicle network and find a better scheme to improve the intelligent transportation system (ITS) in the urban environment.

Resumen

Con el desarrollo de diversas ciencias y tecnologías hoy en día, la gente presta cada vez más atención a todos los aspectos de las ciudades inteligentes, especialmente las redes de vehículos. Sobre la base del aumento de la demanda de transporte, la dependencia de las personas de los vehículos también está aumentando gradualmente, lo que hace que los sistemas de transporte inteligentes sean esenciales. Sin embargo, es inevitable que siempre ocurran algunos accidentes automovilísticos inesperados en el entorno del tráfico urbano. En este proyecto nos centraremos principalmente en la evaluación del rendimiento de la red de vehículos con accidentes automovilísticos en el centro de Barcelona. Analizaremos el impacto de diferentes vehículos y factores ambientales en el tráfico urbano desde diferentes ángulos y perspectivas.

En este proyecto se evaluará el rendimiento de la red de vehículos en una zona del barrio de L'Eixample desde las siguientes cuatro perspectivas: 1. Configuración del vehículo. 2. Velocidad nominal de la carretera alrededor del accidente. 3. Rango de transmisión. 4. Plan de repetición de la información del accidente.

A través del análisis de datos de retardo de paquetes de datos, el porcentaje de vehículos que han sido advertidos por un mensaje de advertencia y la distancia máxima de advertencia, se explora el impacto de diferentes factores en la red de vehículos y se encuentran mejores soluciones para mejorar el sistema de transporte inteligente (ITS) en el entorno urbano.

Resum

Amb el desenvolupament de tot tipus de ciència i tecnologia avui en dia, la gent està prestant més atenció als diferents aspectes de les ciutats intel·ligents, especialment a les xarxes de vehicles. A partir de l'augment de la demanda de trànsit, la dependència de les persones dels vehicles també està creixent gradualment, la qual cosa fa que un sistema de transport intel·ligent sigui crucial. Tanmateix, inevitablement, sempre hi haurà alguns accidents de cotxe inesperats a l'entorn del trànsit urbà. En aquest treball, ens centraríem principalment en l'avaluació del rendiment de les xarxes de vehicles amb accident de trànsit al centre urbà de Barcelona. I començarem des de diferents angles per a una anàlisi multidimensional de l'impacte dels diferents vehicles i factors ambientals en el trànsit urbà.

En aquest projecte, el rendiment de la xarxa de vehicles al districte de l'Eixample s'avaluarà des de les quatre perspectives següents:1. La configuració dels vehicles 2. La velocitat nominal de la carretera al voltant de l'accident 3. El rang de transmissió 4. L'esquema de redifusió del missatge de l'accident.

Mitjançant l'anàlisi de dades del retard del paquet, el percentatge de vehicles advertits i la distància d'avís respectivament, per explorar l'impacte de diversos factors a la xarxa de vehicles i trobar un millor esquema per millorar el sistema de transport intel·ligent (ITS) a l'entorn urbà.

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When the calendar turns to this winter, and the luggage is piled up under the tree, even the bell is urging us to say goodbye. No matter how tightly I hold my hand, I can't grasp the time that flows away like water. My story with Universitat Politècnica de Catalunya began in the fall of 2020 and ended in the winter of 2023. I saved lots of growth and emotions during my campus life.

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Acronyms

WHO World Health Organization

ITS Intelligent Transport System

VANET Vehicular Ad-hoc Network

SUMO Simulation of Urban Mobility

IoT Internet of Things

RFID Radio Frequency Identification

GPS Global Positioning System

SaaS Software as a Service

IVC Inter-Vehicle Communication

RVC Roadside-to-Vehicle Communication

WAVE Wireless Access in the Vehicular Environment

DSRC Dedicated Short-Range Communication

OECD Organization for Economic Cooperation and Development

MANET Mobile Ad-hoc Network

V2V Vehicle to Vehicle

V2I Vehicle to Infrastructure

V2R Vehicle to Roadside Units

V2X Vehicle to Everything

FCC Federal Communications Commission

IEEE the Institute of Electrical and Electronics Engineers

OMNeT++ Objective Modular Network Testbed in C++

IBM International Business Machines Corporation

EU European Union

M2M Machine to Machine

ICT Information and Communications Technology

UHF Ultra High Frequency

VHF Very High Frequency

The U.S. The United States

SCOOT Spilt-Cycle-Offset Optimization Technique

WLAN Wireless Local Area Network

ETC Electronic Toll Collection

MAC Media Access Control

Chapter 1 Introduction

1.1 Problem Statement

With the progress of society and the rapid growth of the world's economy, the transportation industry has also presented a scene of prosperity. Nevertheless, with the rapid increase in the number of vehicles, the probability of traffic congestion and traffic accidents is greatly increased. According to the data gathered by World Health Organization (WHO), more than 1.35 million people die on the world's roads each year, which means that every 24 seconds, someone dies in a traffic accident on average, and as many as 50 million are injured, occupying 30 percent to 70 percent of orthopedic beds in developing countries hospitals. Road traffic injuries have become the leading cause of death for children and young adults aged from 5 to 29 years [1]. Due to the development of society and the economy, people tend to put forward a higher demand for transport level, while the frequent traffic congestion and traffic accidents not only restrict the convenience and safety of users but also cause great troubles to economic development, environmental protection, and energy conservation of each city.

However, the traditional road network construction method has been unable to solve a series of unpredictable traffic accidents and traffic congestion caused by the rapid growth of traffic in large cities where the road network structure tends to be saturated. On the basis of advanced technologies such as automatic control technology, communication technology, and artificial intelligence technology, the existing road network resources could be fully utilized to provide efficient means to solve the problem of traffic accidents. Therefore, ITS (Intelligent Transport System), an essential part of a smart city, was born at the right moment. ITS is an intellective system to improve traffic safety and efficiency and reduce traffic accidents, which works as a key technology to solving the current traffic safety problems. Especially, through its core component VANETs (Vehicular Ad-hoc Networks), which is a wireless network composed of vehicles, pedestrians, infrastructure, and other entities on the road through dedicated communication devices, information interaction between vehicles could be realized to greatly improve traffic safety.

According to the discussion before, it is essential to explore the effect of different factors on the vehicle network with an accident in urban environments from multiple dimensions. And it is also necessary to find an improved message dissemination protocol in as little time as possible to extend the range of warned vehicles so as to reduce the impact of the accident on the surrounding area. This paper would mainly focus on the performance evaluation of the vehicle network with a sudden car accident in the Eixample district in Barcelona.

1.2 Objective

In this section, we would mainly list the purpose of the final master thesis. The general objective of this paper is to evaluate the performance of the vehicle network in an urban environment and propose some strategies to improve traffic safety. In the following part, the specific objectives would be shown:

- Test and study the influence of different vehicle settings on the urban traffic
- Compare the traffic impact of reducing the speed limit on the roads around an accident
- Analyze the influence of the transmission range of the accident message
- Improve the message dissemination protocol with a suitable threshold time for the rebroadcasting

1.3 Requirements and Specifications

The tools used throughout the project would be listed below:

- SUMO (Simulation of Urban Mobility) [2] is an open-source urban traffic simulation software. The system, which has been in use since 2001, allows the modeling of multimodal transport systems, including road vehicles, public transport, and pedestrians. SUMO provides a number of supporting tools to automate the core tasks of creating, executing, and evaluating traffic simulations.
- OMNeT++ [3] is a free, open-source multi-protocol network simulation software for discrete events. By itself, it is not a simulator for all real-world systems, but it does provide the underlying structure and tools for implementing simulation
- Veins [4] is an open-source framework for running vehicular network simulations. It is based on two well-established simulators: OMNeT++ and SUMO. It extends these to offer a comprehensive suite of models for IVC simulation.

1.4 Contents and the Organization of the Master Thesis

According to the purposes mentioned before, the whole paper and research could be divided in to chapters:

- Chapter 2 is Smart City, which introduces its ideas, key technologies, and development history.

- Chapter 3: Intelligent Transportation Systems, which shows its concept, key technologies, and developments.
- Chapter 4: Vehicular Ad-hoc Networks (VANET), which represents its definitions, architectures, key technologies, and state-of-the-art.
- Chapter 5: Simulation Tools, which display the software we need in the project.
- Chapter 6: Experiments, which describe the main simulation scenarios and parameters utilized.
- Chapter 7: Analysis of the Simulation Results, which discusses the results of the simulations.
- Chapter 8: Conclusion and Future Works, which concludes all the things we did in the final master project and puts forward some approaches for future works.

Chapter 2 Smart City

With the increasing number of cities and their population, cities have been given unprecedented economic, political, and technological power, thus enabling urban development to play a dominant role on the world's center stage. Although cities are playing an increasingly important role in human development, can the operating model of today's cities adapt to future development? Will it be able to address the problems hindering development: inefficient urban management, congested transportation systems, ineffective urban emergency response systems, and far-from-perfect environmental monitoring systems? As polis are confronted with these substantial challenges, they must apply new measures and capabilities to make city management smarter. Metropolis must use new technologies to improve their core systems in order to maximize and utilize limited energy resources. With the rapid development of science and technology, scientific and technological innovation has become the dominant force to promote economic and social development. The financial crisis of 2008 gave birth to a new technological revolution represented by the Internet of Things. Based on this trend, the smart city concept originated from the concept of "Smart Earth" proposed by IBM. This section would briefly introduce the relevant content of smart cities like definitions, developments, technology, and its development trend.

Figure 1. Smart City [21]

2.1 Definition of a smart city

The concept of a smart city first originated from the movement of "New Urbanism" and "Smart Growth" in the late 1990s. Its purpose is to solve many problems caused by "urban sprawl" and advocate the formulation of new policies for urban and regional planning.

Portland, Oregon, the United States, is widely regarded as a typical successful case. After 2005, Smart City was taken over by a number of technology services companies for construction, transportation, electricity, education, water distribution, and public safety. In this context, smart cities have become synonymous with "smart life", focusing on smart people, smart environment, smart governance, and smart flow.

From the literal sense, the word "smart" was originally used to describe human wisdom. However, when the word "smart" is used in the “Smart City”, which represents a mixed term that combines artificial intelligence formed by advanced information technology with human insight, foresight, and wise response. While, this also means the perfect integration of today's science and technology with human wisdom and urban development, which promotes the city to realize the efficient utilization and optimal allocation of core resources and then enter the best state of its operation and development

From the technical aspect, a smart city is a technologically modern urban area that uses different types of electronic methods and sensors to collect specific data. The information gained from that data is used to manage assets, resources, and services efficiently; in return, that data is used to improve operations across the city[5]. The smart city utilizes all kinds of anytime and anywhere sensing equipment and intelligent system to perceive and monitor all aspects of the city; Through the urban "neural network" composed of widely existing broadband network technology, the comprehensive interconnection can be realized, interworking and interaction between people and things; Cloud computing and big data are used to store, calculate, and analyze mass data and automate the control of various facilities according to the results of analysis and decision.

In conclusion, as the most concentrated manifestation of human civilization, cities achieve breakthrough evolution by absorbing and integrating the latest and most progressive scientific and technological achievements in the process of development and evolution. The smart city is the concrete embodiment of the city's continuous progress to the advanced stage by integrating advanced information technology, and it is also the deep integration of industrialization, information technology, and urbanization.

2.2 Key Technology used in Smart City

Information technology and its deep application are the important foundation of realizing "smart" development in cities. Whether from the source of the concept of the smart city or the stage of urban progress or the reasons why the smart city can become a hot pursuit in the world, the constructions of the smart city are inseparable from cutting-edge information technology, especially the Internet of Things, big data, and cloud computing. In the blossom of smart cities, these key technologies have entered a new stage of intelligent integration, providing a new means for the intelligent development of cities [6]. In the following section, these critical technical factors would be introduced in brief.

2.2.1 Internet of Things (IoT) in Smart City applications

Internet of Things (IoT), which could also be called the "Internet of everything", refers to the real-time acquisition of any object or process that needs to be monitored, connected, and interacted with through various devices and technologies such as information sensors, RFID (Radio Frequency Identification), GPS (Global Positioning System), infrared sensors, laser scanners. It collects all kinds of needed information like sounds, creatures, and locations, etc., to realize the ubiquitous connection between things and things and between things and people through all kinds of possible network access, and realizes the intelligent perception, recognition, and management of things and processes. The Internet of Things is an information carrier based on the Internet, traditional telecommunications networks, etc., which enables all ordinary physical objects that can be independently addressed to form an interconnected network.

The smart city covers more thorough perception, more comprehensive interconnection, and deeper intelligence. The Internet of Things is a significant element in smart cities, which focuses on the collection and transmission of low-level perceptual information and the construction of ubiquitous networks within the city. The Internet of Things laying a solid technological foundation for smart cities provides urban perception and makes such perception deeper and smarter. Through the perception of the environment, personal health, wireless city portal, and intelligent transportation interaction perception, the smart city can realize the intelligent management of municipal, people's livelihood, industry, and other aspects. In other words, smart cities are the bull's-eye of the Internet of Things.

Figure 2. Internet of Things [22]

2.2.2 Big Data in Smart City applications

The smart city connects physical and digital cities through the ubiquitous Internet of Things, which leads the world would produce unimaginable amounts of big data every day. People exchange ideas, data, and information on the network at a blistering pace every second. Fabulously, within a minute, Google had 2 million search queries; Facebook had 680,000 posts; more than 3 million emails were sent each second. At present, the total number of Internet pages is nearly one trillion and the amount of data is close to 1 petabyte. However, the data volume of this "digital" earth is growing and accumulating at an unprecedented speed. The era of big data has come.

With the gradual construction and application of smart cities, humans will produce more and more data together with various kinds of sensors, and the data mine will become larger and larger. The data magnitude will increase step by step from the current Gigabyte and Terabyte to Petabyte, even to Exabyte. However, the management and operation of the smart city cannot be separated from the support of big data. If these huge amounts of data could be analyzed and valuable information could be extracted from them, the laws of nature and society would be better explored and excavated, which would greatly contribute to the future development of the smart city. The era of smart cities that utilize large-scale data analysis and predictive modeling, visualization, and discovery of new rules is coming. Big data will undoubtedly be an inevitable part of this new era of the smart city.

2.2.3 Cloud Computing in Smart City applications

Cloud computing is the evolution of distributed computing and grid computing, which emerged in the IT world after SaaS (Software as a Service). It mainly realizes the full utilization of software, hardware, and other resources through MapReduce, Xen, and other technologies. It has the characteristics of cost-effective performance, zero maintenance, high security, and elastic expansion of computing and storage capabilities. In 2006, Google took the lead in formally proposing the concept and theory of "cloud computing" in its "Google 101 Plan". Since then, global companies such as Amazon, IBM, Yahoo, and Microsoft have put Cloud computing into the focus of their development, among which Google's EC2-Elastic Computing Cloud and IBM's Blue Cloud are the representatives [7].

As a complex consisting of multiple applications, industries, and systems, a smart city requires information sharing and interaction among various utility systems. This also means that disparate systems need to jointly extract a mass of data for comprehensive calculation and analysis. Cloud computing, working as a model that uses diverse algorithms and models in the cloud to analyze and process massive data and information in real time, providing the basis for real-time control and decision-making, is necessary for the operation of the smart city. The key to smart cities lies in the efficiency of large amounts of urban information management and use. While, by using cloud computing information technology, cities can effectively improve the level of social informatization and promote the transformation of social production mode through comprehensive and integrated computing, storage, network, and other capabilities. That is what smart cities want.

2.3 State of Development of Smart City around the world

The rapid development of science and technology has brought the universal wave of information technology, which has promoted the development of smart cities to a large extent. Countries and government organizations around the world are coming up with plans to rely on the Internet and information technology to change the blueprint of future development. At present, smart cities are being developed in large numbers and with distinctive characteristics. There are about 200 smart city projects being implemented worldwide. In the process of industrial transformation and social development, both developed and developing countries and regions have realized the forward-looking and advanced nature of smart cities and put forward relevant strategic measures successively.

2.3.1 Smart City in the United States

During Barack Obama's presidency, the United States strongly supported IBM's Smart Earth initiative. The main content of IBM's "Smart Earth" strategy is to make full use of the new generation of IT technology in all walks of life, that is, to embed and equip sensors in hospitals, power grids, railways, bridges, buildings, dams, oil and gas pipelines and other objects in every corner of the world, form the Internet of Things through interconnection, and then integrate it through supercomputers and cloud computing. Human beings can manage production and life in a more sophisticated and dynamic way, so as to achieve a global "intelligent" state, and eventually form "Internet + Internet of Things = Smart Earth". With the proposal of the concept of "Smart Earth", IBM has successively launched a variety of "smart" solutions, including intelligent electricity, medical treatment, transportation, etc., among which "smart city" is an important aspect of IBM's "Smart Earth" strategy.

2.3.2 Smart City in European Union

The EU has done a lot of pioneering work around IoT technologies and applications. At the Global Conference on the Internet of Things in November 2009, EU experts introduced the EU Action Plan on the Internet of Things, which aims to lead the development of the Internet of Things industry in the world. More active in the EU are the major operators and equipment manufacturers driving the development of M2M's technology and services. In order to strengthen government management of the Internet of Things and remove obstacles to its development, the European Union has formulated a series of rules for the management of the Internet of Things and established an effectively distributed management architecture, so that the global regulatory bodies can perform the management functions openly, fairly and responsibly.

2.3.3 Smart City in Singapore

Since 2006, Singapore has implemented the Smart Nation 2015 Plan, which aims to build Singapore into an international metropolis driven by ICTs. Over the years, Singapore has been a world leader in the use of ICTs for economic growth and social progress. Singapore's achievements in e-government, "Smart City" and connectivity are even more remarkable. As an important shipping hub in Southeast Asia, Singapore focuses on the use of ICTs to enhance the service capacity of its port and logistics sectors. Led by the government, Singapore strongly supports enterprises and institutions to use RFID, GPS, and other technologies to boost management and service capacity. Through a number of projects and initiatives, Singapore has taken its place in the front ranks of the world in the construction of the smart city.

In addition to these cases, more than 100 smart cities are being built around the world, each tailored to its own situation. At this stage, smart cities are still at the extreme of experimentation and construction, with cities in Europe and Asia taking a more active role in improving it. The European Union has released its Smart Cities Initiative, which will see 25 leading European cities adopt new green energy technologies in large numbers, as well as experiment with smart grids, smart city transport, and related smart healthcare systems. As science and technology become more and more the core driving force of urban development, the smart city will be carried out in more areas, and it will certainly become the development direction of future world cities.

Chapter 3 Intelligent Transportation Systems (ITS)

Transportation is a necessary link for human society to produce, live and develop the economy, which runs through the lifeblood of national and urban development. The existing transportation system mainly includes the following three types: land transportation based on roads, railways, and urban rail transportation; underground transportation based on subways; water transportation based on rivers, lakes, and seas; and air transportation based on aviation and aerospace. With the vigorous development of the global economy, the number of vehicles has been on a large scale in recent decades, and people have a strong dependence on traffic, at the same time which also put forward more demands for traffic day by day. Nevertheless, in both developed and developing countries, the contradiction between cars and roads is becoming increasingly fierce, mainly including traffic congestion, car accidents, etc., and the world is suffering from worsening surface traffic problems. Traditionally, the solution to such traffic problems is mainly to build new roads or expand old ones. However, with the growth of population, the urban per capita living area is increasing, which led that there is less and less space to build roads. At the same time, the traffic system is a complex comprehensive system, which is difficult to solve the traffic problems from the perspective of road or vehicle alone. With this background, Intelligent Transportation System (ITS) comes into being, which integrates vehicles and road systems to solve existing urban traffic problems. In this chapter, several contents related to ITS would be briefly introduced.

Figure 3. Intelligent Transportation System [23]

3.1 Definition of Intelligent Transportation Systems

An intelligent transportation system (ITS) is an advanced application that aims to provide innovative services relating to different modes of transport and traffic management and enable users to be better informed and make safer, more coordinated, and 'smarter' use of transport networks [8].

ITS refers to the effective and comprehensive application of advanced information technology, electronic communication technology, automatic control technology, computer technology, and network technology in the whole traffic and transportation management system to establish a real-time, accurate, and efficient traffic and transportation integrated management and control system that plays a full role in a wide range. It is composed of several subsystems, through the integration of the system will organically combine the road, driver, and vehicle together, strengthening the connection among these three elements. With the help of the intelligent technology of the system, the driver can know the road traffic and the condition of the vehicle in real-time and reach the destination in the safest and most economical way. At the same time, managers improve their efficiency by collecting real-time information on vehicles, drivers, and roads, to make full use of traffic resources [9].

3.2 Key Technology used in Intelligent Transportation System

According to mentioned in the last part, ITS is a comprehensive system with multiple applications of progressive technologies. It builds up a real-time, accurate, and efficient integrated transportation and management system that can be used in large fan circumference and all directions, making the interaction between the three main bodies of the transportation system, "people, vehicles, and roads", present in a new way. Basically, ITS can be divided into the following several communication modes as the following figure shows: vehicle-to-vehicle, vehicle-to-roadside, vehicle-to-pedestrian and etc. While, how to implement such a large and complex traffic system to realize high-efficiency communication among these vehicles and infrastructures? There are some crucial technical factors that need to be presented in the following part. It should be noted that huge technologies are included in ITS entire system, and the following is only a part of them.

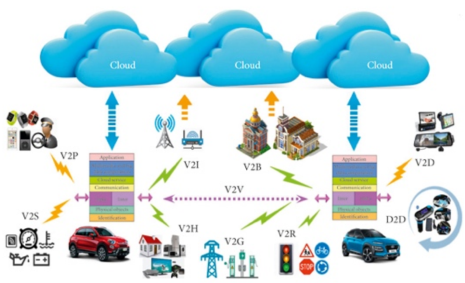


Figure 4. The architecture of ITS [12]

3.2.1 Wireless Communication Technology in Intelligent Transportation Systems applications

With the rapid development of science and technology, ITS makes traffic management more intelligent, businesslike, and convenient by integrating computer technology and network communication technology into a whole. The application of wireless communication technology to ITS can further improve its function and promote the long-term development of transportation.

There are several kinds of wireless communication technologies have been proposed and put into practice in the development process of ITS. Generally, radio modem communication at UHF and VHF frequencies is widely used for short-distance and long-distance communication within ITS.

In order to fully support Inter-Vehicle communication (IVC) and Roadside-to-Vehicle communication (RVC), IEEE began to design the IEEE 802.11p protocol in 2004, which was released in July 2010 [10].

IEEE 802.11p(also known as Wireless Access in the Vehicular Environment, or WAVE) is a standard designed specifically for the networking of vehicles. Its initial design goal is to ensure that the data transmission rate between mobile nodes reaches 6Mbit/s within a transmission distance of 300 meters when the node movement rate reaches 250km/h [11].

IEEE 802.11p makes several improvements to IEEE 802.11a and extends the traditional Dedicated Short-Range Communication (DSRC) for vehicle-to-vehicle communication. To better adapt to the needs of onboard electronic wireless communication and intelligent transportation system applications, such as more advanced access point switching mechanisms, better mobile environment support, higher road safety, and peer-to-peer identity authentication.

In general, wireless communication technology is of great significance to ITS, and the development of wireless communication technology can greatly promote the improvement of ITS. In the past, the role of wireless communication technology is more and more prominent, which would influence a more extensive application of wireless communication technology to ensure and improve people's travel and well-being.

3.2.2 Computational technology in Intelligent Transportation Systems applications

The concept of an intelligent transportation system was put forward in the early 20th century. Due to the influence of the technology environment and other aspects at that time, the research on it has not made a breakthrough. However, with the passage of time, the improvement of the level of science and technology makes the intelligent transportation system get the technical breakthrough. The most intuitive feeling is, the car's individual networked microcontroller/programmable logic controller modules with non-real-time operating systems are winding down, from a few dozen in early 2000 to now more proprietary modules with hardware memory management and real-time operating systems. This is all thanks to advances in computing technology. The application of computing technology is not limited to the automobile's development. Big data, artificial intelligence technology, and cloud computing technology derived from computing technology all play a key role in ITS. Traffic analysis and judgment technology, vehicle-road collaboration technology, video analysis technology, and so on developed from these computational technologies provide support for the development of ITS and solving urban traffic problems.

Obviously, computational technology will continue to grow and blossom in the direction of being applied in the process of urban intelligent traffic management as an inevitable trend of social development. With an eye to the future, people can better enjoy the joy of driverless driving, and the entire city transportation participants can effectively implement transparent management. Some big data formed in the process of urban transport will be used to forecast and analyze urban traffic conditions, which can facilitate the traffic management department to better control the actual situation of road traffic.

3.2.3 Sensing in Intelligent Transportation Systems applications

Sensing is the acquisition of multiple information data through different technologies. The camera based on the vision penetration device uses image processing technology to obtain visibility, water, snow and ice, abnormal data traffic parameters, vehicle height, and a series of information. Based on infrared devices, infrared image processing technology can supplement the deficiency of visual sensing at night. Based on a laser profilometer, the three-dimensional target data can be obtained by using the "time flight" method to make up for the two-dimensional deficiency of vision and infrared. Based on distributed optical fiber pulse signal detection and processing method, reliable basic traffic information can be obtained, and visual traffic parameters can be mutually assisted. Based on radio frequency devices, an RFID identification system can be used for non-contact object recognition and identity verification. Based on satellite navigation and positioning system, using the GPS positioning information processing, information space positioning, and speed of calculation. In conclusion, through multiple sensing devices and methods, can obtain the comprehensive environmental status, the mesh standard parameters, event description, time and space location, and a variety of diverse information, from which lay a foundation for ITS.

The 21st century is an era of information technology. The combination of sensing and ITS is a network mainly composed of sensors, communication networks, and information processing systems in the domain of integrated transportation systems, bonded with transportation infrastructure, which has the functions of data real-time monitoring and control, inductive management, information and information sharing, etc. With the establishment of the concept of "intelligent transportation", sensing plays a more and more significant role in ITS and has also rapidly developed into a hot direction in the current field of scientific and technological competition.

3.3 State of Development of Intelligent Transportation Systems around the world

Since its birth in 1973, intelligent transportation has been vigorously developed. In the early stage, the development speed is relatively slow due to the limited means of communication. From 1995 to 2000, with the rapid growth of data transmission speed and the breakthrough of location service technology and communication technology, the development speed of intelligent transportation was obviously accelerated, and communication technology was no longer a limiting factor. At this time, the development of ITS was mainly limited by computing power. From 2000 to 2010, intelligent transportation technology was comprehensively promoted, and high-definition video, intelligent analysis, research, and judgment were fully applied in the field of urban transportation. Since 2010, with the continuous rising of big data, machine learning, and other technologies, vehicle-road collaboration, autonomous driving and intelligent driving based on human and industrial intelligence will become the key direction of the next stage of technological progress of intelligent transportation systems.

3.3.1 Intelligent Transportation Systems in United States

In the two decades from 1976 to 1997, the number of vehicle miles traveled per year in the United States increased by an average of 77%, while the number of miles of road construction increased by only 2%. During rush hour, 54% of vehicles were blocked. In order to solve this dilemma, the United States began to carry out the research and planning of intelligent transportation systems from the 1980s. In 1990, “Intelligent Vehicle-Highway System America” was created. In 1995, American Transportation officially published the "National Intelligent Transportation System Project Plan", which clearly defined the seven fields of ITS. In 1996, Atlanta City Transportation Bureau developed the Olympic traffic control management system with the technology of the existing intelligent transportation system, which provided effective services for the 26th Olympic Games. In 2001, the U.S. Department of Transportation and ITS America jointly prepared the U.S. National Intelligent Transportation System 10-year Development Plan, which defined the theme of inter-regional development as a whole system construction. Under the existing planning, the construction of ITS in the United States has been continuously improved, alleviating the prominent contradiction formed by the worsening traffic congestion and the inability to continue to expand the transportation infrastructure. At present, the application of ITS in the

United States has covered more than 80% of the transportation facilities, ITS system structure is relatively perfect

3.3.2 Intelligent Transportation Systems in the European Union

Most countries in Europe are small, so ITS research in Europe adopts the policy of the whole European integration. In order to promote ITS development and effectively coordinate international cooperation in the whole of Europe, the Organization for Economic Cooperation and Development (OECD) has included ITS in the "Eureka" joint research and Development Program started in 1986, aiming to build a trans-European intelligent road network. The SCOOT system was developed by the Institute of Transport Research in the UK in 1973 and officially launched in 1979, which has been used in more than 170 cities around the world and has spawned many new versions, including support for bus priority, autonomous SCOOT Traffic Information Database system, accident detection system and vehicle emission estimation. In 1991, the European Organization for the Promotion of the Practical Application of Road Transport Communications Technology was established to coordinate and support ITS activities across Europe. In 2001, the European Union included the ITS plan in the ITS White paper on transport policy for the next 10 years and put forward proposals to realize the ITS integrated market. To this day, the various countries of the European Union are still conducting development and research in a wide range of ITS transportation fields. By applying the research results to practice and carrying out project promotion and follow-up research and development, ITS is constantly improved and changed.

3.3.3 Intelligent Transportation Systems in Japan

Japan, as an island nation, despite its small area, has hundreds of millions of people and 80% of the population lives in cities; About 70 million cars are on the road every day, and about 1 million people are injured or killed in traffic accidents every year. The Japanese government has been trying to solve pressing transportation problems since it formed the "Vehicle, Road and Traffic Intelligence Association" in 1993, hoping to accelerate the development and construction of intelligent transportation systems. Today, all ITS systems are in use. In Japan, ITS has entered a mature period, and the intelligent highway system can fully provide a new and powerful solution to various traffic problems that may appear in the 21st century.

Chapter 4 Vehicular Ad-hoc Networks (VANET)

With the rapid development of the economy and the improvement of people's living standards, the global automobile industry has developed by leaps and bounds. In recent decades, automobiles have been rapidly entering thousands of households. As a result, urban traffic problems are troubling countries all over the world. In order to effectively solve these traffic problems, Europe, the United States, and other major developed countries in the world have put forward the concept of the intelligent transportation system. However, the vehicular ad-hoc network (VANET) can share various traffic and vehicle-related information, such as vehicle running status and traffic light information, with surrounding vehicles, providing important technical support for the wireless communication technology of V2V in ITS. And it is also a special mobile ad-hoc network (MANET), VANET has a significant meaning to the development of smart vehicles and intelligent transportation.

4.1 Definition of VANET

The vehicular ad-hoc network (VANET), also known as a vehicle-based mobile communication network, applies the principle of the mobile ad-hoc network (MANET) to the vehicle field, which means utilizing the principle of spontaneously creating wireless networks for data exchange among the vehicles. It is mainly based on vehicle internal networks, vehicle internetwork, and vehicle cloud networks. According to the agreed communication protocols and data exchange standards, it would be a system network for wireless communication and information exchange between vehicles, vehicles and roadsides, and vehicles and pedestrians.

As a special mobile ad-hoc network, VANET not only inherits some features of MANET but also has its own unique features. As vehicles are always in a state of high speed, the topology structure between vehicles is always in a state of change as a matter of course. Compared with the node of MANET, the vehicle, as the node of VANET, has sufficient energy storage and computing capacity. Another thing needed to be noted is that the communication of VANET has fixed geographical characteristics compared with other networks that use unicast or multicast. The data transmitted in VANET is usually related to something happening at a certain place, and it does not target a single vehicle but corresponds to a certain geographical area. However, due to highly mobile nodes, dynamic topology, and complex urban communication environment, it has higher requirements for modeling and prediction. In some VANET applications, although the network does not require a high data rate, it has more stringent delay constraints to ensure real-time information.

4.2 Architecture of VANET

VANET is a new ad-hoc network consisting of mobile vehicles with sensing and wireless communication capabilities driving on traffic roads and basic communication units located on the roadside. From the node composition, it can be divided into the communication network between vehicles (Vehicle to vehicle, V2V), communication networks between vehicles and associated fixed facilities such as base stations (Vehicle to Infrastructure, V2I), or communication networks between vehicles and roadside units (Vehicle to Roadside Units, V2R). In a broad sense, VANET encompasses a transmission network that is not limited to vehicles and roadside units, such as vehicle-to-pedestrian, vehicle-to-bicycle, etc. As wireless communication technology advances in the future, the model of V2X will derive even more.

Vehicles running on the road are directly formed into V2V networks, which do not require any infrastructure. Vehicles in the network, working as a node, are straightway responsible for communication between vehicles without any fixed infrastructure support. In addition, vehicle nodes have the functions of network terminal and routing in high-speed moving environments, which is mainly used for road safety applications such as rapid distribution of sudden information like accidents. And it also maintains the characteristics of MANET with strong extensibility and high convenience.

Since V2R/V2I network needs fixed facilities, its application is prevailingly on urban main roads and its prime operation mode is through the communication between roadside units and vehicles driving on the road. It is suitable for information applications related to fixed facilities such as ETC and Internet access.

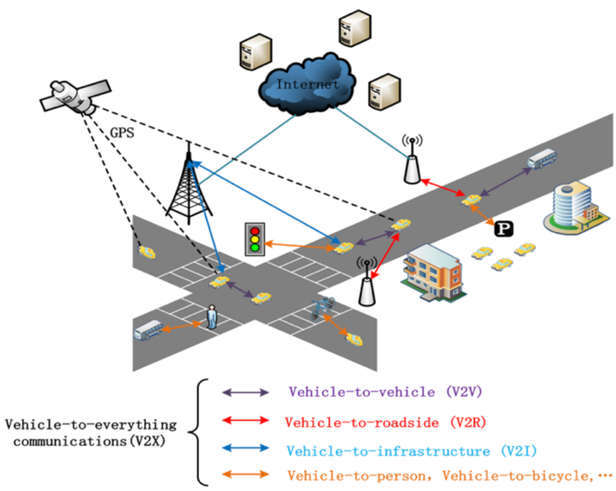


Figure 5. The architecture of VANET [24]

Similarly, there is also a combination of the two mentioned above, V2V and V2I/V2R. In a combined network, V2V is responsible for collecting vehicle node status information on the road. While, these networks can be extended to networks outside the road, such as access to the Internet, and finally this combined network could realize information transmission and share between different vehicle networks.

Then, according to the communication code mentioned before, the topology of the VANET could be classified into three kinds: hybrid mainly used in the communication networks with both V2V and V2I/V2R, WLAN/Cellular primarily working for V2I/V2R, and ad-hoc as a classical topology for V2V, which has been shown in detail in the following figure 6.

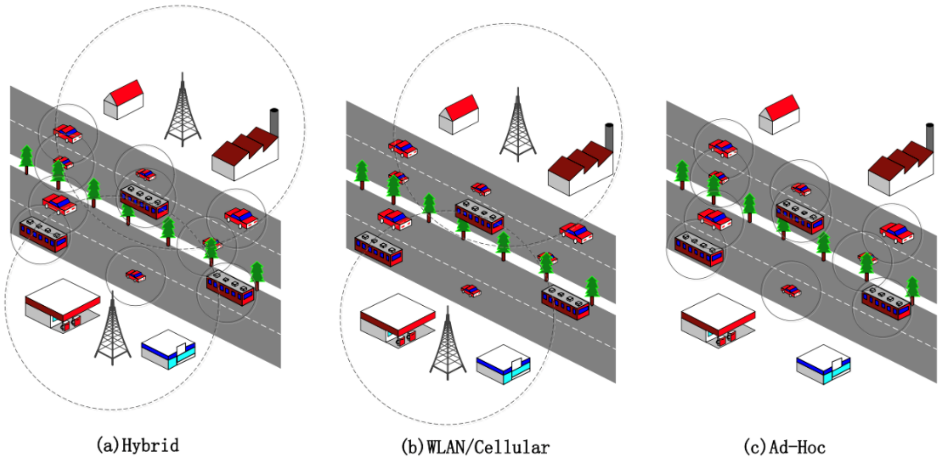


Figure 6. Topology structure of VANET [15]

In sum, VANET does not rely on fixed central facilities, and it is built by mobile vehicles with short - and medium-range wireless transceiver devices, roadside infrastructure, personal electronic devices, and other basic traffic units in the form of self-organization of temporary communication networks. All nodes can join or exit at any time, and through point-to-point peer-to-peer communication, people, vehicles, and roads can be interconnected and intelligently coordinated.

4.3 Key Technology used in VANET

VANET is a new part of the MANET network applied to road traffic, and also the application of the Internet of Things (IoT) in the field of intelligent transportation. Its concept first appeared when the automobile communication standardization conference held by the International Telecommunication Union in 2003. Its realization and application depend on the rapid development of wireless communication technology and the decline in production costs. In the following section, here would introduce two key technologies, DSRC and GPS, for VANET.

4.3.1 Wireless Communication Technology in VANET applications

Back in 1992, the American Society for Testing and Materials proposed Dedicated Short-Range Communication (DSRC) [16], In 1999, the U.S. Federal Communications Commission (FCC) approved the allocation of 75MHz bandwidth near the 5.9GHz band to the DSRC standard. In 2004, the Institute of Electrical and Electronics Engineers (IEEE) established two working groups, 802.11p and 1609, to begin developing protocols for the DSRC standard. The two working groups worked together to formulate Wireless Access in Vehicular Environments (WAVE) [17]. As WAVE has been introduced in chapter 3, this won't go into here.

DSRC is a communication technology proposed for wireless data transmission in VANET. It provides end-to-end and one-to-many wireless communication and realizes the organic connection of constituent units in VANET. Compared with other wireless communication technologies, it is found that DSRC is superior to other communication technologies in vehicle ad-hoc networking in terms of vehicle mobility support, network data transmission efficiency, end-to-end delay control, maximum communication distance, communication bandwidth, and communication frequency band. Therefore, it is more applicable to the communication requirements of V2V and V2I in VANET. A detailed comparison of the parameters would be shown in the following table 1.

Table 1. Comparison between DSRC and other wireless communication technologies

Wireless Communication Technology	DSRC	Wi-Fi	Cellular	WiMax
Delay	<50ms	seconds	Seconds	/
Mobility	>60km/h	<5km/h	>60km/h	>60km/h
Transmission Range	<1000m	<100m	<10km	<15km
Data Speed	3~27Mbps	6~54Mbps	<2Mbps	1~32Mbps
Bandwidth	10MHz	20MHz	<3MHz	<10MHz
Frequency Band	5.86~5.925GHz	2.4GHz/5.2GHz	800Hz/1.9GHz	2.5GHz
IEEE Standard	802.11p	802.11a	N/A	802.16e

Table obtained from [18]

4.3.2 GPS used in VANET applications

Currently, there are four types of Global Positioning Systems (GPS):

(1) Global Positioning System (United States)

There are 24 satellites, distributed in six intersections 60 degrees apart from each other on the orbital plane, the accuracy is about 10 meters, for both military and civilian use. GPS has gone through the first and second generations, and now it has been upgraded to the third generation to maintain its supremacy in navigation and positioning system, which is by far the most accurate and most extensive navigation and positioning system in the world.

(2) Global Navigation Satellite System (Russia)

This system, with a standard configuration of 24 satellites, became operational worldwide on January 1, 2011. At present, there are 24 satellites in normal operation, 3 under maintenance, 3 in reserve, and 1 under test. The accuracy is about 10 meters, which is used for both military and civilian purposes.

(3) Galileo Satellite Navigation System (Europe Union)

Galileo will consist of 30 orbiting satellites at an altitude of 24,000 kilometers. It has an inclination of 56 degrees and is distributed on 3 orbital planes, with 9 working stars and 1 standby star in orbit on each orbital plane. In terms of design objectives, Galileo's positioning accuracy is superior to GPS. If GPS can only find streets, Galileo can find garage doors. Galileo offers ground users three types of signals: a free one, an encrypted one that costs a fee, and an encrypted one that meets higher requirements. The accuracy of the signal has been improved successively. The highest accuracy is 10 times higher than that of GPS, and the accuracy of the signal even for free use is 6 meters.

(4) BeiDou Navigation Satellite System (China)

It consists of 5 geostationary orbit satellites and 30 non-geostationary orbit satellites. Positioning accuracy of 10 meters.

4.4 State of Development of VANET around the work

With the deepening of research on wireless ad-hoc networking by scientists around the world, research institutions and researchers around the world have begun to pay close attention to VANET [13], which is a special wireless ad-hoc networking. Research projects on VANET have been carried out in research institutions, governments, and enterprises in many countries. In 1999, the US Federal Communications Commission (FCC) allocated 75MHz (in the 5.7GHz band) to dedicated DSRC [14], and Japan also allocated 5.8GHz to DSRC. These DSRC roadside devices set up on highways send information, which is then received or sent to roadside devices using onboard terminals.

The projects related to VANET have been studied in various countries around the world, and relevant automobile manufacturers and scientific research institutions have established relevant organizations to study associated technologies of VANET. Table 2 would list some corresponding projects of VANET.

Table 2. Examples of projects about VANETs

Project Name	Organizer	Time	Research Contents
FleetNet	Germany	2000~2003	Application of ad-hoc networking technology based on 802.11 protocol in VANET
C2C-CC	BMW, Mercedes-Benz, Volkswagen, Toyota, Honda, Ford, General Motors and Nissan Motor Co	2001~now	Standard for V2V communication systems
CarTalk 2000	EU	2001~2004	Vehicle cooperative assistance driving
VSC	United States	2002~2005	V2V communication standards that effectively support on-board safety applications
ADASE	EU	2003	Reduce accidents by linking to roadside facilities through active safety systems
WILLWARN	EU	2004~2006	Vehicle safety warning
ASV-4	Japan	2006~2010	Driver assistance system based on shop - shop communication

Table obtained from [15]

As a mainstay of emerging industries, VANET has been vigorously developed in all countries in the world and has huge market application potential. It will certainly provide new market opportunities for the automobile industry, hardware equipment manufacturers, network service providers, and the data communication industry. As the core system of ITS in the future society, it is a system capable of rapid, bidirectional, and large-scale information exchange. The development of information and communication technology provides the necessary conditions for the improvement of VANET. At the same time, the implementation of VANET will also accelerate the progress of information-related technology and equipment and drive the progress of information and telecommunication society in other fields, so as to promote the popularization and development of the information and telecommunication industry.

Chapter 5 Simulation Tools used in this Master Thesis

In this chapter, the requirements of simulation would be simply introduced. In order to realize the simulation of the vehicle networks, it is essential to compose the whole framework with the function of mobility and networks. Generally, these two factors need to be separable in diverse tools. In this project, the entire simulation was constructed on the platform of Ubuntu. The feature of mobility would be simulated in SUMO and the network would be implemented in OMNeT++ through the VANET simulator Veins respectively. The version of these tools would be itemized in the following table 3.

Table 3. Simulation Tools and their version

Tool	Version
Ubuntu	18.04
SUMO	1.8.0
OMNeT++	5.6.2
Veins	5.1

5.1 SUMO. Simulation of Urban Mobility

SUMO (Simulation of Urban Mobility), which has been developed by the Institute for Traffic Systems at the German Aerospace Centre since 2001, is an open-source, highly portable, micro, and continuous road traffic simulation software package designed to handle large road networks [2].

The main function of SUMO includes the following three parts:

(1) Simulation of static scene maps. Most studies of vehicle networks should rely on real traffic scenes. SUMO not only contains the feature and generation mechanisms to import a variety of road networks but also can carry out secondary development of maps to adapt road topology, traffic light control, and other information according to the demand of multiple simulations.

(2) Simulation of vehicle movement model. Through the analysis of the actual driving model, according to the realistic situation of the road and traffic rules, SUMO could realize the simulation of vehicle driving, overtaking, lane change, and other vehicle traveling states.

(3) Simulation of the microscopic vehicle and road model. The main purpose is to achieve a spectator traffic model by using diverse car-following models on a static map.

When simulating in SUMO, first of all, the detailed information of the map can be downloaded through OpenStreetMap [19], and then convert these lane attributes into a traffic topology network of actual roads such as *node.xml*, *edge.xml,* and *poly.xml* through its own tools such as NetConvert and PolyConvert. Then, on the basis of different requirements, related parameters of traffic flow, such as velocity and minimum stopping distance, can be designed to generate in a *rou.xml* file for the running traffic flow, and finally, a spectator traffic model can be taken shaped with the *sumo.cfg* for the simulation.

5.2 OMNeT++. Event-based Simulator for Communication Networks

OMNeT++ [3] (Objective Modular Network Testbed in C++) is an open-source component-based modular open-network simulation platform developed by OpenSim Ltd. As a discrete event simulator, it has a powerful and perfect graphical interface and embedded simulation kernel. Network topology can be defined easily, with programming, debugging, and tracking support. It is mainly used for communication networks and distributed system simulations.

An OMNeT++ simulation model is composed of various modules. The at-ground level module is called the simple module, which can be connected through predefined gates for communication or directly transmitted to the destination module in the wireless communication simulation. Multiple simple modules can be combined and nested to form compound modules without any limitations on the depth of nesting. The modules can communicate with each other with messages. Finally, the user can create system modules to form the network of the simulation model, which is the largest structure in OMNeT++. The parameters of a module are used to customize the behavior of the module or to represent its topology.

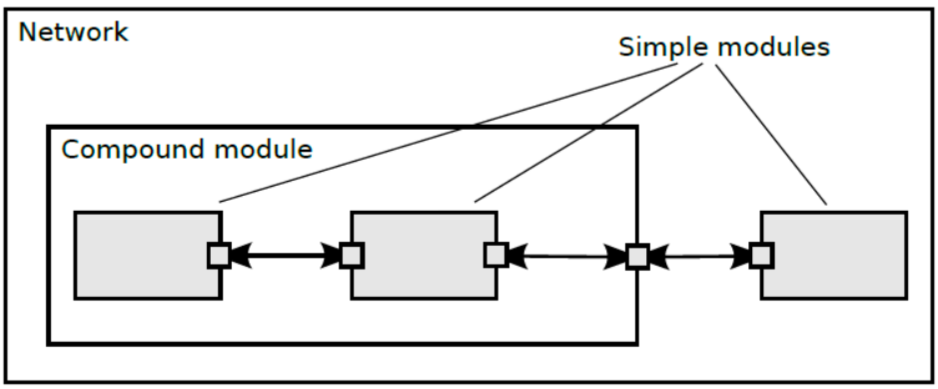


Figure 7. The architecture of OMNeT++

An integrated OMNeT++ model file needs to contain the following sections:

(1) The network initialization file (*.ini file*) set up the main configuration for the whole system.

(2) The network description files (*.ned file*) describe the module structure using parameters, gates, etc.

(3) Message definition files (*.msg files*) define various messages and add data segments.

(4) The base module source files (*.cc/.h file*) describe the function of each simple module.

5.3 VEINS. Vehicular Networks Protocol Stack

Veins [4] is an open-source framework for wireless communication simulation in a vehicle-mounted mobile environment. Because the development of the underlying structure of the vehicle wireless network in Veins has been quite perfect, so on this basis for the routing protocol or the other aspects of research on wireless communication are very convenient. In addition, it is also of great help to the research at the application level, such as vehicle autonomous driving in the environment of the Internet of vehicles, route planning, etc., so that researchers no longer need to spend time and energy on some non-major research content like MAC layer.

The following figure would show the architecture among Veins, OMNeT++, and SUMO. These models run simulation events through the interaction of a discrete event-based network simulator (OMNeT ++) with a road traffic simulator (SUMO), while other components of Veins would be responsible for setting parameters about the simulation events, running and monitoring the simulation.

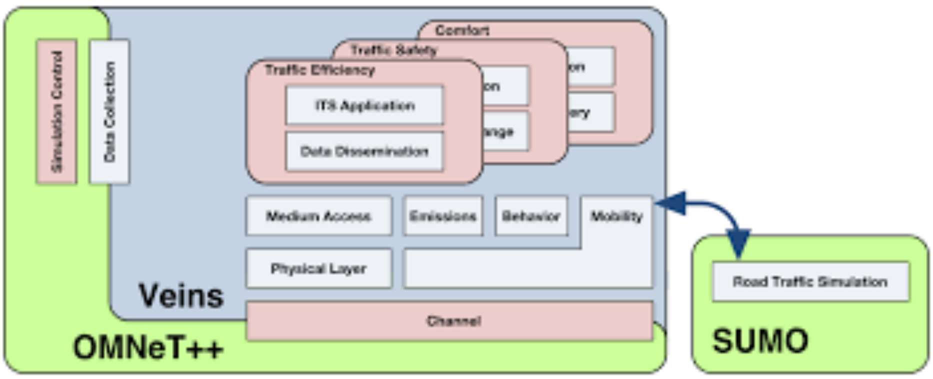


Figure 8. The working framework of Veins [4]

Chapter 6 Evaluated Scenario

In the previous chapter, we have reviewed the relevant technical background and simulation tools used in the project. ITS, as a key segment in smart cities, could immensely enhance the efficiency of urban transportation and guarantee the safety of urban traffic. Further on, VANET, working as a significant technology of the ITS, through the perception of cars and roads in the city, has been regarded as an efficient solution to the traffic problems plaguing countries around the world. However, as we all know, in a city, its vehicle network is not necessarily constant but changes dynamically with plentiful factors. This is also the content we want to discover and research. Therefore, the main proposal of this project is to evaluate the performance of the VANETs with the influence of diverse elements like velocity, and urban environmental factors in the city. In this section, we would chiefly introduce the evaluated vehicle scenario and the basic parameters and algorithms of the simulation.

6.1 An Urban Scenario

As we have discussed before, according to the social status quo of different countries and regions, the municipal and traffic conditions all over the world are absolutely disparate, which leads grand impact on the performance evaluation of the vehicular network. However, as a case study, we need to focus on more realistic circumstances.

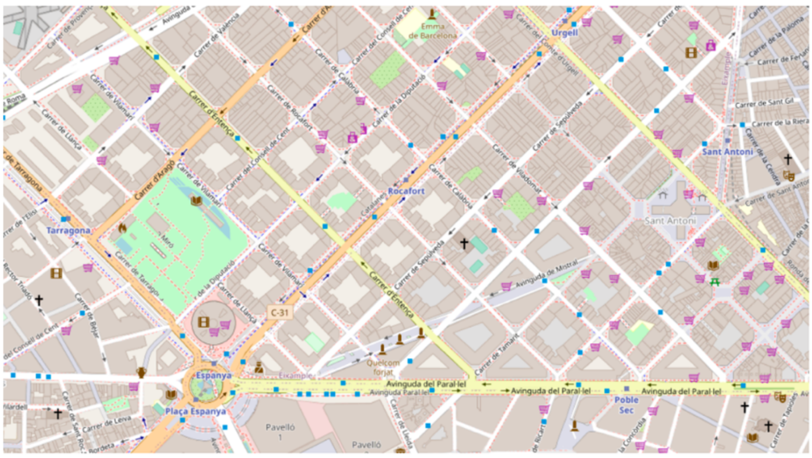


Figure 9. The overview of the simulation region in the Eixample district of Barcelona

The Eixample, as a district of Barcelona with a population of over 26 thousand, is characterized by long straight streets, a strict grid pattern crossed by wide avenues, and square blocks with chamfered corners. And it also could be regarded as an exciting convergence of urban transit and retail in Barcelona. Therefore, an area with a cover of 3.5 km^2 in the Eixample district in the center of Barcelona city would be chosen as an example to be used in this project. The above figure 9 shows the simulation scenario part in the Eixample district.

6.2 Vehicles and Packet Traffic

As a future intelligent transportation infrastructure, VANET forms a unified wireless communication network through vehicle-to-vehicle and vehicle-to-roadside node communication to deliver real-time services such as assisted driving and accident avoidance, which is crucial for safe driving. As one of the main functions of VANET in traffic-related applications, accident information transmission could have a positive effect on reducing and avoiding regional traffic jams caused by unexpected car accidents. In this article, we also assumed such a scenario that there is a sudden accident of the vehicle brought to a standstill, as the following figure 10 showed. After an accident, these surrounding vehicles use VANET to transmit accident information collected by their sensor devices to each other.

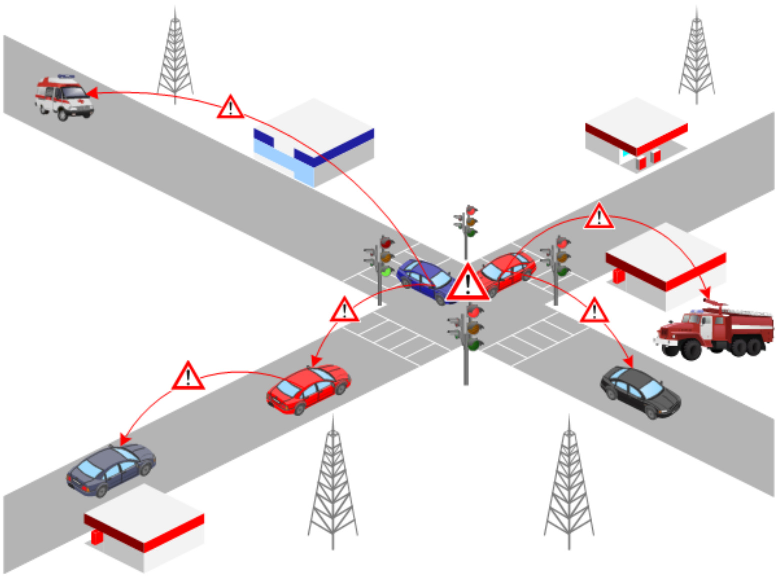


Figure 10. Evaluated Scenario [25]

6.2.1 Maximum Vehicle Speed

As we have mentioned previously, we chose a part of the Eixample district as the simulation scenario. In figure 11 shown below, which is a plot with the average velocity distribution of the selected region, we could easily find that in the selected area, the average speed of vehicles is generally relatively slow, with most distributed between 20km/h and 30km/h. Therefore, we have selected the following five speeds as the maximum speed for the vehicle: 10km/h, 20km/h, 30km/h, 40km/h, and 50km/h. These five speeds also represent three kinds of traffic circumstances: 10km/h represents a low vehicle running, which usually means that there are more vehicles in this period, such as the rush hour; 20km/h and 30km /h are relatively average driving speeds in this region, which means that the road conditions at this time are correspondingly stable; The speed of 40km/h and 50km /h is a little bit higher than the others, which mostly happens in the middle of the night and at these moments the road is relatively empty. These maximum vehicle speeds would be listed in Table 4.

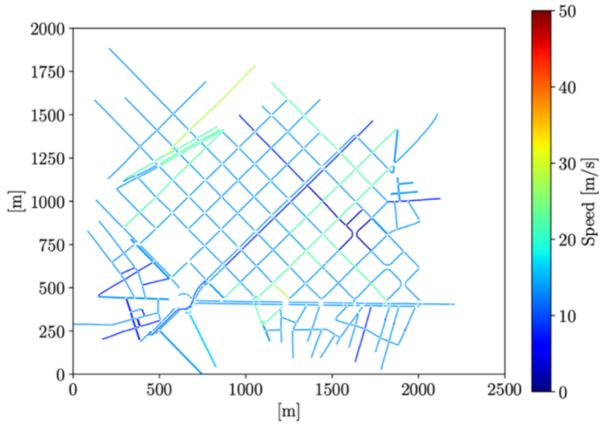


Figure 11. The velocity distribution in the simulation region

Table 4. Maximum Vehicle Speed

Level	Velocity(km/h)
Low	10
Mid	20
Mid	30
High	40
High	50

6.2.2 Vehicles' Density

For another aspect, we also need to consider the vehicles' density, which could represent the road condition most directly. Similarly, vehicle density is divided into the following four levels: 50Veh/km^2, 100Veh/km^2, 150Veh/km^2, and 200Veh/km^2. They represent low, medium, high, and extremely high levels of traffic congestion, respectively, which has also been listed in Table 5.

Table 5. Vehicle Density

Level	Number of Vehicle	Vehicle Density(Veh/km^2)
Low	175	50
Mid	250	100
High	525	150
Traffic Jam	700	200

6.2.3 Car-Following Model

Finally, we would like to talk about the car-following model we set in this simulation. Car-following models, which describe the one-by-one following processes of vehicles in the traffic flows, have been studied for nearly a half-century. In the car-following model, the speed of the vehicle behind depends on the speed of the vehicle ahead. And in most cases, the following vehicle always tries to keep a safe distance from the leading vehicle.

The default car-following model in SUMO is Krauss Model, which is also the car-following model we set here. In the Krauss model, the safe velocity is calculated first. The desired speed is equal to the safe speed if the safe speed does not exceed the maximum speed or the achievable speed in the next time step. Otherwise, the expected velocity is only equal to the smaller of the two limits. Then, the speed of the following vehicle in the next time step is equal to the expected speed minus a small random number to simulate the uncertainty in driving, and finally get the position of the subsequent vehicle. In the real scene, drivers deal with the situation in the process of driving based on their own driving experience and personality characteristics based on the surrounding environment and road conditions. In road driving, the driver's behavior process is divided into three steps: first, the driver knows the road condition, which is the most basic step in the driver's behavior, would be affected by the weather environment and the driver's physical and psychological state; Then, they make a decision based on the perceived situation, this step is generally related to the driver's personality characteristics; The last step is to execute the decision, which is related to the driver's driving experience. The experienced and skilled driver can generally reach the ideal state in the Krauss model.

6.3 Message Dissemination Protocol

VANET application has its particularity that information-receiving nodes are generally multiple nodes with randomness and uncertainty. In this data distribution mode, broadcast becomes one of the most effective ways for VANET to transmit various information [20]. To expand the area where emergency traffic information is distributed and to provide traffic information services to more relevant nodes in the region, the project utilized multi-hop broadcast schemes to transmit the information.

When an accident occurs, the accident vehicle will first flood the accident information through VANET to the surrounding vehicles connected with the accident car. The information is then transmitted again by the vehicle which has received the accident information to other vehicles traveling within a certain radius. Spread it repeatedly in VANET, and eventually as many nearby cars as possible will receive the crash information and reroute themselves to prevent more serious traffic jams around the area of the accident.

Chapter 7 Analysis of the Simulation Results

In the previous chapter, we have elaborated on the simulation scenarios, vehicle configuration, and data distribution methods used in the project. By combining SUMO with the Veins framework based on the OMNET++ emulator, we simulate the vehicular network in a portion of the Eixample district of Barcelona and then evaluate its performance. Here, we mainly through the following three aspects to make a brief assessment: packet delay, percentage of warned vehicles, and warning distance. In this chapter, we will analyze the impact of diverse vehicle configurations and urban environmental factors on the vehicular network in case of accidents from the following four aspects:1. maximum vehicle speed 2. reduced nominal road speed 3. different transmission range 4. Improved message dissemination protocol

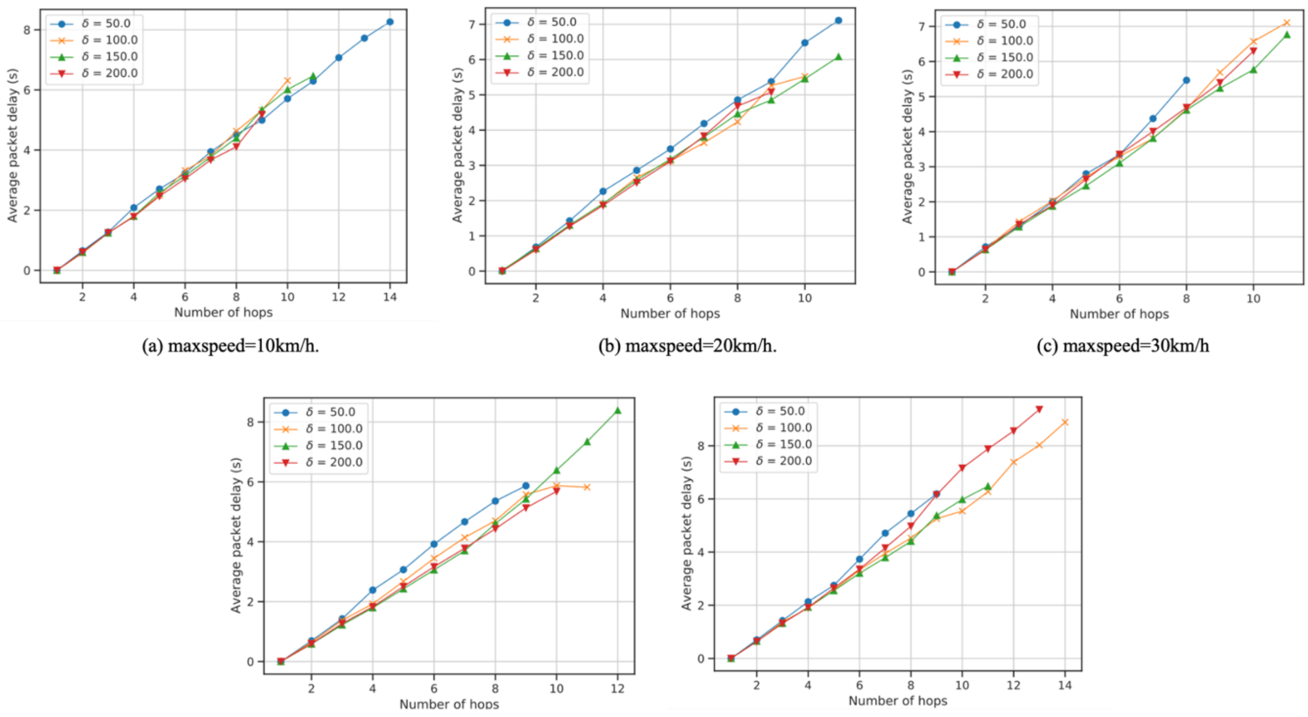
Before starting to analyze the results, we will once again give a brief summary of the simulation parameters, although we have characterized them in detail in the previous chapter. Our simulation was built based on real-life conditions and lasted for 300 seconds in a 3.5 square kilometer area in the Eixample district, which is regarded as the center of Barcelona to meet the requirements of urban environments. And we will set up a car accident on one of the roads in the simulation scenario, which will occur 10 seconds after the start of the simulation and continue until the end of the simulation. In the whole simulation process, we would set four different vehicle densities to evaluate the performance of vehicular network under different traffic conditions. All the simulation parameters could be found in the following table 6.

Table 6. Simulation Settings

Settings	Values
Area	$3.5km^2$
Simulation Time	300s
Accident Time	290s
Vehicle Density (veh/km^2)	50,100,150,200
Number of Accident(s)	1
Transmission Range	250m

7.1 Maximum Vehicle Speeds

Firstly, let us take a look at the packet delay of the alert message transmission. Generally speaking, vehicle speed has a significant impact on packet delay. Under the circumstances of different speed and vehicle density distribution, the overall change trend is obvious. When the vehicle density is low, such as 50 veh/km^2, its packet delay decreases with the increase of the vehicle speed. However, when the vehicle density increased to 100 veh/km^2, the opposite trend occurred that the packet delay increased with the rise of the speed, showing a positive correlation. This situation also appears in the case of 150 veh/km^2 and 200 veh/km^2, but different from the vehicle density of 100 veh/km^2, they change when the speed reaches 40km/h, 150veh/km^2 generates the peak value of packet delay at this moment, while 200 veh/km^2 suddenly decreases.



(a) maxspeed=10km/h.
(b) maxspeed=20km/h.
(c) maxspeed=30km/h
(d) maxspeed=40km/h
(e) maxspeed=50km/h

Figure 12. Packet Delay for Diverse Maximum Vehicle Speed

Then, for the aspect of % of warned vehicles. From the following picture, we could easily find that the changing trend of % of warned vehicles with the density of vehicles is the same regardless of the maximum speed. When the vehicle density reaches 150 veh/km^2, it peaked at % of warned vehicles. It is worth noting that when we further raise the vehicle density to 200 veh/km^2, a level of traffic jams, we can find a significant decrease in % of warned vehicles. From the perspective of vehicle density, the percentage of warned vehicles increases with the ascend of speed, excluding the low speed of 10km/h and 20km/h.

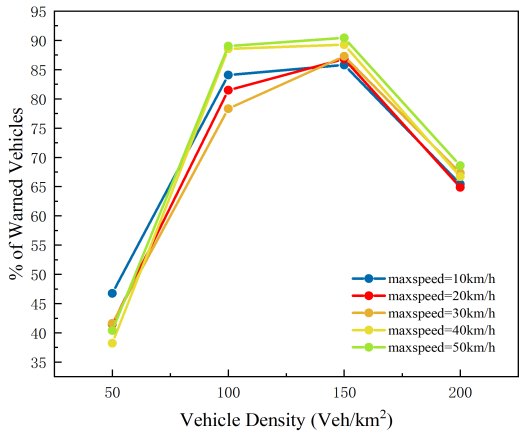


Figure 13. Warned Vehicles for Diverse Maximum Vehicle Speed

Finally, how about the warning distance? From figure 14, the comparison of the warning distances of diverse maximum speeds, we can clearly divide the situation into two types: the low-speed situation with the speed of 10,20,30 km/h and the relatively high-speed situation with the speed of 40,50 km/h. When we are in a low-speed situation, we can find that the trend of warning distance changes from 50 veh/km^2 to 100 veh/km^2, which is relatively gentle; from 100 veh/km^2 to 150 veh/km^2, it goes up dramatically; When the density of vehicles exceeds 150 veh/km^2, there is a sharp decline. For high speeds, the change from 50 veh/km^2 to 100 veh/km^2 is relatively significant; It goes from 100 veh/km^2 to 150 veh/km^2, the changing trend is gentle; Above 150 veh/km^2 to 200 veh/km^2, the decline is more stable. From the perspective of vehicle density, when the speed is low, the smaller the speed, the longer the warning distance, the two are inversely correlated; When the speed is higher, the faster the speed, the longer the warning distance, these are the positive correlation.

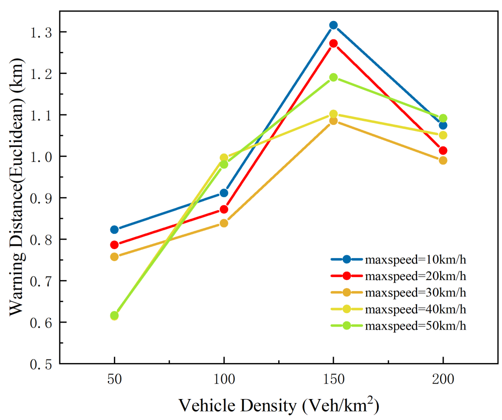


Figure 14. Warning Distance (Euclidean) for Diverse Maximum Vehicle Speed

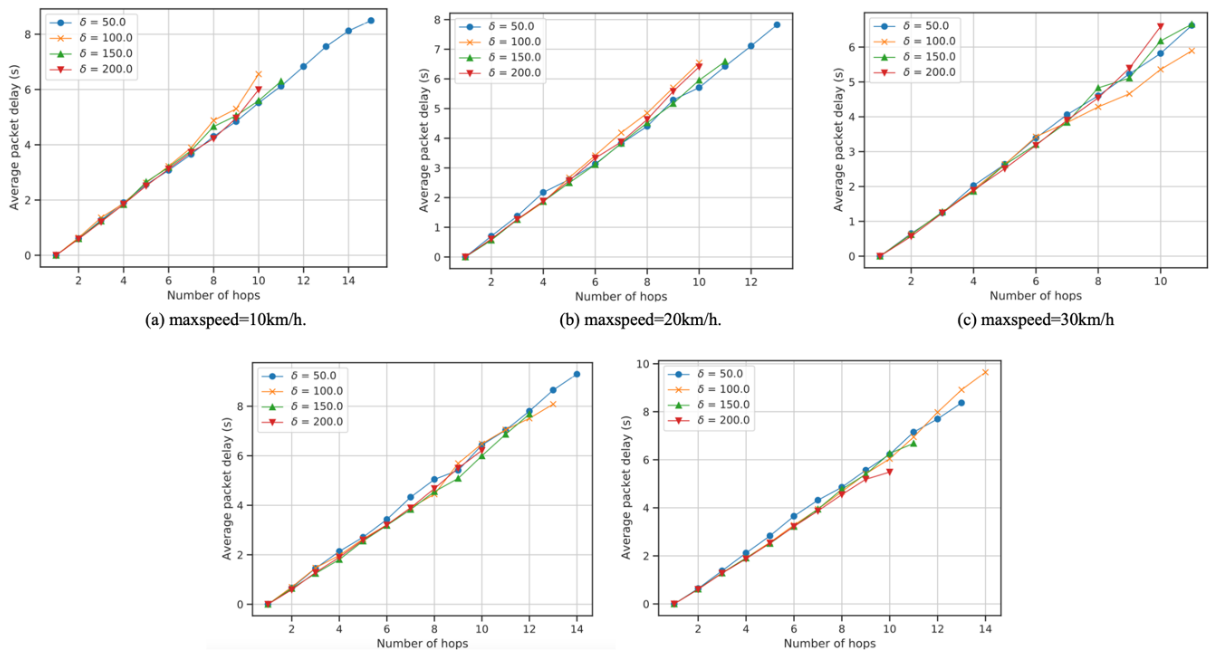
In conclusion, the maximum speed of the vehicle greatly affected the transmission of emergency information. However, this does not mean that pure high speed or low speed is better for the transmission of accident information. When we think about this problem, the performance evaluation of urban traffic, when we focus on this most basic setting, the speed of the vehicle, we should also pay more attention to the current area of traffic, namely the density of vehicles, which also represents the disparate road conditions and has an influence for the transmission of the accident message.

7.2 Reduced Nominal Road Speeds

Traffic accidents, as one of the important sources of traffic jam, usually leads to traffic moving forward slowly and reducing the capacity of the roads. Sometimes we wonder if we could lower the speed limit on the road around the accident, would traffic performance be better? Therefore, we make such a simulation here: since the speed limit of the road and lane within the 100-meter area around the accident is mostly around 30km/h to 50km/h, we lower it to 15km/h and 10km/h respectively and observe whether there are some changes.

7.2.1 The Nominal Road Speed = 15km/h

Same as in the previous part, we still start analyzing from the aspect of packet delay, see figure 15.



(a) maxspeed=10km/h. (b) maxspeed=20km/h. (c) maxspeed=30km/h
(d) maxspeed=40km/h (e) maxspeed=50km/h

Figure 15. Packet Delay for the Reduced Nominal Road Speed (=15km/h)

According to its changes, it can be basically divided into two camps, the maximum driving speed of 10km/h,20km/h, and 30km/h at low to medium vehicle speed and 40km/h and 50km/h at relatively high vehicle speed. First, let us focus on the low-and-medium speed camp with the maximum vehicle speed of 10km/h,20km/h, and 30km/h. In general, the value of packet delay and the number of hops required to transmit information remain basically unchanged, only with a small increase. However, for the case of low vehicle density, especially 50veh/km^2 and 100 veh/km^2, when the maximum speed of the vehicle reaches 30km/h, the value of packet delay and the number of hops rises very surprisingly, particularly when the speed continues to increase, the information transmission time and hop required by it are greatly raised. However, when we pay attention to the case of higher vehicle density, that is, 150veh/km^2 and 200veh/km^2, we can obviously find that when the speed reaches 40km/h or 50km/h, their average packet delay and the number of hops decrease to a large extent. In sum, for the aspect of packet delay, reducing the speed limit on the road around the accident is more favorable for the condition of higher vehicle density and speed.

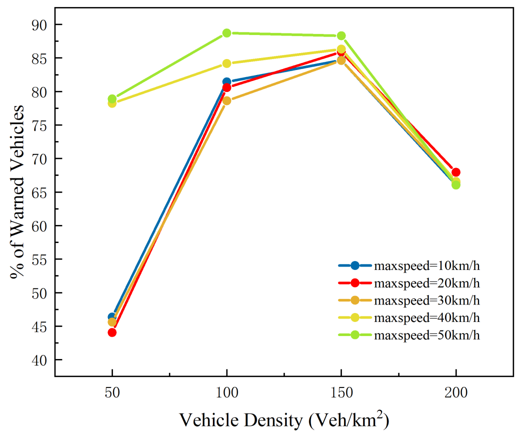


Figure 16. Warned Vehicles for the Reduced Nominal Road Speed (=15km/h)

Secondly, for the part of the warned vehicles see figure 16, we can clearly see that it is very effective in improving the coverage of the transmission of the alert messages in low vehicle density of 50 veh/km^2 and 100 veh/km^2, especially in the situation with the vehicle traveling speed of 40km/h and 50km/h, which has significant improvements of % of the warned vehicles. While, in the circumstance of high vehicle density of 150 veh/km^2 and 200 veh/km^2, it did not show a more positive effect that most of the situation remained unchanged as before.

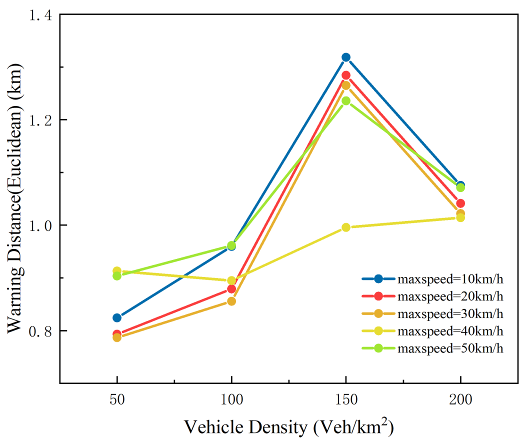


Figure 17. Warning Distance for the Reduced Nominal Road Speed (=15km/h)

Finally, for the part of warning distance see figure 17, in most cases, there is not too much improvement, but at the vehicle density of 100 veh/km^2, all the warning distances drop off significantly. If we look at the overall trend of the curve, the decline is most pronounced when the top car speed is 40km/h. In summary, the road speed limit of 15km/h, doesn't do much for the aspect of warning distance.

7.2.2 The Nominal Road Speed = 10km/h

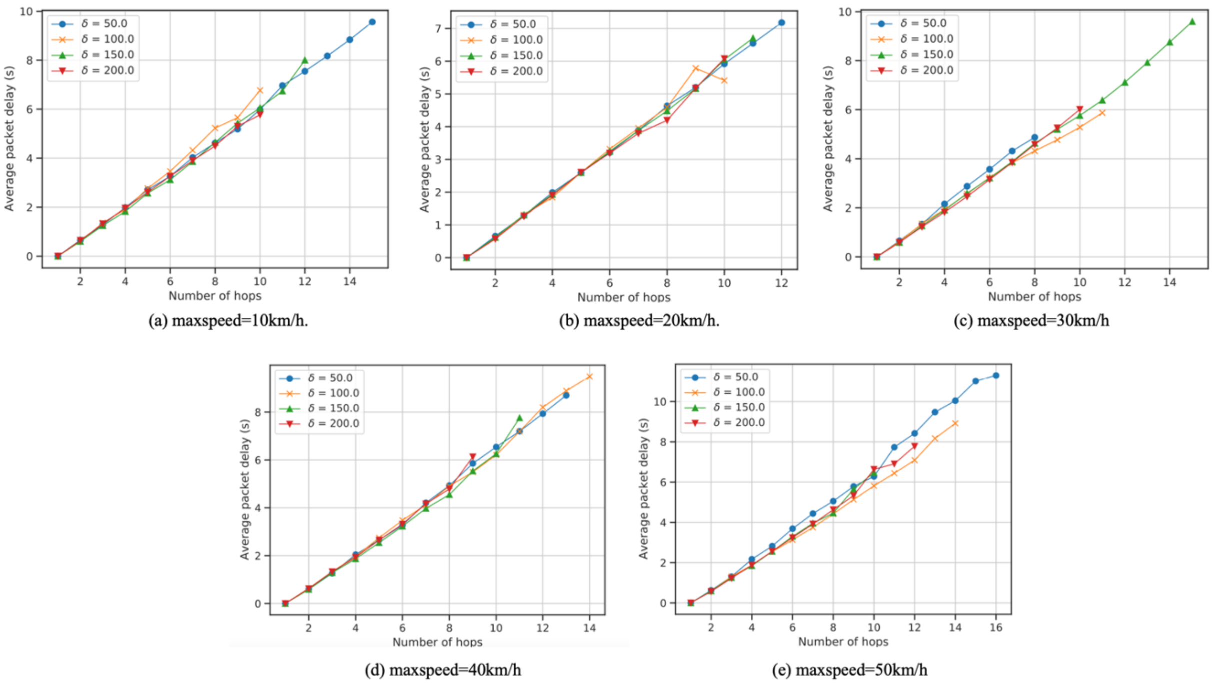


Figure 18. Packet Delay for the Reduced Nominal Road Speed (=10km/h)

In the case of packet delay see figure 18, it is quite different from the previous comparison in that each one has great changes compared with the original ones. Firstly, for the maximum vehicle speed equal to 10km/h, the average packet delay and hop required for all vehicle densities increased with the same amplitude. For the speed of 20km/h, there is no significant fluctuation in their data at the lower vehicle density of 50 veh/km^2 and 100 veh/km^2, but for the higher density of 150 veh/km^{2}and 200 veh/km^2, they both rise up. Compared to the case where the speed is 10km/h, the growth rate is less. As the speed goes up to 30km/h, all the values go down except for the vehicle density of 150 veh/km^2, where it goes up. The same is true for 40km/h and 50km/h. At 40km/h, the value for 100 veh/km^2 is increasing; At 50km/h, the value for 50 veh/km^2 is going up. In general, the impact of road speed limit on packet delay is complex and needs to be analyzed by case.

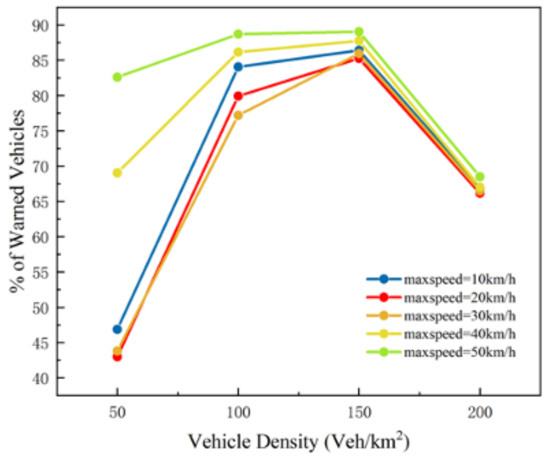


Figure 19. Warned Vehicles for the Reduced Nominal Road Speed (=10km/h)

Secondly, for the part of the percentage of warned vehicles, see figure 19, the curves shown in the figure also have the same tendency as the previous situation of the nominal road equal to 15km/h that the % of the warned vehicles has ascended a lot in the lower vehicle density of 50 veh/km^2, especially in the higher vehicle speed of 40km/h and 50km/h. However, for the other vehicle densities, it did not make many influences.

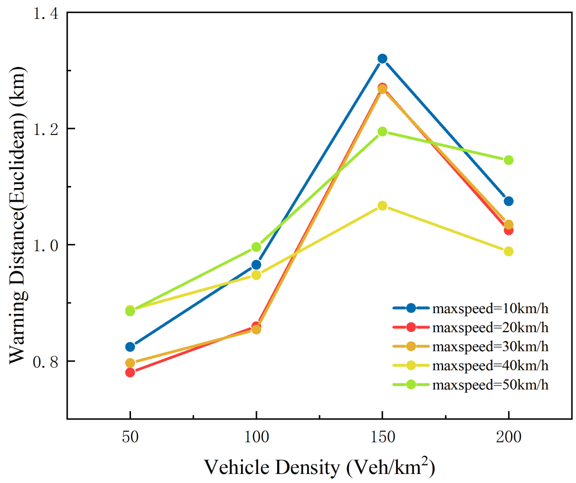


Figure 20. Warning Distance for the Reduced Nominal Road Speed (=10km/h)

Finally, let us take a look at the part about warning distance. Here, we can still divide the curves shown in Figure 20 into two parts to illustrate: the lower-and-normal vehicle speed situation of 10km/h,20km/h, and 30km/h and the higher vehicle speed of 40km/h and 50km/h. For the lower speed parts, although their data fluctuated, overall, there was not much change. But at higher speeds, when their vehicle density is 50 veh/km^2, there is a significant upward movement. And when the vehicle density is 100 veh/km^2 with the condition of 40km/h, it has a definite decrease. For the other density cases, as same for the lower speed cases, there has only some small fluctuation.

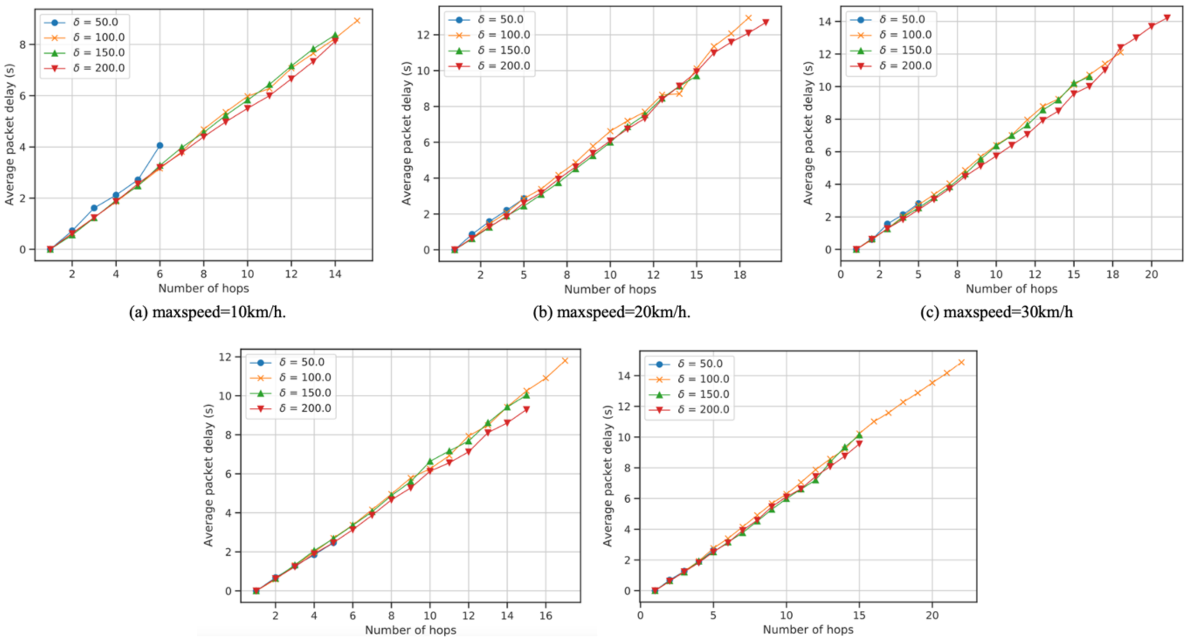
7.2.3 Conclusions

In sum, the speed limit for areas within 100 meters of the accident makes a more positive effect when the traffic density is low, particularly based on the circumstances combined the lower vehicle density of 50 veh/km^2 or 100 veh/km^2 with the higher maximum vehicle speed of 40km/h or 50km/h. For the rest of the case, although it didn't make anything beneficial to improve the delivery of warning messages across the vehicle network, similarly, it also didn't make the situation worse either.

7.3 Different Transmission Ranges

In the previous section, we have reviewed the impact of the maximum vehicle speed and the reduced nominal speed on the performance evaluation of the vehicular network in the urban environment with a sudden car accident happened. In addition to the above two factors, the distance between vehicles can be connected and transmitted is also an important reference factor for the Internet of vehicles. In VANET, we consider the edge of the transmission range as the point, at which the probability of receiving the message is zero. In the default configurations, we set the transmission range as 250m. In the following part, we will reduce the maximum transmission distance to 150m and increase the maximum transmission distance to 500m respectively, so as to find the impact of different transmission distances on the performance of vehicle network.

7.3.1 Transmission Range = 150m



(a) maxspeed=10km/h. (b) maxspeed=20km/h. (c) maxspeed=30km/h (d) maxspeed=40km/h (e) maxspeed=50km/h

Figure 21. Packet Delay for Different Transmission Ranges (=150m)

We still start from the perspective of packet delay to analyze the performance evaluation of the vehicle network, see figure 21. Obviously, we can divide the above curves of four different vehicle densities into two parts, the reduction of average packet delay represented by the vehicle density of 50 veh/km^2 and the increase of the average packet delay for the remaining three vehicle densities represented by 100 veh/km^2, 150 veh/km^2 and 200 veh/km^2. Surprisingly, the reduced transmission distance actually played a good role at the lower vehicle density, effectively reducing the time and number of hops required to transmit accident information when the vehicle density was 50 veh/km^2. However, similarly, the decrease in the transmission distance that the antenna can travel on the vehicle itself leads to the situation of the other three vehicle densities in that the average packet delay and the number of hops dramatically raised. In short, this strategy may be better for the super-low vehicle density like 50 veh/km^2 in the aspect of the packet delay but this needs to be illustrated by the others aspects.

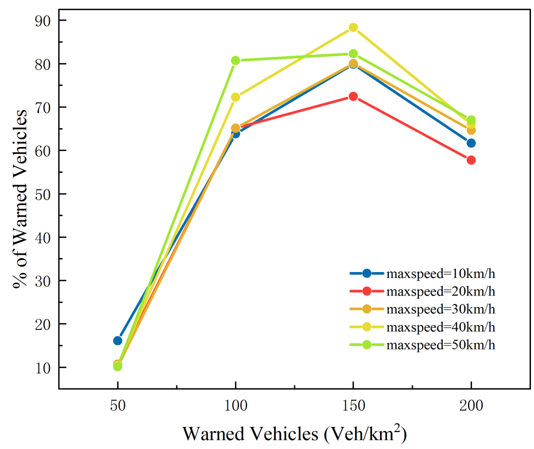


Figure 22. Warned Vehicles for Different Transmission Ranges (=150m)

When we focus on the aspect of % of the warned vehicles, see figure 22, we can clearly find that all the percentages of the warned vehicles are descended especially the % in the vehicle density of 50 veh/km^2, from around 40% dropping to only about 10%. This is the reason why the average packet delay in 50 veh/km^2 is much lower than the others. For the rest of the vehicle density, although the coverage of the information they transmit has narrowed, it is basically stable at 5% to 10%.

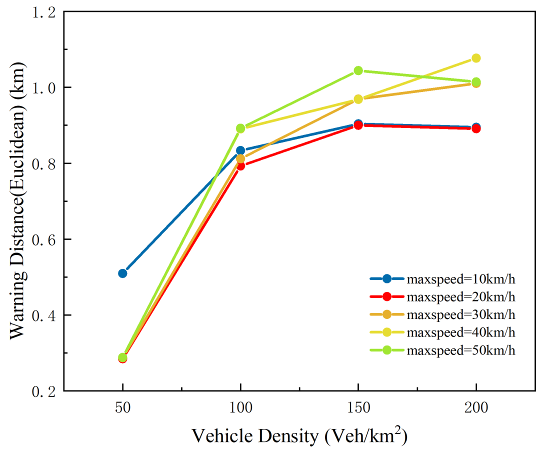


Figure 23. Warning Distance for Different Transmission Ranges (=150m)

For warning distance see figure 23, due to the shorter transmission range, it also showed a downward trend as a whole, just like the previous performance of warned vehicles. The declining trend of warning distance is also more significant at the lower vehicle density of 50 veh/km^2, which also verifies the remarkable reduction in the number of hops mentioned before. In brief, the decrease in transmission range does not help improve the performance of the accident vehicle network.

7.3.2 Transmission Range = 500m

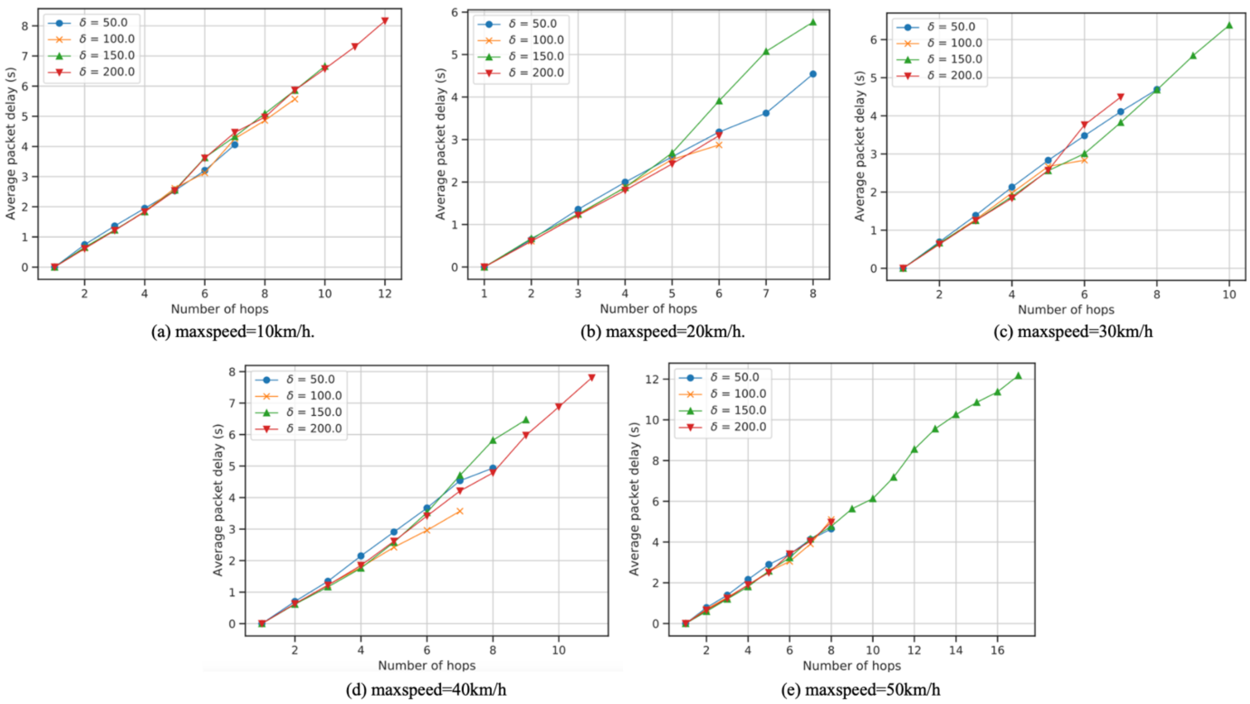


Figure 24. Packet Delay for Different Transmission Ranges (=500m)

In the previous part, we explored the impact of a shorter transmission range (=150m) on the performance of the vehicle network and found that it was not conducive to the dissemination of emergency information within the region of 3.5 km^2, resulting in poor overall performance. In this section, we will explore whether longer transmission distances will have a positive effect on vehicle networks.

First of all, we still start the discussion from the most familiar part of packet delay. On the whole, we can clearly find that the average packet delay and hop number in warning message transmission show an obvious decreasing trend in most curves. However, we still need to note that there are still some special cases in these curves and trends. For example, when the maximum driving speed is 10km/h, the number of hops and the time length of the average packet delay of the curve with a vehicle density of 200 veh/km^2 are added. The same is true for the curves with a vehicle density of 200 veh/km^2 again at the maxspeed of

40km/h and for a vehicle density of 150 veh/km^2 at the maxspeed of 50km/h. From the perspective of the vehicle density with 200 veh/km^2, the amount of increase in average packet delay and the number of hops is relatively small, maintaining around 10%. But this situation ceases to exist when the vehicle density is 150 veh/km^2. Although it only went up when the vehicle's top speed is 50km/h, its value has already doubled. In spite of some peculair cases, in general, we can still see the extraordinary benefits of a longer transmission range to the information transmission performance of the vehicle network.

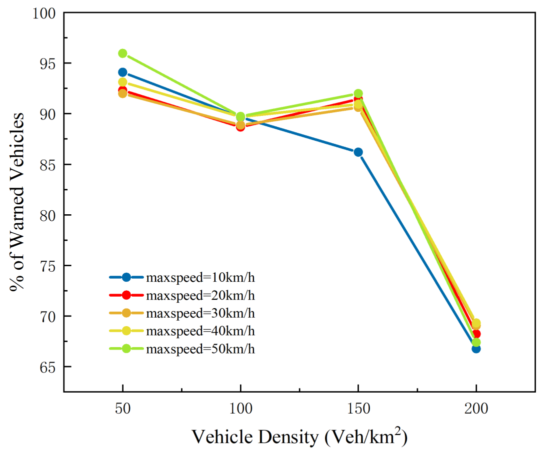


Figure 25. Warned Vehicles for Different Transmission Ranges (=500m)

Secondly, let us put the emphasis on the part of the warned vehicles, see figure 25. Overall, the longer transmission range plays an awfully positive-going role for % of the warned vehicles, with all the data showing an upward trend or maintaining a stable trend. Here, we can clearly find that it has an extra friendly and forward effect on the low vehicle density, especially when the vehicle density is 50 veh/km^2. In the situation of the vehicle density of 50 veh/km^2, the % of warned vehicles raised from around 40% to about 95%, which could be regarded as a huge improvement. The great progress of % of the warned vehicles also manifested when the vehicle densities are 100 veh/km^{2}and 150 veh/km^2, which increase by 5% to 10%. It is a little unfortunate that it doesn't improve the status of the vehicle density at 200 veh/km^2, but the good news is that the data of the % of the warned vehicles basically remain the same.

In the end, from the following figure 26, we can discover that the maximum warning distance between the accident node and the most faraway node is getting longer at all levels of vehicle density and vehicle speed. Of these, the most obvious increase is during the period of the vehicle density of 50 veh/km^2 with the higher velocity of 40km/h and 50km/h, which ascended from 0.6km to 1.2km now. However, the maximum warning distances also increased by at least 0.2km for the rest of the road conditions. In general, this is a very good phenomenon, which effectively expands the transmission range of the warning information so that more vehicles can receive the accident information and change their routes in advance to avoid traffic jams around the accident area.

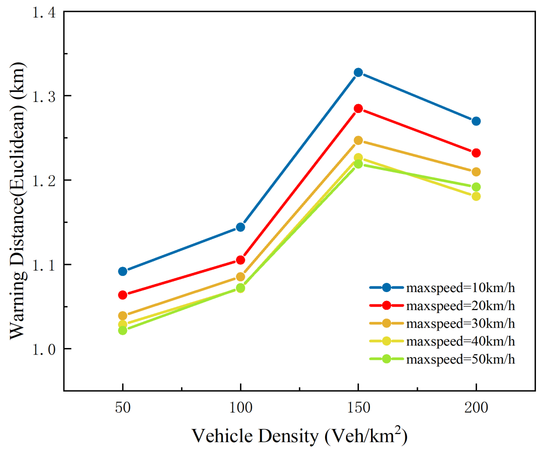


Figure 26. Warning Distance for Different Transmission Ranges (=500m)

7.3.3 Conclusions

From the previous simulation results, we can clearly find that setting an appropriate transmission range of the antenna on the vehicles plays a crucial role in the performance evaluation of the vehicle network. From the above analysis, we can conclude that the longer transmission distance does help the transmission of some emergency information, such as accident information, particularly in cases of low vehicle density. But we also need to be clear that this does not mean that going for very long transmission ranges is necessarily good as when vehicle density is gradually enlarging, the positive impact of the long transmission range is becoming weakened. This could also be illustrated in the previous analysis with the transmission range of 500m, in which with the ascent of vehicle density, the improvement of vehicle network performance flattens out bit by bit. In brief, when we think about setting the range of information that the vehicle antenna can transmit, we should refer to some information about the vehicle network to find a value of the transmission range that maximizes the performance improvement of the vehicle network based on it.

7.4 Improved Message Dissemination Protocol

In the previous several parts, we mainly discussed and studied the relationship between some setting parameters related to the vehicle itself and the performance of the vehicle network. In this section, we will pay more close attention to the aspects related to the message dissemination protocol. As we all know, in the vehicle network, when an accident happened, the vehicle in the accident itself will first deliver a warning message to the surrounding vehicles connected with it. The receiving vehicle will then relay the accident information to the vehicle connected to it again. Alert information spreads out in this way, layer by layer. However, in most of the message dissemination protocols, these vehicles around the accident always transmit information the moment they receive it. But is this really the most efficient way to transfer information, especially in a low vehicle density? Are there alternatives with higher percentages of warned vehicles and low average warned time? In this section, we would probe into this problem.

Here we propose a new scheme when the vehicles around the accident receive the warning message sent by the vehicle approaching the accident, they do not immediately forward it, but wait for a threshold time which means that they will transmit the emergency message after waiting for several seconds. We mainly set threshold times of four different lengths: 5s, 10s, 15s, and 20s. In the following part, we will analyze and compare the effects of these four threshold times on vehicle network performance by focusing on the % of warned vehicles generated after setting them.

7.4.1 Threshold Time = 5s

In the first place, we would analyze the performance of these new rebroadcasting schemes according to the different lengths of the threshold time. The comparison of the manifestation based on these threshold times would be represented in the next section.

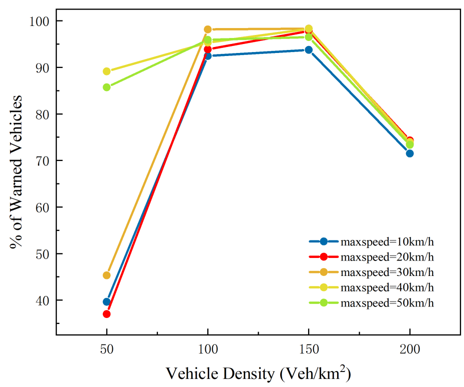


Figure 27. Warned vehicles for Message Dissemination Protocol with Threshold Time (=5s)

For the threshold time equal to 5s, see figure 27, first, on the whole, we can say that the transmission coverage of accident information under different road conditions has been expanded. Compared with the above curve and the previous one when no threshold time was added, the biggest difference is the performance of the high-speed car with a velocity of 40km/h or 50km/h at a free road condition with the vehicle density of 50 veh/km^2. The significant ascent of % of the warned vehicles raised up from around 40% to 90%, which is an amazing growth. Another point worth noting is that when the vehicle density is 100 veh/km^2, the difference between the values of % of the warned vehicles at different vehicle speeds are decreasing. In conclusion, although it only added 5s as the waiting time for the vehicles around the accident to rebroadcast the warning messages, it does enhance the transmission performance of dangerous information in the vehicle network to a certain extent.

7.4.2 Threshold Time = 10s

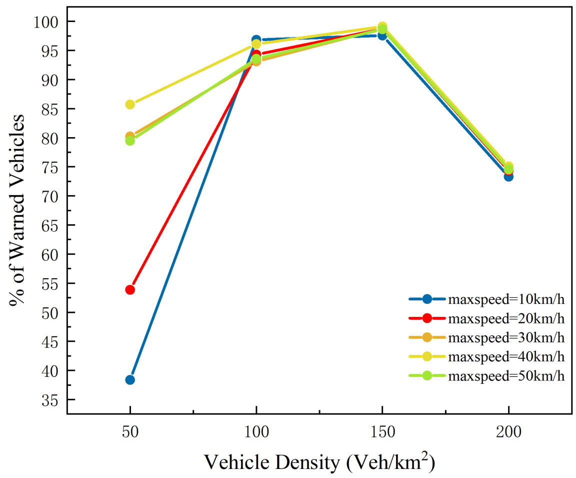


Figure 28. Warned vehicles for Message Dissemination Protocol with Threshold Time (=10s)

According to figure 28 above, we could obviously find that the basic trend of change of % of warned vehicles is the same as before. As a whole, most of the data of the % of the warned vehicles have improved with an progress around 5%. However, in the case of higher vehicle densities like 150 veh/km^2 and 200 veh/km^2, it has less difference among the situations of the various maximum vehicle speeds. While, on the basis of the vehicle density of 50 veh/km^2, the distinction between cars at diverse speeds is huge. The coverage of warned vehicles is still smaller at lower vehicle speeds, between 35% and 55 %, and then following the same rule, the higher the speed, the wider the range. Under normal and high-speed conditions with maximum vehicle speeds of 30km/h, 40km/h, and 50km/h, % of warned vehicles can basically reach more than 80%, which is relatively good for us. By looking at the values of % of warned vehicles, we can say that it does a pretty good job of expanding emergency consultation in the vehicle network and thus enhancing the traffic safety features in VANET.

7.4.3 Threshold Time = 14s

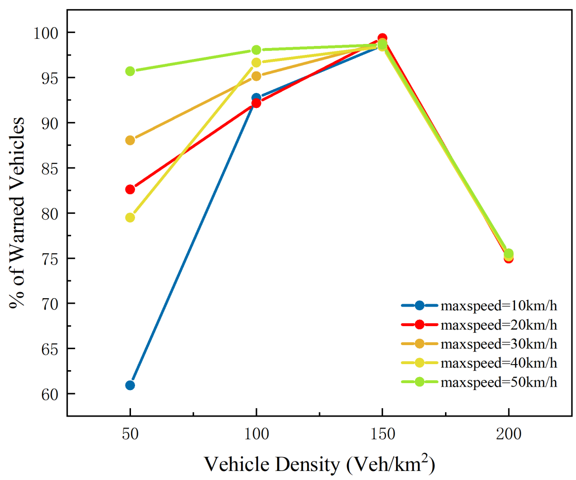


Figure 29. Warned vehicles for Message Dissemination Protocol with Threshold Time (=14s)

On the basis of the above figure 29, first, with the vehicle density of 150 veh/km^2 and 200 veh/km^2, it is clear that their percentage of warned vehicles is almost identical at different speeds. This also shows from the side that the delayed resending time has the same effect on the high vehicle density, regardless of the speed. Secondly, based on the vehicle density of 100 veh/km^2, at the lower velocities of 10km/h and 20km/h, both of % of warned vehicles are surprisingly reaching 90%. For higher speeds, 30km/h, 40km/h, and 50km/h, the range of transmission increases with the rising trend of speed, up to more than 95%. Finally, with regard to vehicle density of 50 veh/km^2, except coverage of 10km/h is about 60%, the rest are basically above 80%. It performs well at 20km/h with nearly 85% of the warned vehicles, exceeding the coverage of 40km/h. The best one is still occupied by the higher velocity of 50km/h with the % of warned vehicles slightly over 95%, but this time the situation of 30km/h is also good with the data close to 90%. In brief, all the data show a good upward trend in this case.

7.4.4 Threshold Time = 20s

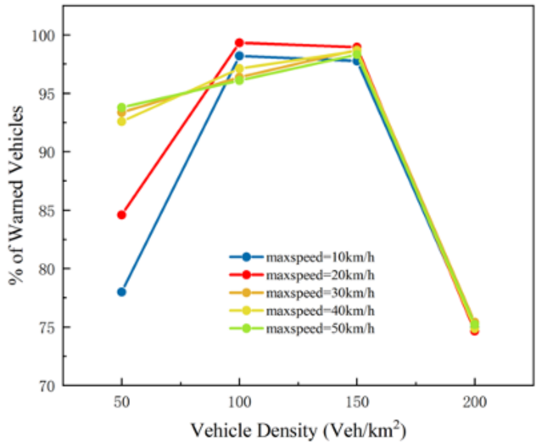


Figure 30. Warned vehicles for Message Dissemination Protocol with Threshold Time (=20s)

As a whole, when the threshold time reaches the 20s, the values of % of the warned vehicles at different speeds become more similar at the same vehicle density, especially at a vehicle density of 100 veh/km^2. However, what is different from the performance with the other threshold time(5s, 10s, and 20s) is that when the vehicle density is 150 veh/km^2, although the value of % of warned vehicles is still very similar, some subtle differences gradually appear. However, in the case of 10s and 14s, their values almost overlap at different speeds. In the case of this threshold time(= 20s), at the lower vehicle density of 50 veh/km^2 and 100 veh/km^2, the values of % of warned vehicles located at the higher speed, 30km/h,40km/h, and 50km/h, can be said to be almost the same, between 90% and 95%. For the lower vehicle speed of 10 km/h and 20km/h, at the situation of the vehicle density of 50 veh/km^2, they have a large gap compared with other velocity conditions due to the value of % of warned vehicles above and below 80% respectively. However, these values are pretty higher data for them. At the vehicle density of 100 veh/km^2, low-speed vehicles perform better than high-speed vehicles, and their coverages are already very close to 100%. Therefore, it can be said that, based on this threshold time equal to 20s, the data of % of warned vehicles presented in the figure above has been increased to a large extent, thus improving road traffic safety and alleviating traffic jams in the accident area.

7.4.5 Comparison of the results for the Different Threshold Time

In this part, we would mainly focus on the performance evaluation of the message dissemination protocol with diverse threshold times based on the same maximum vehicle speed. Let us start with the situation based on the maximum vehicle speed of 10km/h, see figure 31.

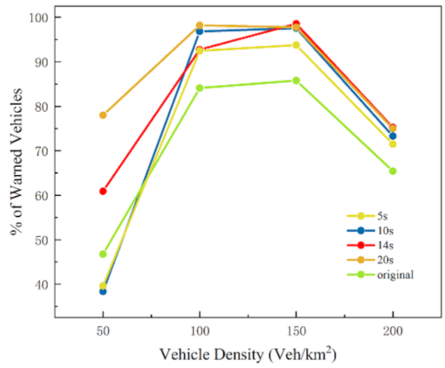


Figure 31. Comparison of Warned Vehicles of Diverse Threshold Times (maxspeed=10km/h)

The first thing to be mentioned here is that since the values of % of warned vehicles change less with vehicle speed or threshold values at the higher vehicle densities of 150 veh/km^2 and 200 veh/km^2, our analysis would more focus on the situations of the vehicle densities of 50 veh/km^2 and 100 veh/km^2. At the vehicle density of 150 veh/km^2, most cases of % of warned vehicles almost reach 100%, excluding the exceptional case of 5s with a value of about 92%, which is also an extremely high % of warned vehicles. While, at the vehicle density of 200 veh/km^2, the value maintains at about 73%.

At a vehicle density of 50 veh/km^2, there have some special points, that is, when the threshold time was set as 5s or 10s, due to the short retransmission time set and the low vehicle speed and density, this mechanism does not have a positive impact on enlarging the coverage of flooding the warning message but reduces it. For the other two threshold times, the longer time we set them, the higher the % of warned vehicles will be, which also means the more powerful function of the traffic safety in VANET.

At a vehicle density of 100 veh/km^2, the coverage of the warning message has improved very well, being above 90%. What is more shocking is what happens at the 10s and 20s thresholds, when their coverage is 95% and close to 100%.

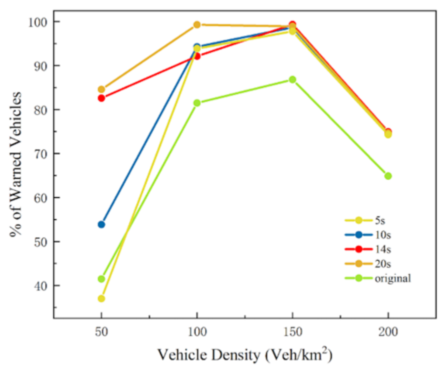


Figure 32. Comparison of Warned Vehicles of Diverse Threshold Times (maxspeed=20km/h)

From above figure 32, we could see that most of the points are located at the upper part of the original curve, except for the case at the vehicle density of 50 veh/km^2 with a threshold time of 5s, which is a little lower than the original point. At a vehicle density of 50 veh/km^2, in spite of the exceptional situations mentioned before, the prevalence of the alert message has broadened. And based on this circumstance, % of warned vehicles rises as the threshold enhances. However, when the threshold time is 10s, the improvement effect is not as good as the other two threshold times, only about 10%. When the threshold time is set as 14s and 20s, both % of warned vehicles improve to more than 80%. Although the value of 20s was slightly larger than the one of 14s, the overall boost was significant.

At a vehicle density of 100 veh/km^2, there are some differences here. The best effect in the propagation of the warning message is when the threshold time is set to 20s, and the value of % of warned vehicles can reach nearly 100%. However, at this time, the improvement effect of 5s, 10s, and 14s is similar, basically making % of warned vehicles could attain about 90%, and even the effect of the threshold time of 5s and 10s is slightly higher than that of 14s.

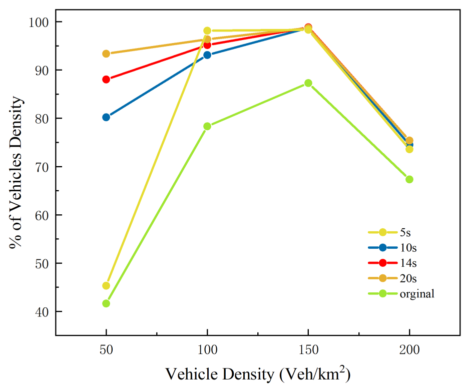


Figure 33. Comparison of Warned Vehicles of Diverse Threshold Times (maxspeed=30km/h)

In the case of a maximum vehicle speed of 30 km/h, see figure 33, we could clearly find that % of warned vehicles grows with the rise of threshold time, and the gap between these values of % of warned vehicles decreases with the ascent of vehicle density. When the vehicle density comes up to 150 veh/km^2 and 200 veh/km^2, the values for different threshold times are completely consistent, which means that when the vehicle density is in a high state, it is ineffective to increase the waiting time for the vehicles receiving the accident information to broadcast the information to the surrounding vehicles. At a vehicle density of 100 veh/km^2, their values are almost identical, with a difference of only 1% to 2%. Nevertheless, at a vehicle density of 50 veh/km^2, the gap between the three has widened, particularly the difference between the point of 5s and other points. This also means that using the threshold time of 5s is less effective in this case. Generally, these threshold times have greatly improved the performance of vehicle network security information transmission based on the vehicle speed of 30km/h.

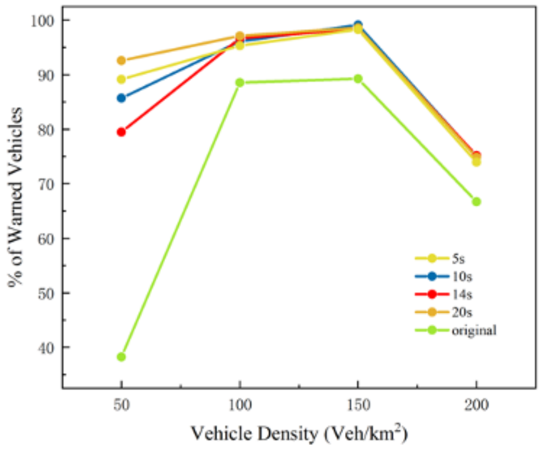


Figure 34. Comparison of Warned Vehicles of Diverse Threshold Times (maxspeed=40km/h)

Now, let us look at the situation on the basis of the vehicle speed of 40km/h, see figure 34. On the whole, the trend of % of warned vehicles is basically the same as when maxspeed=30km/h. however, there still exists two evident distinctions. One is that when the vehicle density is at 100 veh/km^2, the value of % of achieving the alert accident information overlaps under different threshold times. Another is the situation of the vehicle density of 50 veh/km^2 accompanied by the threshold time of 5s. It performs much better than before that the % of warned vehicles has gone up to about 90%.

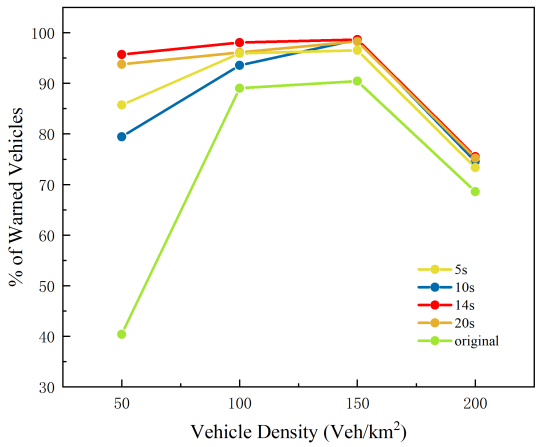


Figure 35. Comparison of Warned Vehicles of Diverse Threshold Times (maxspeed=50km/h)

Overall, under the circumstance of maxspeed=50km/h, the values of % of warned vehicles continue to grow as the threshold time is set, apart from the case of 5s. However, at this time, the variation tendency of the values of % of warned vehicles by 14s and 20s is similar, but all the values of 14s even are slightly higher than that of 20s. Another point of note is that the threshold time of 5s performed well in this case. It has almost the same changing trend and values as the best situation of 14s and 20s with vehicle density of 100 veh/km^2, 150 veh/km^2 and 200 veh/km^2. And it also attains about 85% of the warned vehicles in the case of 50 veh/km^2.

7.4.6 The relationship between the Threshold Time and Vehicle Speed/Density

Firstly, we could find the relationship between the threshold delay time with the vehicle density, see the following figure 36. As a whole, it presents a trend of increasing first and then decreasing. And we could find that the delay would reach the peak value when the vehicle density is 100 veh/km^2. In general, this is also in line with the trend of our information dissemination: when the density of vehicles is higher, we don't need to wait a long time to transmit accident information to many surrounding vehicles.

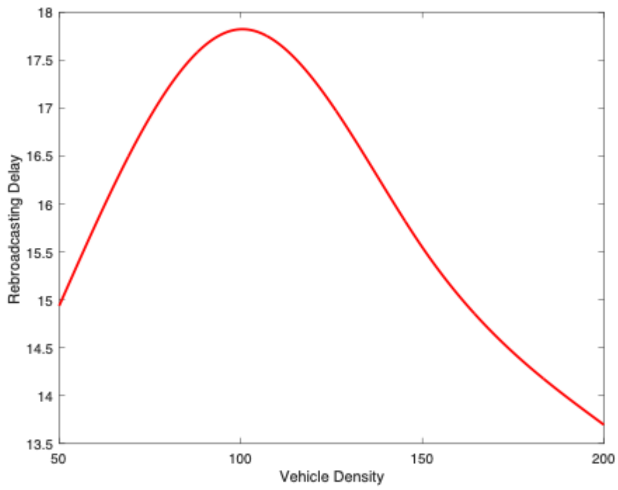


Figure 36. The Relationship between Threshold Time and Vehicle Density

Secondly, let us take a look at the function of rebroadcasting delay and vehicle speed, see figure 37. We can see that it shows an overall decreasing trend. When the speed keeps increasing, the threshold time of delay keeps decreasing, especially when the speed is greater than 30km/h, the decrease is more obvious. This is also consistent with our understanding that when a vehicle travels faster, it will also travel a longer distance in the same time, thus extending the transmission range of accident information.

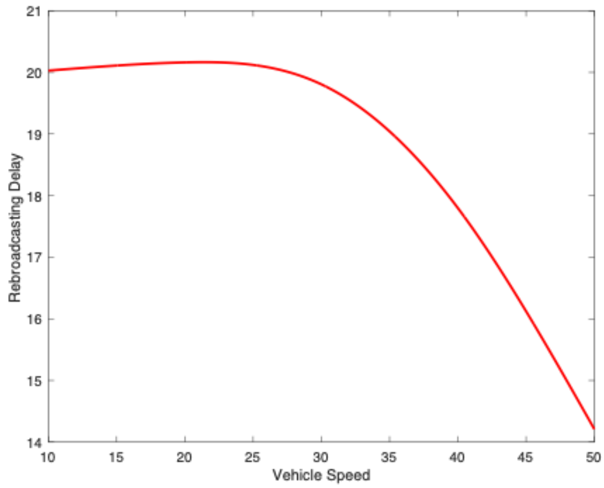


Figure 37. The Relationship between Threshold Time and Vehicle Speed

7.4.7 Conclusions

In conclusion, according to the previous discussions, we could obviously find that adding an intelligent rebroadcasting scheme with a threshold time for the vehicle that has received the accident messages in the first time from the accident car would greatly improve the coverage of warning message transmission. However, we need to note that when we set a threshold time to delay re-sending them to surrounding vehicles, we also need to consider the vehicle density and speed of the area to find and define a more appropriate time. In the following part, we would try to find the relationship between the threshold time and traffic conditions.

Chapter 8 Conclusions and Future Works

In this chapter, we will summarize the work we have done in this final master thesis and give an outlook on how to carry out further research on this topic.

8.1 Conclusions

At present, more and more crowded roads and car accidents, and other problems seriously affect people's travel safety. How to improve the traffic conditions and aggrandize the capacity of the transportation networks, which requires the comprehensive utilization of modern information and communication technology and other means to enhance the efficiency and convenience of communication. As an important part of the intelligent transportation system (ITS), the vehicular ad-hoc network (VANET) has been paid much attention by academia and the automotive industry. The vehicular network is a kind of emerging network technology belonging to the category of the ubiquitous network that also has an incremental influence on contemporary traffic safety with the progress of science and technology. This paper mainly focuses on the performance evaluation of the vehicular network with a sudden accident that happened in an urban area of 3.5 km^2 in the Eixample district in Barcelona.

First of all, we start the paper with the content introduction of the smart city and then go deeper and deeper step by step, describing the matters related to ITS and VANET, which are regarded as the important technology of urban transportation development.

Secondly, we give a brief introduction to the relevant software and tools used in the simulation, and then we elaborate on a series of experiment-related contents such as simulation scenarios and parameters.

Finally, we analyzed and discussed the experimental results from three aspects: packet delay, % of warned vehicles, and warning distance. These aspects reflect the accuracy, delay, and consumption of the scheme. In the simulation process, we explored the impact of the basic velocity configuration, the road speed limit around accidents, the information transmission ranges, and the broadcasting delay of the warning messages on the vehicle network. Through deep analysis, we obtained the following results:

- According to the comprehensive analysis of various aspects of vehicle network performance under different vehicle speeds, we can see that vehicle speed has a great impact on the performance of the vehicle network. But we can't conclude whether high speed or low speed would be better. As the most basic variable in vehicle networks, we need to dialectically view the impact of speed on the basis of different road conditions.

- By reducing the road speed limit within 100m area around the accident, we can increase the coverage of emergency information transmission and reduce the congestion in the accident area, especially in the case of low vehicle density and fast vehicle speed, which does great help.
- For the aspect of transmission range, setting a longer transmission distance does enhance the transmission coverage within the vehicle network, but it is worth noting that it is more effective at low vehicle density and low vehicle speed. When the accident situation occurs in an urban area with high vehicle density, although it has some improvement effect, it is not much.
- By adding a delayed forwarding time to the surrounding vehicles around the accident, the propagation range of warning messages is greatly improved, thus improving traffic safety. This measure is particularly obvious for the situation of the low vehicle density, in some threshold time, % of warned vehicles can even increase to more than 90%. Compared to the original one before, the data doubled. This is also very friendly for other high vehicle density situations with almost all the coverages over 95%.

8.2 Future Works

In this thesis, the performance of the vehicular network is fully analyzed and studied, and some preliminary results are obtained. Due to time limitations, there are still some shortcomings in the paper, which need to be studied further:

- In the simulation experiment of this thesis, we only used one vehicle type, the normal passenger car. However, in real life, there are many kinds of cars on the road. We could add trucks, emergency vehicles, even some bicycles, and pedestrians to simulate a more realistic urban traffic environment in future works.
- Urban traffic network is huge and complex. With the popularization of machine learning and artificial intelligence algorithm, it can be used to further analyze existing traffic data and extract more valuable information, so as to have a better evaluation system for vehicle networks in urban environments.

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