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Presented by: Ms. AOUINANE Khadidja

Comparative Analysis of Vehicle-to-Vehicle Communication Protocols for Enhanced Road Safety

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Defended on 15, June 2026 in front of the jury composed of:

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List of Abbreviations

ADAS	Advanced Driver Assistance Systems
AI	Artificial Intelligence
AODV	Ad hoc On-Demand Distance Vector
ATIS	Advanced Traveler Information Systems
ATMS	Advanced Traffic Management Systems
AU	Application Unit
BSM	Basic Safety Message
C-V2X	Cellular Vehicle-to-Everything
CACS	Comprehensive Automobile Control System
DARPA	Defense Advanced Research Projects Agency
DENM	Decentralized Environmental Notification Message
DSDV	Destination-Sequenced Distance-Vector
DSRC	Dedicated Short-Range Communications
ERTICO	ITS Europe
ETC	Electronic Toll Collection.
EVs	Electric Vehicles.
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HMI	Human–Machine Interface .
IoT	Internet of Things.
ITS	Intelligent Transportation Systems.
LTE	Long-Term Evolution
LSTEA	Intermodal Surface Transportation Efficiency Act
IoT	Internet of Things
M2M	Machine-to-Machine
MPRs	Multi-Point Relays
NHTSA	National Highway Traffic Safety Administration
NS-3	Network Simulator 3
OBU	On-Board Unit
OLSR	Optimized Link State Routing
PDR	Packet Delivery Ratio.
RFID	Radio-Frequency Identification
RREP	Route Reply.
RERR	Route Error

RREQ	Route Request
RSU	Road Side Unit.
RTPI	Real-Time Passenger
SEA	Society of Automotive Engineers
SUMO	Simulation of Urban MObility
TRACI	Traffic Control Interface
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VANET	Vehicular Ad hoc Network

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Abstract

The continuous growth of road traffic and the increase in accident rates have made the development of efficient vehicular communication systems a critical research priority.

This work investigates the performance of Vehicle-to-Vehicle (V2V) routing protocols within Vehicular Ad Hoc Networks (VANETs), simulated over the real urban road network of Saida City, Algeria, extracted from OpenStreetMap.Using an integrated SUMO–NS-3–TraCI simulation environment with IEEE 802.11p wireless standard, three routing protocols are evaluated under two vehicle density scenarios (50 and 100 vehicles): the reactive AODV (Ad hoc On-Demand Distance Vector), the proactive OLSR (Optimized Link State Routing), and the proactive DSDV (Destination-Sequenced Distance-Vector). Performance is measured in terms of Packet Delivery Ratio (PDR), end-to-end delay, jitter, and throughput.

In a second part, two V2V safety message types are evaluated: Basic Safety Messages (BSM) for continuous periodic monitoring, and Decentralized Environmental Notification Messages (DENM) for event-driven driver fatigue warnings.

Keywords: VANET , V2V Communication , AODV , OLSR , DSDV , BSM , DENM , NS-3 , SUMO , IEEE 802.11p , Intelligent Transportation Systems , Urban Network ,Saida City.

Résumé

La croissance continue du trafic routier et l'augmentation du nombre d'accidents ont fait du développement de systèmes de communication véhiculaire efficaces une priorité de recherche essentielle.

Ce travail étudie les performances des protocoles de routage véhicule-à-véhicule (V2V) au sein des réseaux ad hoc véhiculaires (VANET), simulés sur le réseau routier urbain réel de la ville de Saïda, en Algérie, extrait d'OpenStreetMap. À l'aide d'un environnement de simulation intégré SUMO–NS-3–TraCI avec la norme sans fil IEEE 802.11p, trois protocoles de routage sont évalués sous deux scénarios de densité de véhicules (50 et 100 véhicules) : le protocole réactif AODV (Ad hoc On-Demand Distance Vector), le protocole proactif OLSR (Optimized Link State Routing) et le protocole proactif DSDV (Destination-Sequenced Distance Vector). Les performances sont mesurées en termes de taux de livraison des paquets (PDR), de délai de bout en bout, de gigue et de débit.

Dans une seconde partie, deux types de messages de sécurité V2V sont évalués : les messages de sécurité de base (BSM) pour la surveillance périodique continue et les messages de notification environnementale décentralisée (DENM) pour les alertes de fatigue du conducteur déclenchées par des événements.

Mots-clés : VANET , Communication V2V , AODV , OLSR , DSDV , BSM , DENM , NS-3 , SUMO , Systèmes de transport intelligents , Réseau urbain, Ville de Saïda.

ملخص

أدّى النمو المستمر في حركة المرور عبر الطرقات وتزايد معدلات الحوادث إلى الحاجة لتطوير أنظمة اتصال بين المركبات وجعلها من الأولويات البحثية الأساسية. تتناول هذه المذكرة دراسة وتقييم أداء بروتوكولات التوجيه في شبكات المركبات المتنقلة اللاسلكية (VANET) ضمن نموذج اتصال مركبة-بمركبة (V2V)، وذلك باستخدام شبكة الطرق الحضرية الحقيقية لمدينة سعيدة في الجزائر، المستخرجة من خريطة OpenStreetMap.

تمّ بناء بيئة محاكاة متكاملة تجمع بين برنامجَي SUMO وNS-3 عبر واجهة TraCI، مع استخدام شبكة الاتصال اللاسلكي IEEE 802.11p. تم خلال هذا العمل تقييم ثلاثة بروتوكولات توجيه في سيناريوهين للكثافة (50 و100 مركبة) تشمل: البروتوكول التفاعلي AODV، والبروتوكولان الاستباقيان OLSR وDSDV. تشمل مقاييس الأداء: معدل تسليم الحزم (PDR)، التأخير من طرف إلى طرف، الاهتزاز الزمني (Jitter)، وسرعة التدفق.

في الجزء الثاني من العمل ، تمّ تقييم نوعين من رسائل السلامة: رسائل السلامة الأساسية (BSM) المخصصة للمراقبة الدورية المستمرة، ورسائل الإشعار البيئي اللامركزي (DENM) المخصصة للتحذير من تعب السائق مثلا وفق آلية إرسال يتم تشغيلها بناءا على حصول الحدث.

الكلمات المفتاحية:

الشبكة المتنقلة الخاصة بالمركبات, اتصال مركبة بمركبة, أنظمة النقل الذكية, بروتوكل التوجيه, رسائل السلامة, شبكة النقل الحضرية, مدينة سعيدة.

General Introduction

Context

Road transportation plays a fundamental role in modern society by supporting mobility, economic development, and daily activities. However, the rapid growth of urban populations and the increasing number of vehicles have created significant challenges for road networks. Traffic congestion, frequent accidents, unsafe driving behaviors, close following distances, and driver fatigue have become major concerns affecting both road safety and transportation efficiency.

Imagine a transportation environment where vehicles can communicate with each other in real time by exchanging information about their position, speed, direction, and road conditions. Such communication would allow vehicles to anticipate hazards, warn drivers earlier, and react faster to dangerous situations. This concept forms the basis of intelligent transportation and connected vehicle technologies designed to create safer and more efficient roads.

Among these technologies, Vehicular Ad Hoc Networks (VANETs) and Vehicle-to-Vehicle (V2V) communication provide a promising solution by enabling vehicles to exchange information continuously and support safer driving decisions.

Problem Statement

Despite advances in transportation systems, road traffic continues to face several critical issues. Traffic congestion reduces mobility and increases travel time, while road accidents remain one of the leading causes of injuries and economic losses. Many of these problems are associated with traffic indiscipline, insufficient safety distances between vehicles, delayed driver reactions, and fatigue.

In connected vehicular environments, communication performance becomes another important challenge. Delivering information quickly and reliably between vehicles is essential to ensure that safety warnings reach drivers on time. Therefore, selecting efficient routing protocols and evaluating safety communication mechanisms are necessary to guarantee reliable vehicle communication under different traffic conditions.

Objectives of the Work

The main objective of this work is to study how intelligent vehicular communication technologies can contribute to improving road safety and traffic efficiency.More specifically, this work aims to:

Study the role of Vehicular Ad Hoc Networks (VANETs) and Vehicle-to-Vehicle (V2V) communication in traffic monitoring.

Evaluate and compare the performance of routing protocols (AODV, OLSR, and DSDV) under different vehicle densities.

Analyze network performance using metrics such as Packet Delivery Ratio (PDR), throughput, delay, and jitter.

Investigate the effectiveness of safety messages in reducing risks and improving driver awareness.

Compare Basic Safety Messages (BSM) and Decentralized Environmental Notification Messages (DENM) to determine their impact on communication reliability and road safety.

Demonstrate how connected vehicle technologies can contribute to reducing congestion and preventing accidents.

To achieve these objectives, traffic scenarios based on Saida City were simulated using SUMO and NS-3.

Organization of the dissertation

This work is organized as follows:

Chapter I: Presents the concept of Intelligent Transportation Systems (ITS), traffic monitoring, and the main road traffic challenges including congestion and accidents.

Chapter II: Introduces connected vehicle technologies, VANET architecture, Vehicle-to-Vehicle (V2V) communication, and their applications in road safety.

Chapter III: Studies and compares the routing protocols AODV, OLSR, and DSDV, presenting their mechanisms, advantages, and limitations. And compares the safety messages BSM and DENM .

Chapter IV: Describes the simulation environment and presents the obtained results and performance evaluation under scenarios with 50 and 100 vehicles.

Part II: Focuses on the analysis and comparison of BSM and DENM safety messages to evaluate continuous communication and event-driven alert mechanisms for improving traffic safety.

Through the combination of traffic monitoring, routing protocol evaluation, and safety message analysis, this work demonstrates how intelligent vehicular communication can enhance road safety, reduce congestion, and support the development of smarter transportation systems.

Chapter I

Overview of Intelligent Transport Systems

I.1 Introduction

With the conception of smart city transmuting cities into digital societies, making the life of its citizens easy in every facet, Intelligent Transport System becomes the indispensable component among all. In any city mobility is a key concern; be it going to school, college and office or for any other purpose citizens use transport system to travel within the city. Leveraging citizens with an Intelligent Transport System can save their time and make the city even smarter. Intelligent Transport System (ITS) aims to achieve traffic efficiency by minimizing traffic problems (Figure 1.1). It enriches users with prior information about traffic, local convenience real-time running information, seat availability etc. which reduces travel time of commuters as well as enhances their safety and comfort.

In order to enhance safety, we need to start and improve the Vehicle to Vehicle “V2V” and Vehicle-To-Infrastructure “V2I” technologies. Intelligent Transportation Systems (ITS) is a diverse and expanding subject, with some of its constituents converging or overlapping. For example, transport and travel information might be viewed under a Smart Cities agenda, and similarly “connected cars” are an articulation of Machine-to-Machine(M2M) Communications and the Internet of Things (IOT), V2V communications is usually developed as a part of intelligent transportation systems (ITS).

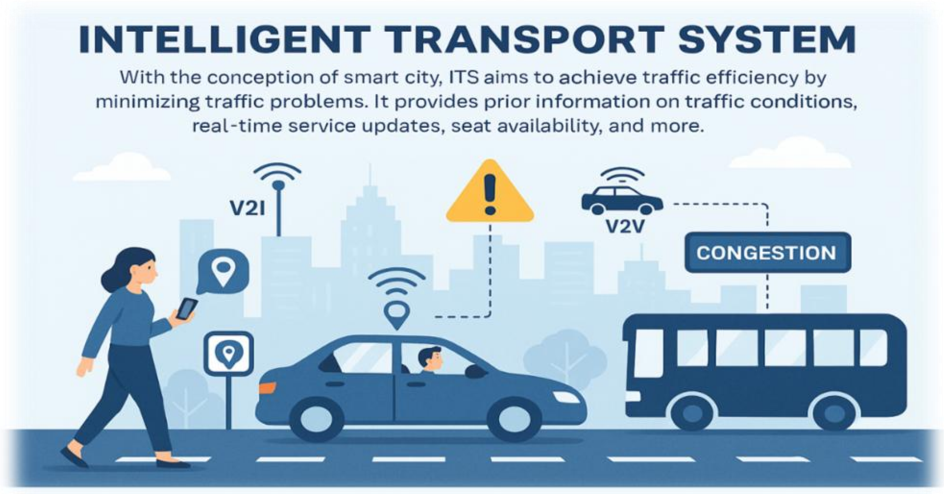


Figure 1.1 Intelligent transport systems

I.2 Definition of ITS

The phrase “*intelligent transportation system*,” and especially word “system” within this phrase, means that there is a group of agents that have mutual objective and that they execute tasks according to specific regulations. The word “*transportation*” is related to the fact that these agents collaborate when moving passengers, or transporting cargo. Finally, word “*intelligent*” assumes that agents have the ability to use available information, to learn, and adapt to new situations.

Intelligent transportation systems (ITS) represent a group of technologies that can improve transportation system management and public transit, as well as individual decisions surrounding many aspects of travel. ITS technologies include state-of-the art wireless, electronic, and automated technologies with a goal to improve surface transportation safety, efficiency, and convenience.

I.3 History

a. Early Origins (Pre-1980s)

The conceptual roots of Intelligent Transportation Systems (ITS) can be traced back to General Motors' *Futurama* exhibit at the 1939 New York World's Fair, which envisioned automated highways and electronically controlled vehicles. Early implementations included electric traffic lights (1928), computer-controlled signals in the 1960s, and improved road signage to optimize traffic flow. With the post-WWII(world war II) economic boom and suburban expansion, traffic volumes surged, prompting governments to invest in large-scale interstate networks through the Federal-Aid Highway Act of 1956 and foundational traffic safety systems. Pre-1980s ITS research emphasized in-vehicle navigation and route guidance, though technology remained opportunistic with limited manufacturer involvement.

b. Development Phases (1980s–1990s)

The 1980s marked the formal start of ITS research programs worldwide. In the U.S., initiatives included the Automated Traffic Surveillance and Control System**,** Operation Greenlight, and DARPA's early autonomous vehicle studies. Japan developed the Comprehensive Automobile Control System (CACS), while Europe launched projects such as ARI (1974, Germany) to reduce highway congestion. The 1990s represented a second phase of ITS development, supported by legislation like ISTEA (1991) in the U.S. Key inventions included electronic toll collection (E-ZPass)**,** traffic management centers, and advanced road safety systems. Europe's PROMETHEUS and DRIVE programs promoted vehicle safety, driver assistance, and V2V/V2I communication. The creation of ERTICO (1991) further institutionalized ITS across Europe.

c. Modern ITS (2000s to 2010s)

The early 2000s saw ITS expand into driver assistance systems**,** advanced traveller information services such as real-time bus stop information**,** integrated corridor management**,** and automated vehicle testing. The widespread adoption of GPS navigation systems in vehicles significantly improved mobility, while connected vehicle technologies (V2V/V2I) enabled real-time data exchange between vehicles and infrastructure. The 2010s placed greater emphasis on integrating ITS into smart cities, with the emergence of autonomous vehicle prototypes such as Google's self-driving car, alongside the use of advanced analytics and sensor networks to reduce congestion and provide predictive information to road users**.** Congestion pricing schemes supported by electronic toll collection (ETC) were also deployed, enhancing efficiency, safety, and environmental outcomes.

d. Contemporary ITS (2010 – Present)

Since 2010, Intelligent Transportation Systems (ITS) have evolved rapidly, driven by the emergence of smart cities, autonomous vehicles, and multimodal transport coordination. This period has witnessed major breakthroughs such as autonomous vehicle prototypes like Google's self-driving car and Tesla's Autopilot, alongside the development of Advanced Driver Assistance Systems (ADAS) including lane-keeping, adaptive cruise control, and automatic emergency braking. Connected vehicles utilizing V2V and V2I communication have enabled cooperative driving, while big data analytics and artificial intelligence have enhanced predictive traffic management and accident prevention. At the same time, ride-sharing platforms such as (Uber, Lyft, and DiDi) have reshaped urban mobility, and the rise of electric vehicles (EVs) with smart charging infrastructure has supported sustainable transport. Drone technology has also been introduced for traffic monitoring and logistics. Collectively, these innovations have improved safety, reduced congestion, lowered emissions, and transformed transportation into a central pillar of smart, sustainable urban development [1]

I.4 Types of Intelligent Transportation Systems

1.4.1 Advanced Traffic Management Systems (ATMS) [2]

These systems use sensors, cameras, and control centers to monitor and manage traffic flow in real time. They optimize traffic signals, detect incidents, and manage congestion to improve road efficiency and safety.

Example: Singapore's Electronic Road Pricing (ERP) system uses adaptive traffic lights that adjust based on current traffic conditions.

1.4.2 Advanced Traveller Information Systems (ATIS)

These systems provide travellers with real-time information about traffic conditions, travel times, incidents, and alternative routes through apps, websites, or roadside signs.

Example: Google Maps and Waze offer dynamic routing based on live traffic data, while highway dynamic message signs update drivers on congestion or accidents.

1.4.3 Vehicle-to-Everything (V2X) Communication

V2X enables vehicles to communicate with other vehicles (V2V), infrastructure (V2I), pedestrians (V2P), and networks (V2N). This communication helps prevent collisions, manage traffic flow, and enhance safety.

Example: Tesla's Autopilot system uses V2I communication to interact with traffic signals and road infrastructure for better navigation.

1.4.4 Electronic Toll Collection (ETC)

ETC systems automate toll payments using technologies like RFID. Vehicles passing through toll booths are detected and charged automatically, reducing the need for stopping and thus decreasing congestion.

Example: E-ZPass in the US and FASTag in India facilitate quick toll payments and smoother traffic movement at toll plazas.

1.4.5 Public Transport Optimization

ITS tools optimize the operation of buses, trains, and other public transit by using AI and real-time data to improve scheduling, reduce waiting times, and provide accurate arrival information.

Example: London’s Real-Time Passenger Information (RTPI) system informs passengers about bus and train schedules, delays, and arrivals.

1.4.6 AI-Powered Traffic Prediction

Machine learning algorithms analyze historical and real-time traffic data to predict congestion, accidents, or delays. This enables proactive traffic management and dynamic rerouting.

Example: NVIDIA Metropolis leverages AI for city-wide traffic analysis and forecasting to help urban planners and traffic controllers.

1.4.7 Autonomous Vehicle Integration

Self-driving vehicles are integrated with ITS to navigate safely and efficiently by communicating with surrounding infrastructure and other vehicles.

Example: Waymo’s autonomous taxis in Phoenix connect with traffic systems to optimize routes and ensure passenger safety.

I.5 Role of ITS in Enhancing Road Safety

Intelligent Transportation Systems (ITS) integrate advanced technologies, such as sensors, cameras, and data analytics, to improve the efficiency and safety of transportation networks. ITS plays a crucial role in enhancing road safety by providing real-time monitoring and management of road conditions, traffic flow, and incidents. By leveraging ITS, transportation agencies can respond quickly to incidents, reduce congestion, and prevent accidents. For instance, ITS can be used to detect incidents, such as accidents or road closures, and provide real-time information to drivers through dynamic message signs or mobile apps. [3]

I.6 Challenge and Limitation of ITS

ITS is a powerful tool for safer, smarter cities, but its success depends on overcoming challenges in cost, privacy, and citizen cooperation, more precisely:

- Intelligent Transportation Systems require advanced equipment such as cameras, sensors, communication networks, and control centers.
- These systems demand large financial investments, in addition to ongoing operating and maintenance costs. In developing countries, funding is a major obstacle to widespread implementation.
- ITS relies on real-time data collection from vehicles, sensors, and mobile devices. This raises privacy concerns, as data can be used to track individuals.
- There are also cybersecurity risks such as hacking, system disruption, or data breaches.
- The effectiveness of ITS depends on citizen behavior and compliance, such as following dynamic signs or using mobile applications.

- Transport habits vary across cities For example, both Amsterdam and Chicago are mature cities, but they have very different characteristics that will affect transportation ambitions in them: in Amsterdam, more than 50% of daily trips are made walking or by bicycle, while in Chicago, about 90% of trips are made using private cars.
- Low public awareness or lack of trust in technology can reduce adoption and effectiveness [4]. These limitations are resumed in the following table.

Table 1.1 Limitation of ITS

Limitation	Impact
High cost of deployment	Restricts adoption in low-income regions
Complex integration	Slows rollout across jurisdiction
Data privacy concerns	Reduces public trust
Cybersecurity risks	Threatens system reliability
Technology gaps	Older infrastructure may not support ITS

I.7 Motivation for V2V communication

Vehicle-to-Vehicle (V2V) communication is motivated by the need to improve road safety, reduce traffic congestion, and lower operational costs. By enabling vehicles to exchange real-time information directly, V2V enhances situational awareness, supports autonomous driving, and strengthens Intelligent Transportation Systems (ITS). Its potential is especially significant in developing countries where infrastructure is limited, making V2V a practical and cost-effective solution for smarter mobility [5]:

- Direct communication between vehicles helps prevent collisions by sharing speed, position, and direction data, provides drivers with a 360-degree awareness of road conditions, including blind spots and sudden braking.
- Enables instant alerts about accidents or hazardous situations, improving reaction times and reducing risks.
- Helps reduce congestion by coordinating vehicle movements more smoothly.
- Supports dynamic rerouting to avoid traffic jams.
- Supporting Autonomous Driving : example, automatic braking (the car stops when it detects a collision risk).

Figure 1.2 Vehicle to vehicle communication

1.8 Conclusion

Intelligent Transportation Systems (ITS) have reshaped urban mobility by harnessing sensors, cameras, and real-time data to ease traffic, reduce congestion, improve safety, and cut environmental impact. ITS makes traffic management more effective: operators can adjust signals, handle incidents, and redirect flows based on live data, which shortens travel times and creates smoother journeys. On the environmental side, ITS helps lower emissions by reducing idling, promoting walking and cycling.

Chapter II

Connected Vehicles Technology and Road Safety

II.1 Introduction

The rapid evolution of wireless communication technologies has paved the way for Vehicular Ad Hoc Networks (*VANETs*)—a transformative foundation for modern Intelligent Transportation Systems **(***ITSs***)**. VANETs enable seamless interaction between vehicles and infrastructure (*V2I)* and among vehicles themselves (*V2V*), revolutionizing how mobility is managed and experienced. These networks not only enhance road safety and traffic control but also unlock a new area of infotainment and real-time data services.

One important development in transportation is V2V communication, where vehicles can share information with each other. By exchanging data on speed, location, and road conditions, V2V systems help prevent accidents, reduce congestion, and optimize fuel consumption. This vision of interconnected mobility—once considered futuristic—is now rapidly becoming a reality, driven by the demand for safer, smarter, and more sustainable transportation solutions.

II.2 VANET Definition

Vehicular Ad Hoc Network (VANET) is a type of network that enables communication between nearby vehicles and roadside infrastructure. This network is self-organizing, as vehicles can act as wireless routers to create a communication network within a range of 100 to 300 meters in urban areas, and up to 1000 meters on highways [6]

In urban areas, the VANET communication range is shorter (100–300 m) because buildings, vehicles, and obstacles block and weaken wireless signals. On highways, the range can reach up to 1000 m because the roads are open with fewer obstacles, allowing signals to travel farther.

II.3 Communication Types in VANET

Communication types in VANET are grouped into 4 classes which are briefed as:

a) In vehicle communication: It detects the inner system data or performance of the vehicle and determines factors such as driver exhaustion or drowsiness etc. Determination of such factors and their extent is crucial for public safety as well as driver safety.
b) Vehicle to Vehicle communication (V2V)
c) Vehicle-to-road infrastructure (V2I) communication
d) Vehicle-to-Pedestrian (V2P) [7]

Figure 2.1 illustrates VANET/V2X communication, including vehicle-to-vehicle (V2V), vehicle-to-pedestrian (V2P), and vehicle-to-infrastructure (V2I). These connections enable vehicles to exchange real-time information with nearby vehicles, pedestrians, and roadside infrastructure to improve traffic awareness, road safety, and the detection of traffic events.

Figure 2.1 VANET/V2X communication

II.4 VANET System Architecture

A VANET framework consists of several components that operate across three main domains. The key elements are: the On-Board Unit (OBU) inside the vehicle, the Application Unit (AU) for software applications, and the Roadside Unit (RSU) as part of the fixed infrastructure [8].

a) On-Board Unit (OBU)

OBUs are vehicle-based devices that enable communication between RSUs and other vehicles. They include a CPU, user interface or software, communication modules, and wireless connectivity. Their functions cover routing, security, and IP mobility.

b) Application Unit (AU)

An AU is a device within the vehicle that runs applications using the OBU's processing power. It can be connected wirelessly, through a wired link, or embedded directly in the OBU. While closely related, AU and OBU have distinct logical roles.

c) Roadside Unit (RSU)

RSUs are fixed infrastructures placed along roads. They use IEEE 802.11p for short-range wireless communication and extend network coverage by linking vehicles to the fixed network.

II.5 VANET Domains

- **In-Vehicle Domain:** Handles communication between vehicles, including V2V (vehicle-to-vehicle) and V2I (vehicle-to-infrastructure). Each vehicle acts as a mobile ad hoc node, forming part of the VANET.

- **Infrastructure Domain:** Stores and manages messages exchanged between vehicles, RSUs, and wireless hotspots, supporting both safety-related and non-safety applications. [9]

II.6 Wireless Access Technologies

VANET relies on advanced wireless technologies to optimize traffic and improve safety. Common standards include :

- **WiMAX IEEE 802.16** for wide-area communication.
- **IEEE 802.11p** for short-range communication, widely used in vehicular environments (WAVE) [10].

The ITS frequency band (5.85–5.925 GHz) determines communication capabilities between vehicles and RSUs.

II.7 VANET Application

Figure 2.2 shows the taxonomy of VANET applications, meaning the different categories of services and functions that Vehicular Ad-hoc Networks can provide [7].

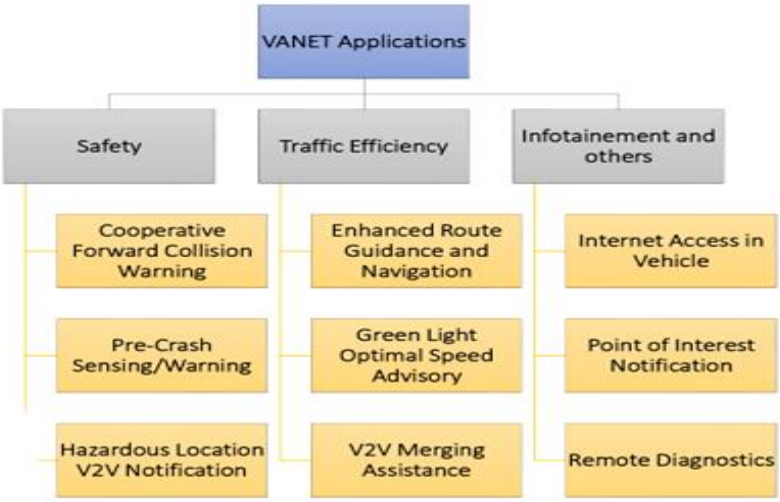


Figure 2.2 Taxonomy of VANET applications

a. Safety Applications

These are designed to protect drivers, passengers, and pedestrians by preventing accidents and alerting vehicles to dangerous situations.

- **Cooperative Forward Collision Warning:** Vehicles share information to warn each other of possible collisions ahead.
- **Pre-Crash Sensing/Warning:** Systems detect imminent crashes and prepare safety measures (like airbags).

- **Hazardous Location V2V Notification:** Cars notify each other about dangerous spots (sharp turns, icy roads, construction zones).

b. Traffic Efficiency Applications

These aim to improve traffic flow, reduce congestion, and make driving smoother.

- **Enhanced Route Guidance and Navigation:** Vehicles receive optimized routes based on real-time traffic data.
- **Green Light Optimal Speed Advisory:** Cars are advised on the best speed to catch green lights, reducing stops.
- **V2V Merging Assistance:** Vehicles coordinate with each other to merge safely and efficiently.

c. Infotainment and Other Applications

These focus on comfort, convenience, and entertainment for drivers and passengers.

- **Internet Access in Vehicle:** Cars provide connectivity for passengers.
- **Point of Interest Notification:** Drivers get alerts about nearby services (restaurants, gas stations, landmarks).
- **Remote Diagnostics:** Vehicles send performance data to service centers for maintenance and troubleshooting.

II.8/ Vehicle to infrastructure communication

Figure 2.3 V2I communication

II.8.1 Definition

Vehicle-to-road infrastructure (V2I) communication is taking place between mobile vehicles and roadside fixed infrastructure in order to gather data. It provides updates related to environmental sensing and monitoring such as real time traffic update or weather update [11].

II.8.2 Working Principle of V2I

Smart vehicles are equipped with sensors (like cameras and laser scanners) that constantly monitor their own state (speed, location, braking) and surroundings. A special communication device in the car (the OBU) bundles this data and sends it wirelessly to fixed "smart boxes" located on the roadsides or at intersections (RSUs). These RSUs receive and analyze the incoming information, using it to make real-time decisions, such as changing traffic light patterns to improve flow or giving drivers warnings. This creates a cycle where cars share data, the infrastructure reacts, and cars respond, leading to smoother traffic and fewer accidents [12] .

II.8.3 Flow diagram of V2I communication

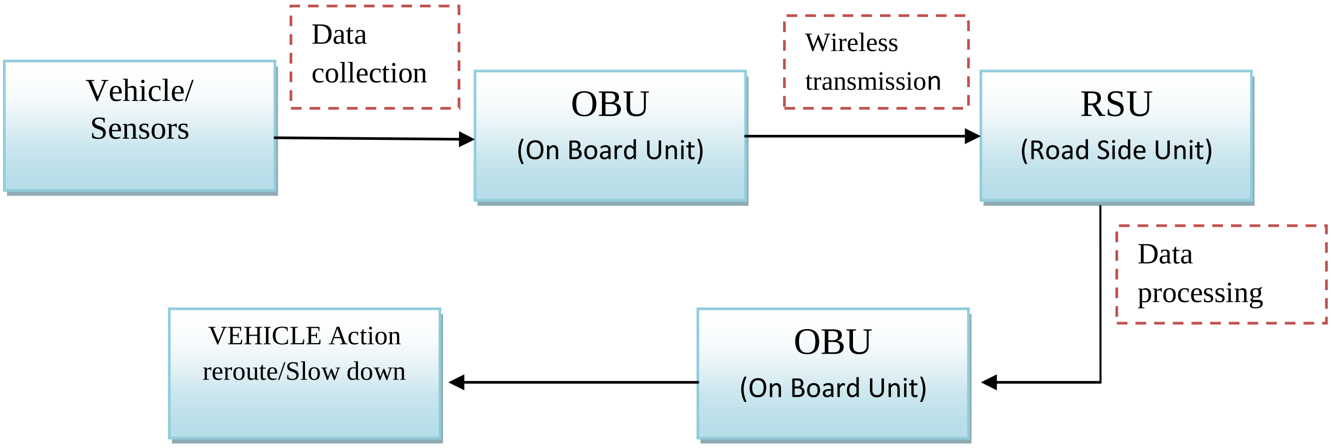


Figure 2.4 V2I communication Flow Diagram

II.8.4 Technologies Behind V2I

Vehicle-to-Infrastructure communication relies on a set of complementary technologies that work together to ensure fast, reliable, and secure data exchange [12]:

- **DSRC(Dedicated-Short-Range-Communications):** DSRC is a wireless communication technology similar to Wi-Fi, designed for low-latency data exchange over short distances (approximately 300 meters). It is one of the earliest solutions adopted for V2I applications and is known for its reliability and quick response time.
- **C-V2X(Cellular-Vehicle-to-Everything):** C-V2X is a more recent alternative to DSRC that utilizes cellular networks such as 4G LTE and 5G. It provides extended communication range, improved scalability, and better support for large-scale deployment in smart city environments.

- **5G Networks and Edge Computing**: 5G technology offers extremely low latency, reaching values as low as 1 millisecond, which enables real-time communication even in highly dense urban areas. When combined with edge computing—where data processing occurs close to the data source—it allows rapid decision-making without relying on remote cloud infrastructure.
- **IoT and Big Data Integration**: V2I systems integrate data from multiple sources, including vehicles, traffic signals, road infrastructure, and environmental sensors. This data is analyzed using big data techniques to detect patterns, predict traffic conditions, and identify potential risks such as congestion or hazardous driving zones

II.8.5 Benefits of V2I

Vehicle-to-infrastructure (V2I) communication technology offers numerous benefits for intelligent transportation systems, as presented in the following figure [13]:

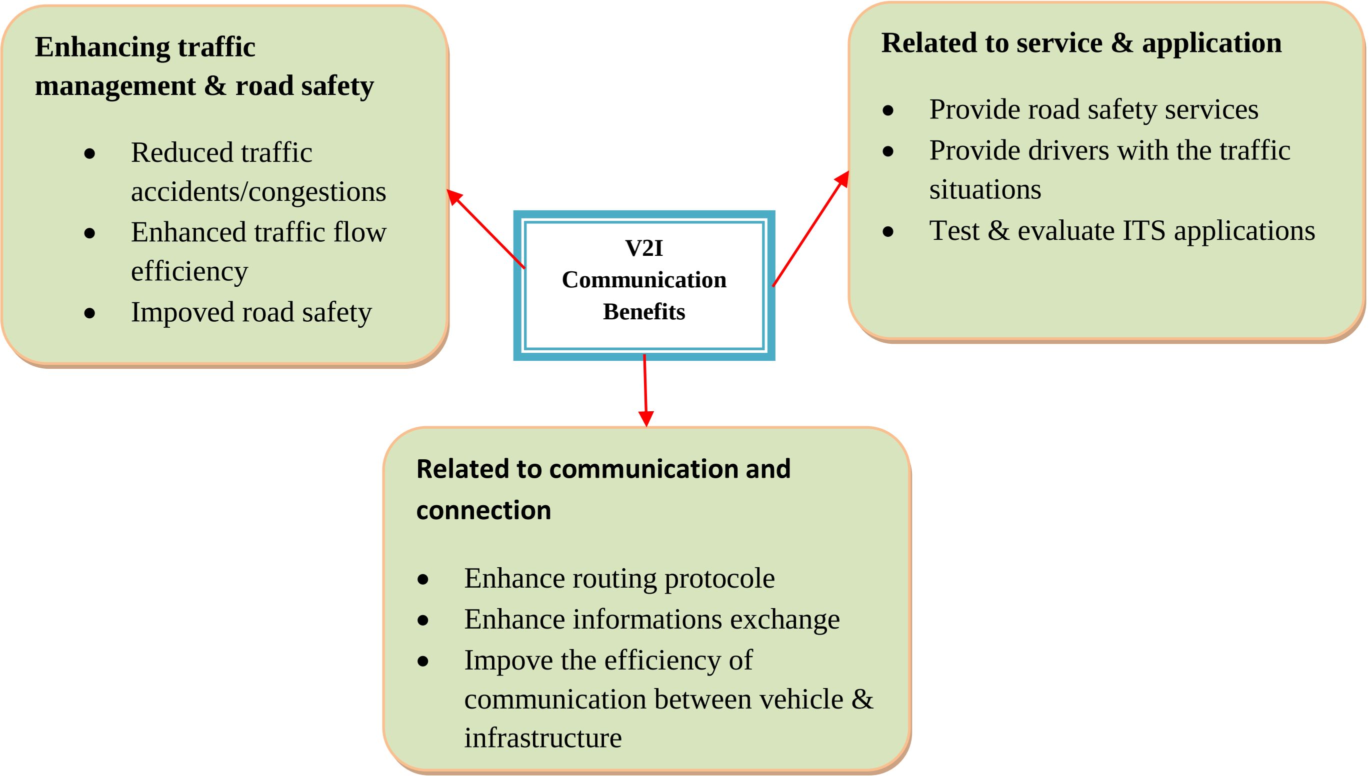


Figure 2.5 V2I Benefits

II.9/ Vehicle to pedestrian communication

Figure 2.6 V2P communication

II.9.1 Definition

Vehicle-to-Pedestrian (V2P) communication is a subset of Vehicle-to-Everything (V2X) technology that enables cars to exchange safety messages with pedestrians via smartphones or wearable devices in real time, aiming to reduce accidents at crossings and in urban areas [14].

II.9.2 Working Principle of V2P

Vehicle-to-Pedestrian (V2P) systems operate through a coordinated flow of technologies designed to enhance road safety. The process begins with pedestrians using mobile applications or smart devices that share their location and movement information through wireless communication technologies such as DSRC, C-V2X, or Bluetooth. At the same time, vehicles rely on sensors and cameras, including LiDAR and radar, to detect nearby pedestrians and collect real-time environmental data. This information is then processed by artificial intelligence algorithms that analyze pedestrian behavior and assess potential collision risks. Based on this analysis, warning systems generate visual, auditory, or haptic alerts to notify both drivers and pedestrians of possible dangers, enabling them to take appropriate actions such as slowing down or avoiding hazards. In addition, the collected data can be transmitted to cloud-based infrastructure for storage, large-scale analysis, and continuous system improvement [15].

II.9.3 Flow diagram

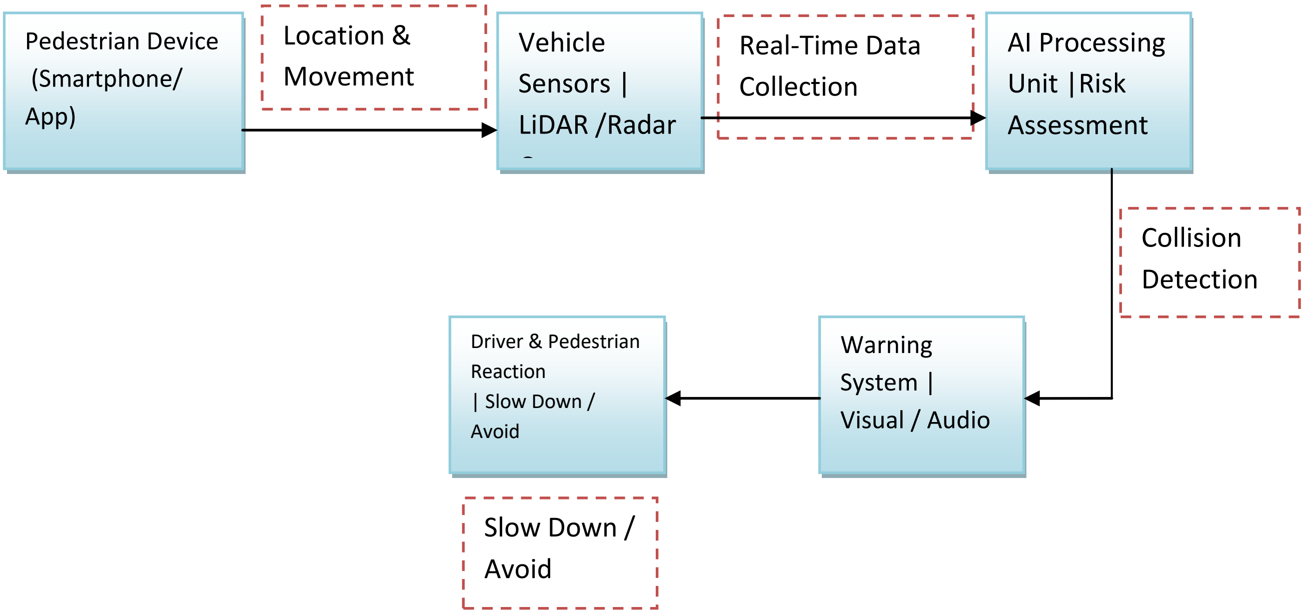


Figure 2.7 V2P communication Flow Diagram

II.9.4 The Role of Vehicle-to-Pedestrian Systems in Modern Transportation

a. Enhancing Safety with Vehicle-to-Pedestrian Systems

Safety lies at the heart of Vehicle-to-Pedestrian (V2P) systems. According to the World Health Organization, more than 1.3 million people die each year in road traffic accidents, with pedestrians constituting a significant proportion of these fatalities. V2P systems help reduce these risks by delivering [16]:

- **Real-Time Alerts**: instant notifications sent to both drivers and pedestrians about potential collision threats, enabling timely evasive action.
- **Enhanced Visibility**: Advanced sensors and communication technologies that help detect pedestrians in low-light conditions, blind spots, or obscured environments.
- **Behavior Prediction**: AI-driven analysis of pedestrian movement patterns to anticipate their next actions, allowing vehicles to respond proactively rather than reactively.
- **Seamless Integration with Autonomous Vehicles**: critical support for self-driving cars, enabling them to safely navigate shared spaces with pedestrians.

b. Improving Traffic Efficiency

- **Optimized Traffic Management**: Communication with traffic signals to dynamically prioritize pedestrian crossings, reducing unnecessary delays for both vehicles and pedestrians.

- **Intelligent Routing**: Vehicles can adjust their routes in real time based on pedestrian density, helping avoid crowded areas and improving overall traffic flow.

- **Faster Emergency Response**: Rapid, automated alerts to emergency services following an incident, significantly shortening response times. [17].

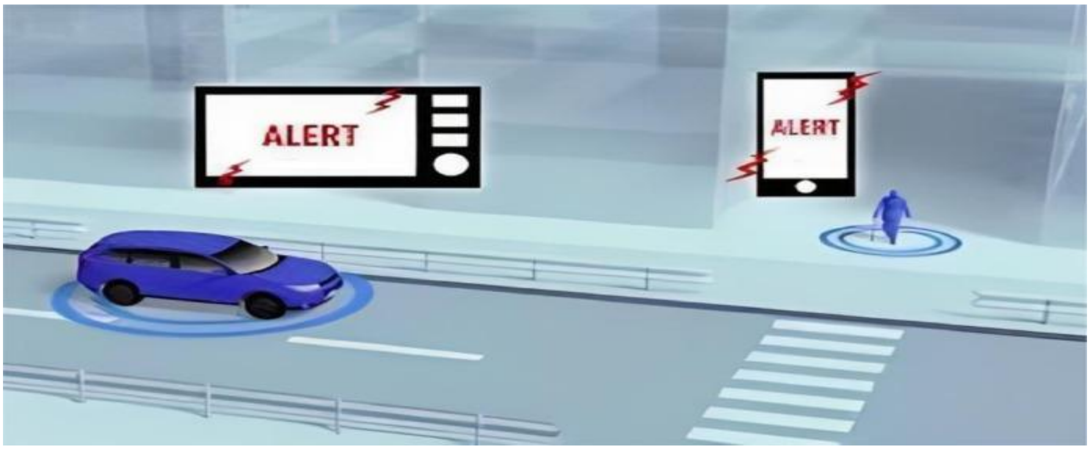
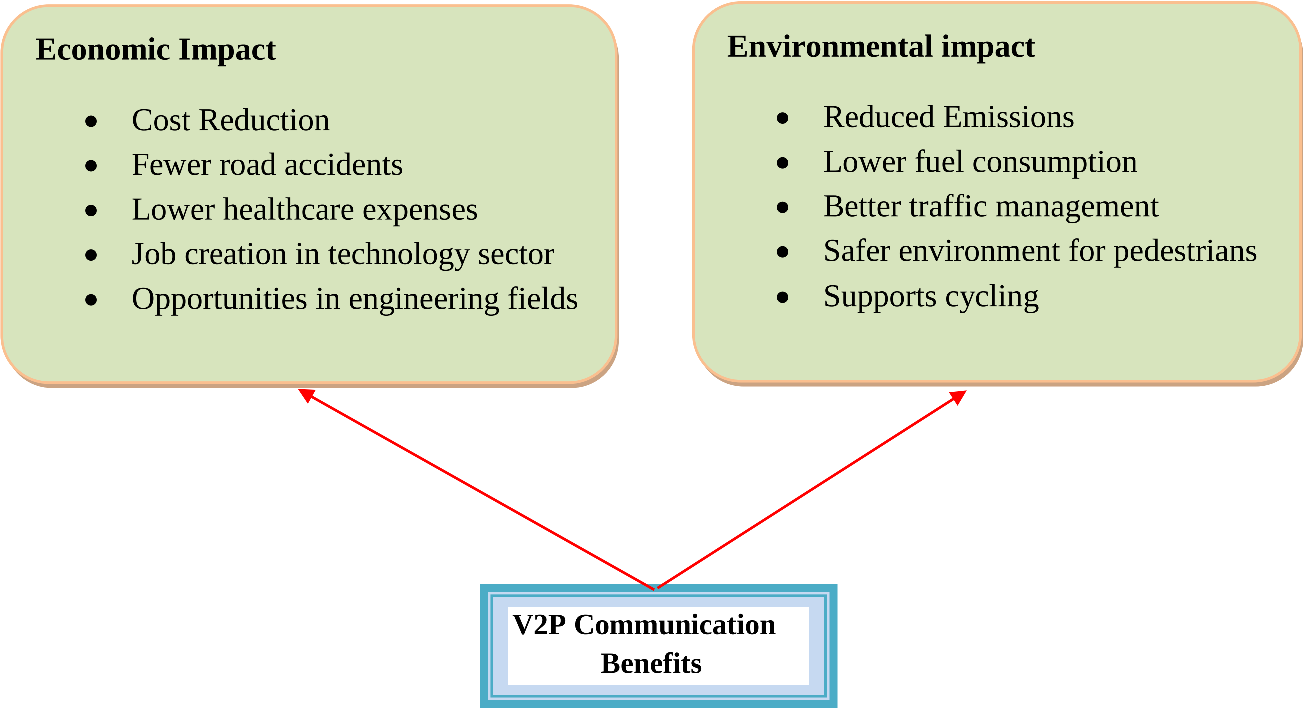


Figure 2.8 A warning message sent to both the pedestrian and vehicle

II.9.5 Benefits of V2P

Vehicle-to-Pedestrian (V2P) communication offers several benefits for road safety and intelligent transportation systems as presented in the following figure [16] :



Economic Impact

- Cost Reduction
- Fewer road accidents
- Lower healthcare expenses
- Job creation in technology sector
- Opportunities in engineering fields

Environmental impact

- Reduced Emissions
- Lower fuel consumption
- Better traffic management
- Safer environment for pedestrians
- Supports cycling

V2P Communication Benefits

Figure 2.9 V2P Benefits

II.10 Vehicle to vehicle communication

Figure 2.10 Real World V2V communication

II.10.1 Definition

Vehicle to Vehicle communication (V2V) refers to the data exchange between different vehicles so as to assist the driver by informing them about warnings and other critical information to one another. V2V communication does not rely on fixed infrastructure for data exchange to happen and it helps in dissemination, safety and security applications.

The idea behind Vehicle-to-Vehicle (V2V) communication is straightforward but important: by sharing information about their movements, vehicles work together as part of a connected traffic system. Unlike traditional sensors like radar or cameras, which can only detect what is directly in front of them, V2V allows vehicles to have a full 360-degree awareness. This helps prevent accidents, especially at intersections, during lane changes, or in poor visibility conditions [12].

V2V is one part of the larger system called Vehicle-to-Everything (V2X) communication. As depicted previously, V2X also includes communication between vehicles and road infrastructure (V2I), pedestrians (V2P), and networks or cloud services (V2N). Together, these technologies improve traffic safety and efficiency.

II.10.2 Brief History and Evolution of V2V

The development of Vehicle-to-Vehicle *(V2V)* communication technology began in the early 2000s, motivated mainly by the automotive industry’s goal to reduce traffic accidents and improve road efficiency. In the United States, the National Highway Traffic

Safety Administration *(NHTSA)* was instrumental in researching and testing early V2V systems [18].

Initially, the technology used Dedicated Short Range Communication (*DSRC*), a Wi-Fi-like protocol created specifically for vehicle communication [19]. Over time, newer methods such as Cellular V2X *(C-V2X)* have been developed, using 4G and 5G networks to improve the range and reliability of V2V communication.

Pilot programs and real-world tests in places like Michigan, Europe, and Japan have demonstrated that V2V communication is practical. Many modern vehicles already have the basic hardware needed for V2V, though the technology is not yet fully activated or widely regulated for public use.

II.10.3 Working Principle of V2V

The operational principle of Vehicle-to-Vehicle (V2V) communication is fundamentally based on the deployment of On-Board Units (OBUs) within vehicles, which continuously collect and process critical vehicular data such as precise geolocation, velocity, and directional vectors. These data points are transmitted in real-time to surrounding vehicles using dedicated communication protocols, primarily Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X) technologies [19]. DSRC operates within a reserved spectrum to facilitate low-latency, high-reliability direct vehicle-to-vehicle data exchanges, independent of cellular infrastructure. Conversely, C-V2X leverages existing cellular networks (4G LTE and 5G) to enable both direct and network-assisted communication modes, enhancing range, scalability, and integration with broader intelligent transportation systems.

II.10.4 Flow diagram

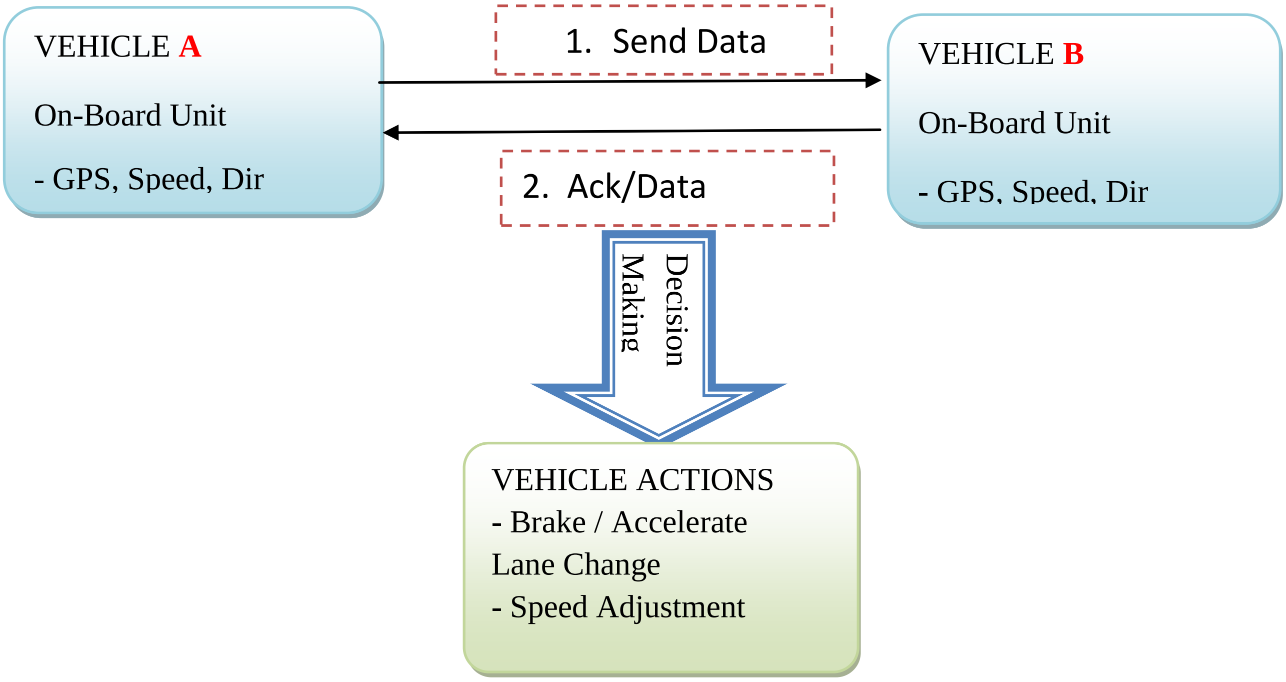


Figure 2.11 V2V communication Flow Diagram

II.10.5 Comparison of DSRC and C-V2X Technologies in V2V Communication [20]

Table 2.1 comparaison between DSRC &C-V2X

Feature	**DSRC (Dedicated Short-Range Communication)**	**C-V2X (Cellular Vehicle-to-Everything)**
Communication Type	Wi-Fi based (IEEE 802.11p)	Cellular-based (LTE and 5G)
Typical Range	Up to 300 meters	Up to 1 kilometer
Latency	Very low	Low (improving with 5G)
Infrastructure Dependency	Operates independently without relying on cellular towers	May depend on cellular infrastructure but supports direct communication
Standardization Status	Well-established with regional support	Rapidly developing with global alignment towards 5G
Industry Adoption	Limited adoption, mainly in pilot trials	Expanding adoption, supported by major automotive OEMs

II.10.6 Real-World Applications of V2V Technology

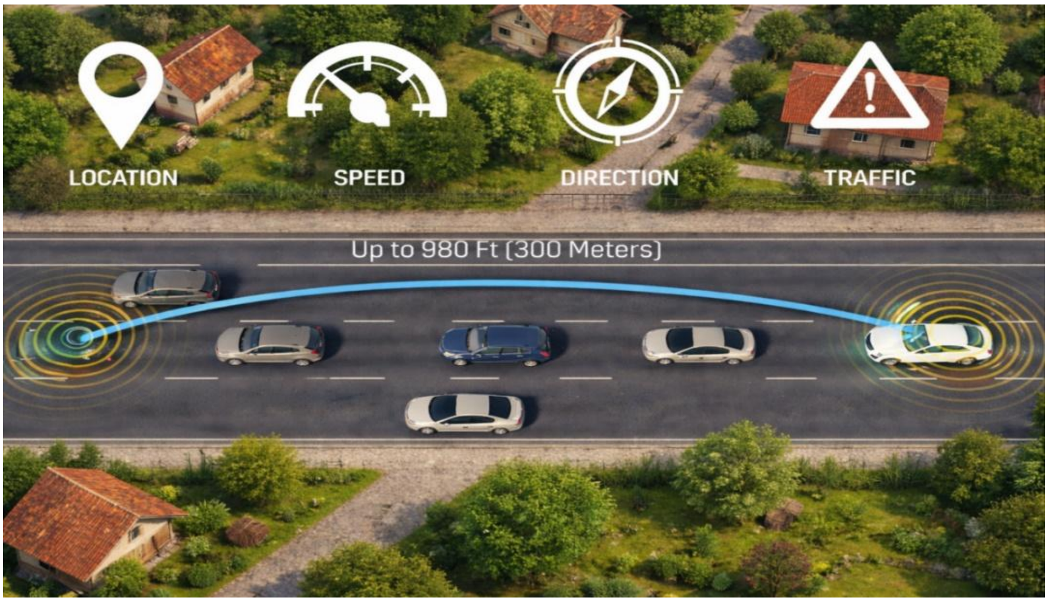


Figure 2.12 Collision avoidance systems

One of the most immediate and life-saving applications of Vehicle-to-Vehicle (V2V) communication is collision avoidance [21]. V2V systems continuously monitor the position and speed of nearby vehicles, enabling them to detect potential collisions before they happen—even if the vehicles are out of sight or obscured by obstacles. When a risk is identified, the system can alert the driver or activate automatic safety mechanisms such as emergency braking.

For example,(see figure 2.) if a vehicle suddenly brakes ahead in traffic but is hidden behind another car, V2V communication allows the following vehicles to receive that braking signal instantly, reducing reaction time and the likelihood of rear-end collisions.

II.10.7 The internal structure of the communication system in modern vehicles

The following figure shows the internal elements of the communication system deployed in the modern vehicles **[22]**.

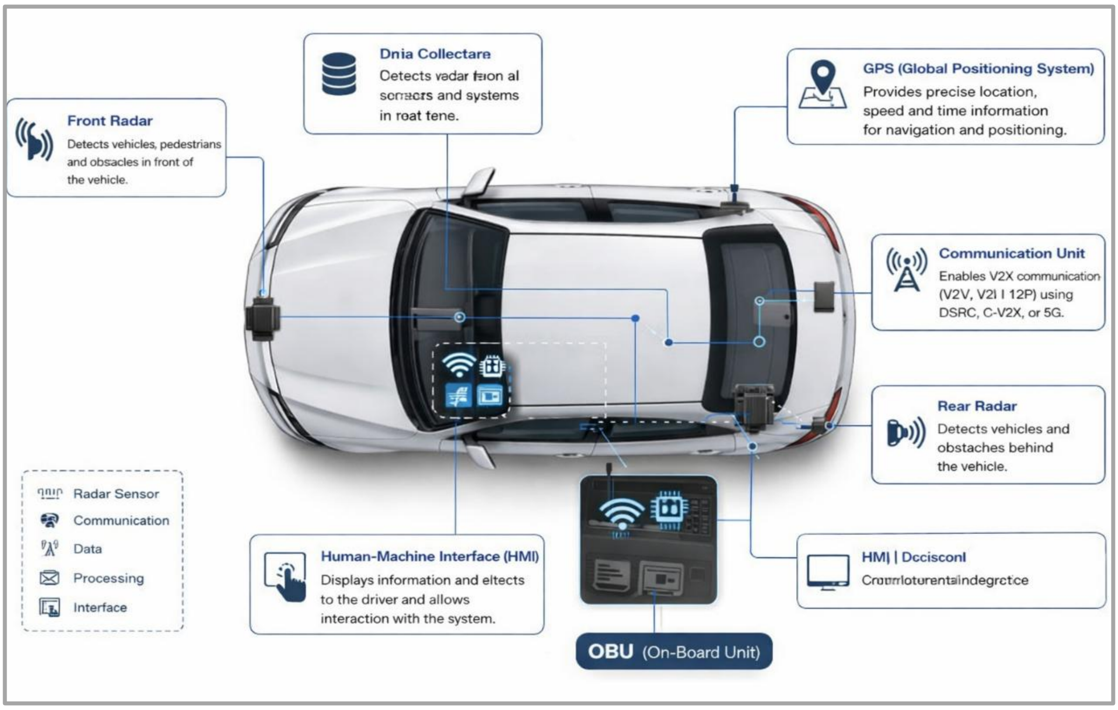


Figure 2.13 The components of a Smart Vehicle

- **Antenna**: A device that sends and receives wireless signals. It connects the vehicle to other vehicles by transmitting and receiving communication signals like DSRC, C-V2X, or mmWave.
- **Communication Unit (Transceiver + Baseband)**: A system that translates signals between radio and digital forms. It takes the wireless signals from the antenna, converts them into data that the vehicle can understand, and sends back data as radio signals. It works with technologies like WiFi, LTE, or 5G.
- **Sensors**: Devices that collect information about the vehicle and its environment.
    - GPS/GNSS: Gives the vehicle’s position.
    - Radar, Camera, LiDAR: Detect objects, vehicles, and obstacles.

  - Gyroscope/Accelerometer: Measure movement, speed, and direction.
- **Central Processor (Application Processor)**: the "brain" of the system. It receives data from sensors and communication units, analyzes it, and decides what action to take (for example, detecting danger or sending warnings).
- **Driver Interface (HMI – Human Machine Interface)**: the part that communicates with the driver. It shows alerts using a screen or sound (like warning messages). It can also interact with vehicle systems such as brakes or cruise control.
- **Power System (Power Regulators)**: a system that provides stable electrical power. It ensures all components work properly, even when conditions like temperature or voltage change.

II.10.8 Simplified diagram of the V2V system

The following figure shows a simplified scheme of the V2V system.

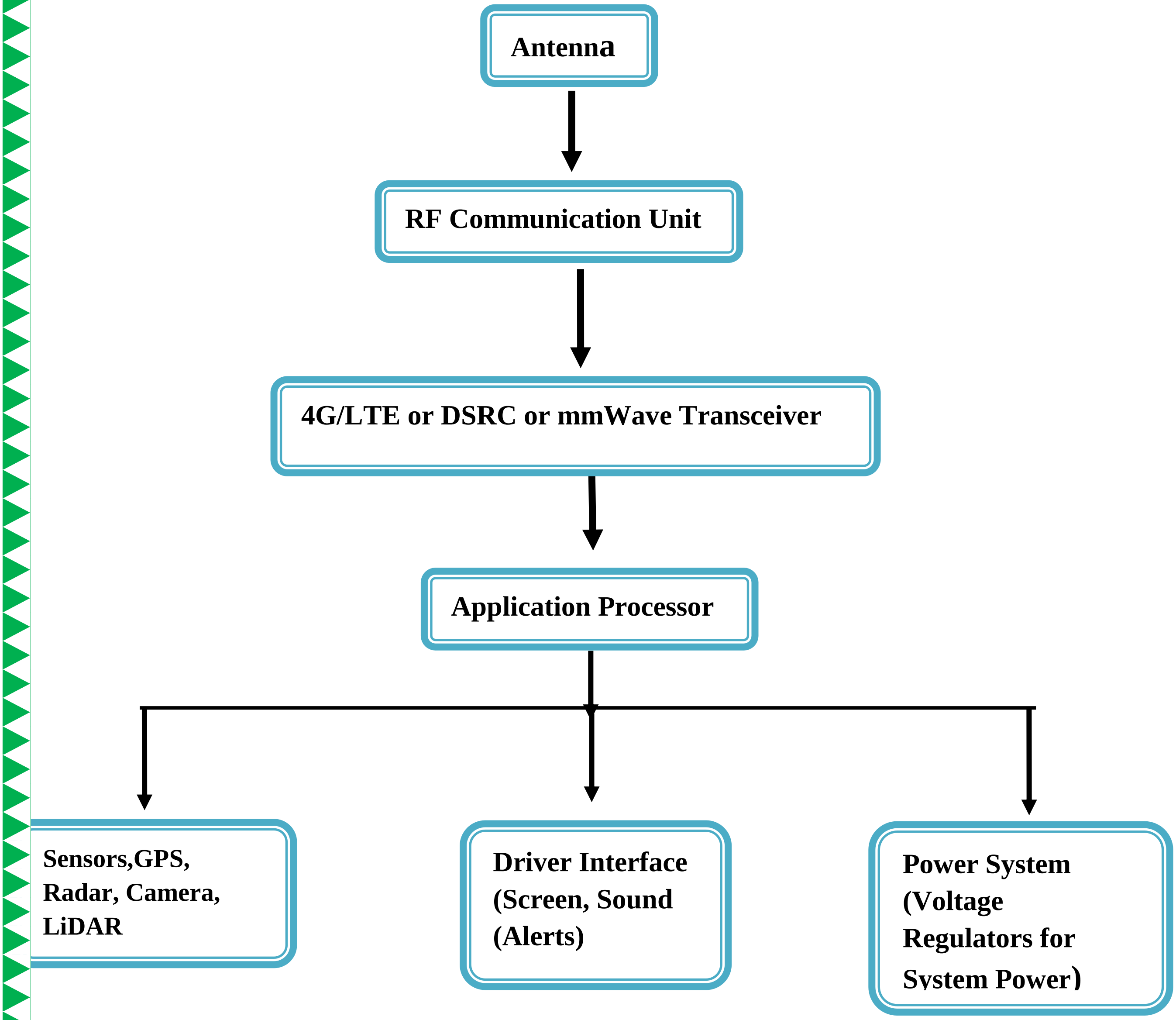


Figure 2.14 Simplified diagram of the V2V system

II.10.8.1 Data Flow

a) The antenna receives and transmits wireless signals.
b) The RF communication unit regulates frequencies and prevents interference.
c) The modem (Transceiver) converts signals into digital data.
d) The central processor analyzes the data and decides on the response.
e) Sensors provide the system with additional information (location, speed, direction).
f) The driver interface displays warnings or intervenes with the car systems.
g) The power system ensures stable operation of all components.

II.10.9 Benefits of Vehicle-to-Vehicle (V2V) Communication

Vehicle-to-Vehicle (V2V) communication play an important role in improving modern transportation systems [23] including:

a) Enhanced Safety

Safety is the most significant advantage of V2V communication. With numerous motor vehicle crashes causing thousands of fatalities daily, V2V technology plays a critical role in preventing accidents by enabling vehicles to share real-time data about their position, speed, and hazards, which helps drivers avoid collisions.

b) Environmental Benefits

Many commercial fleets are adopting V2V communication to support eco-friendly practices. By improving driving efficiency and enabling features like platooning (close formation driving), fleets can reduce fuel consumption and emissions, helping to enhance their public image and contribute to sustainability.

c) Improved Traffic Management

V2V communication aids law enforcement and traffic management authorities by providing real-time data from vehicles. This information helps manage and decongest traffic flows, enforce speed limits, adjust traffic signals, and assist in vehicle tracking. For drivers, this means avoiding traffic jams and maintaining safe distances.

d) Driver Assistance

V2V systems provide important warnings and assistance to drivers, such as alerts about low-clearance bridges, nearby parked vehicles during parking manoeuvres, and lane-keeping support to prevent unsafe drifting. These features are especially valuable for drivers of large trucks or vehicles carrying oversized cargo.

e) Fuel Efficiency

Vehicle platooning enabled by V2V communication improves fuel economy by maintaining steady speeds and close spacing between trucks. Studies indicate fuel savings of up to 5% for the lead vehicle and up to 10% for following vehicles, reducing overall fuel costs.

f) Route and Direction Optimization

V2V technology delivers vital travel information directly to drivers, including optimized routes, destination locations, and real-time map updates. This helps fleets improve delivery efficiency and reduce travel times.

g) Crash Prevention

Motor vehicle accidents cause approximately 33,000 deaths worldwide annually. Despite safety improvements, human error remains the leading cause of crashes. V2V communication can reduce accident rates by 70% to 80% by providing early warnings and automated responses to potential hazards.

II.11 Comparison between V2V, V2I and V2P

The following table resume the main differences between the above described V2V, V2I and V2P communication systems [24] [25] [26].

Table 2.2 Comparison between V2V.V2I.V2P

Feature	V2V (Vehicle-to-Vehicle)	V2I (Vehicle-to-Infrastructure)	V2P (Vehicle-to-Pedestrian)
Definition	Communication between vehicles	Communication between vehicles and road infrastructure	Communication between vehicles and pedestrians
Main Goal	Avoid collisions between cars	Improve traffic management and road safety	Protects pedestrians from accidents
Communication Type	Direct vehicle ↔ vehicle	Vehicle ↔ traffic lights, RSU, signs	Vehicle ↔ smartphone or wearable
Devices Used	On-Board Units (OBU) in vehicles	OBU + Road Side Units (RSU)	OBU + smartphone/wearable
Infrastructure Needed	NO	YES	Minimal
Communication Tech	DSRC, C-V2X	DSRC, C-V2X, 4G/5G	Bluetooth, WiFi, C-V2X
Range	Medium (300–500 m)	Long (up to kilometers)	Short to medium
Advantages	Fast, direct, low delay	Better traffic control, smart cities	Protects vulnerable users
Limitations	Needs many equipped vehicles	High cost (infrastructure)	Depends on pedestrian participation

II.12 Conclusion

Currently, Vehicle-to-Vehicle (V2V) communication systems primarily serve to send warnings to drivers, alerting them to potential hazards. Although the technology has matured beyond its early stages, ongoing development is focused on creating next-generation V2V systems integrated with autonomous driving capabilities. This advancement will enable vehicles to take direct control to avoid imminent dangers, significantly enhancing safety.

In this work we focus on V2V communication which holds great promise for saving lives and improving driving efficiency, this can lead to substantial gains in fleet productivity. Moreover, its widespread adoption has the potential to positively impact communities and large cities worldwide by reducing road congestion. This, in turn, contributes to lowering carbon emissions in urban areas, supporting environmental sustainability effort

Chapter III

V2V Routing Protocols and Safety Messages

III.1 Introduction

In intelligent transportation systems, particularly within vehicular ad hoc networks (VANETs), communication between vehicles is a critical component for enhancing both safety and traffic efficiency. Vehicle-to-Vehicle (V2V) communication enables the real-time exchange of crucial information, including speed, location, and safety alerts, among vehicles on the road. The primary objectives of V2V technology are to reduce traffic accidents, optimize traffic flow, and support safety-related applications such as driver fatigue detection and alerts. The effectiveness of these systems, however, relies heavily on the underlying routing protocols that govern the transmission of data between highly mobile vehicles.

This chapter will focus on studying and analyzing key V2V routing protocols, with particular attention to AODV (Ad hoc On-Demand Distance Vector), OLSR (Optimized Link State Routing), and DSDV (Destination-Sequenced Distance Vector). Emphasis will be placed on evaluating their performance within the rapidly changing and dynamic environment characteristic of VANETs. Moreover, some safety messaging services will be introduced.

III.2 Definition of Routing Protocol

A routing protocol is a set of rules and procedures that routers use to exchange information and determine the most efficient path for data packets to travel across a network. It ensures that data moves reliably from source to destination [27].

III.2.1 Topology-Based Routing Protocol

Topology-based routing techniques use network link information to transport data packets from source to destination. Proactive (table-driven) and reactive (on-demand) routing strategies are subcategories of topology-based routing [28], the following figure shows a classification o routing protocol based on topology.

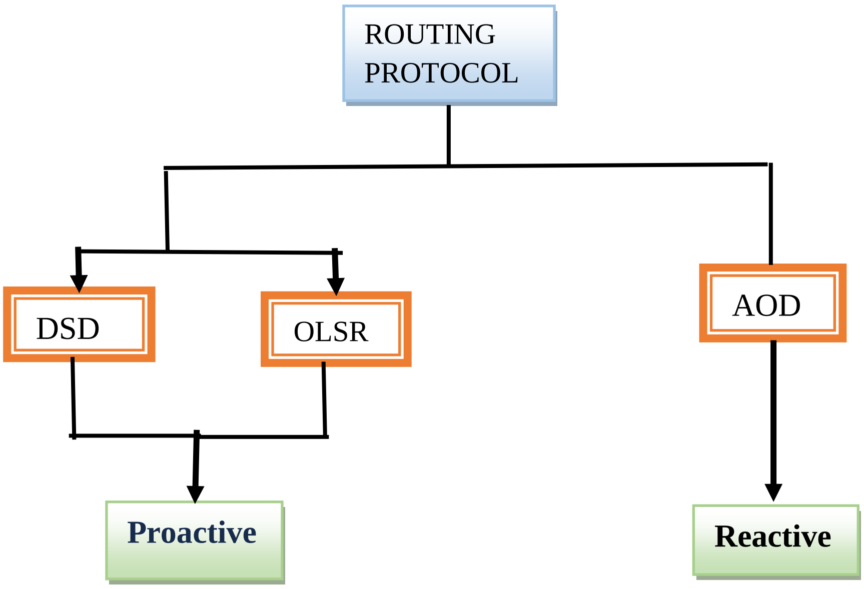


Figure 3.1 classification of routing protocols based on topology

III.3 Comparison between PROACTIVE and REACTIVE protocols [20].

The following table shows a comparison between proactive and reactive routing protocols.

Table 3.1 Comparison between PROACTIVE and REACTIVE protocols

Feature	**Proactive Routing Protocols**	**Reactive Routing Protocols**
Route Maintenance	Maintain routes continuously, updating tables regularly	Discover routes only when needed (on-demand)
Route Availability	Routes are immediately available	Routes are established with some delay
Latency	Low latency due to pre-established routes	Higher latency due to route discovery process
Bandwidth Usage	Higher bandwidth usage due to frequent updates	Lower bandwidth usage as updates occur only when necessary
Overhead	Can generate high overhead, especially in dynamic networks	Generally lower overhead
Suitability	Best for networks with stable or slow-changing topology	Best for highly dynamic or frequently changing networks
Examples	DSDV, OLSR	AODV, DSR

III.4 AODV PROTOCOL

III.4.1 Definition

AODV (Ad-hoc On-demand Distance Vector) is an on-demand routing protocol that establishes communication routes only when they are needed. This approach reduces routing overhead, making AODV well-suited for networks with frequently changing topologies. The protocol dynamically builds routes as data transmission requests occur and maintains them efficiently, conserving network resources while quickly adapting to network changes to ensure effective data delivery.

III.4.2Working Principle of AODV

- Finding a route:
  If a vehicle (node) wants to send data but doesn't know the way, it asks nearby vehicle by sending a Route Request (RREQ). This request is passed along until it reaches the destination or another that knows the way.

- Replying with the route:
  The vehicle that gets the request sends back a Route Reply (RREP) to the sender, telling it the path to use. Then, the sender can start sending data.

- Fixing broken routes:
  If a vehicle moves and the path breaks, a Route Error (RERR) message is sent to let others know. The sender can then ask again to find a new route [29].

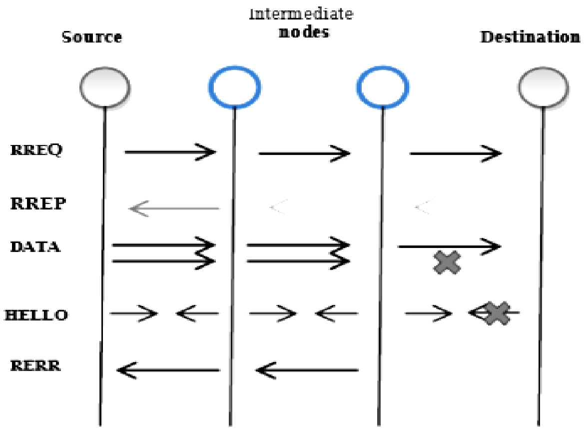


Figure 3.2 AODV Mechanisms

III.4.3 AODV ADVANTAGES AND LIMITATIONS [30].

The following table presents the advantages and limits of AODV protocol.

Table 3.2 AODV advantages and limitations

ADVANTAGES	LIMITATION
AODV adapts quickly to network changes, making it effective in dynamic environments.	AODV takes long time to build the routing table.
AODV has lower setup delay for connections and detection of the latest route to the destination	AODV has a high processing demand.
AODV adds no extra overhead to data packets because it doesn't use source routing.	Link breakages in AODV generate many control packets, which increase congestion on active routes.

III.5 OLSR PROTOCOL

III.5.1 Definition

OLSR (Optimized Link State Routing) is a proactive routing protocol used in mobile ad hoc networks [31]. It works by regularly exchanging information about the network's topology so that each node always has an updated routing table. This allows OLSR to provide quick and efficient routes between vehicles, making it suitable for networks where connections change frequently.

III.5.2 Working Principle of OLSR

In OLSR (Optimized Link State Routing), MultiPoint Relaying (MPR) is used to reduce the number of retransmissions during the flooding of control messages [31]. Each node selects a set of its neighbors as MPRs, which are responsible for forwarding broadcast messages. Neighbors not selected as MPRs receive the messages but do not forward them. This selective forwarding ensures that control packets efficiently reach all nodes in the network while minimizing redundant transmissions, reducing network congestion and improving scalability.

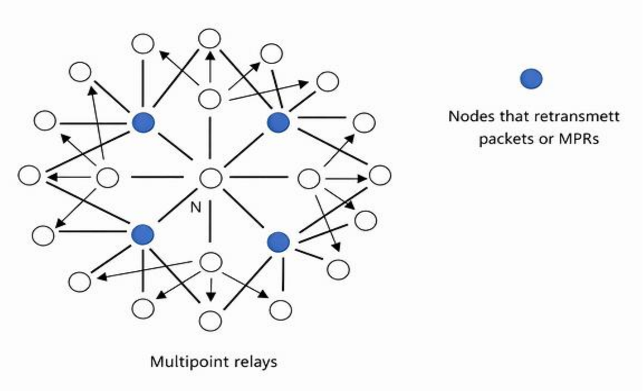


Figure 3.3 MultiPoint Relaying

III.5.3 OLSR ADVANTAGES AND LIMITATIONS.

The following table presents the advantages and limits of OLSR protocol [32].

Table 3.3 OLSR ADVANTAGES AND LIMITATIONS

ADVANTAGES	LIMITATION
OLSR can find multiple routes between source and destination nodes, enhancing the network's reliability and resilience.	As the number of mobile nodes increases, control message overhead also rises.
OLSR quickly adapts to changes in network topology, making it well-suited for dynamic environments like mobile ad hoc networks.	It requires more processing power than other protocols to discover alternate routes.
OLSR has lower average end-to-end delay, making it ideal for applications that require minimal delay.	OLSR's route updates can introduce latency, potentially affecting applications that require real-time responses.

III.6 DSDV PROTOCOL

III.6.1 Definition

DSDV (Destination-Sequenced Distance Vector) is a proactive routing protocol where each node maintains complete routing tables that are updated regularly. It uses sequence numbers to ensure that routing information is always current and free from loops, providing immediate route availability. However, in highly dynamic networks, DSDV can generate significant overhead due to frequent updates.

III.6.2 Working Principle of DSDV

Each device keeps a list of all the other devices it knows about, along with how to reach them. This list includes the device's address, how fresh the information is (using a sequence number), how many steps it takes to get there (hop count), and the next step to send data [33].

Devices share their lists in two ways: regularly every 15 seconds, and instantly whenever something changes. When a device gets new information, it trusts the newest updates or the ones with the shortest path. To avoid too many updates when things change quickly, devices wait a little before sending out new info. If a route isn't known yet, devices hold onto a few messages until they can find a way to send them.
This helps keep communication smooth and accurate even when devices move around a lot.

III.6.3 DSDV ADVANTAGES AND LIMITATION

The following table presents the advantages and limits of DSDV protocol [34].

Table 3.4 DSDV ADVANTAGES AND LIMITATION

ADVANTAGES	LIMITATION
It works well for small networks with a limited number of nodes	It regularly updates routing tables, which consumes battery power and bandwidth even when the network is idle.
DSDV is one of the earliest routing algorithms designed for ad hoc networks.	Weak performance in highly mobile networks
DSDV guarantees for loop free path.	Slow reaction to topology changes

III.7 Safety messages

III.7.1 Introduction

Safety messages play an essential role in modern Vehicle-to-Everything (V2X) communication by allowing vehicles to exchange information and respond more effectively to road situations. Their main objective is to improve road safety, reduce accidents, and support smoother traffic flow through fast and reliable communication between vehicles.

Two commonly used safety messages are **Basic Safety Message (BSM)** and **Decentralized Environmental Notification Message (DENM)**. BSM is periodically transmitted to share basic vehicle information such as position, speed, and direction, helping nearby vehicles remain aware of each other's movements. On the other hand, DENM is generated only when a specific event occurs, such as an accident, traffic congestion, or a dangerous road condition, allowing vehicles to receive warnings and react in time. Together, BSM and DENM enhance driving awareness and contribute to the development of safer and more intelligent transportation systems.

III.7.2 / Basic Safety Messages (BSMs)

III.7.2.1 Definition

Basic Safety Messages (BSMs) are important for vehicle safety in Intelligent Transport Systems (ITS). They share information about a connected vehicle's location and movement. These messages are sent regularly, at least 10 times every second (every 100 milliseconds), so vehicles can stay aware of what's around them. This helps with safety features, cooperative driving, and is key to Vehicle-to-Everything (V2X) communication.

BSMs use special radio technologies like Dedicated Short-Range Communications (DSRC) and Cellular-V2X (C-V2X), both working in the 5.9 GHz frequency range and designed for cars. The details about what information BSMs include and how the messages are structured come from a standard called SAE J2735. This standard makes sure all vehicles and road infrastructure can understand each other and work together smoothly [35].

SAE J2735 is a standard developed by the Society of Automotive Engineers (SAE) that defines the data elements and message formats used in Vehicle-to-Everything (V2X) communication. It specifies how vehicles and infrastructure share information like location, speed, and other important details through messages such as Basic Safety Messages (BSMs). This standard ensures that all devices in the V2X ecosystem can communicate reliably and understand each other, helping improve road safety and traffic efficiency [36].

III.7.2.2 Structure of the Implemented BSM

The implemented Basic Safety Message (BSM) contains several data fields used to exchange real-time, a description of these data are given in the following table.

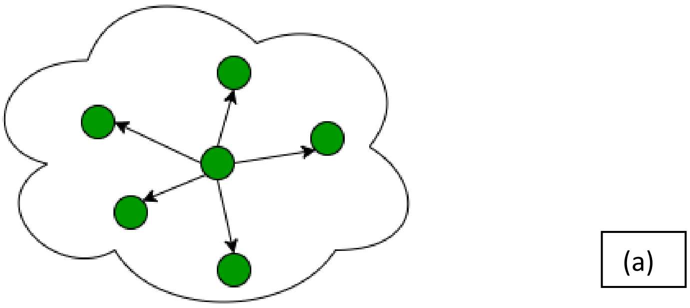
Table 3.5 BSM Header

FIELD	DESCRIPTION
senderId	Unique identifier of the transmitting vehicle
x	Vehicle X-axis position
y	Vehicle Y-axis position
speed	Current vehicle speed
angle	Vehicle movement direction
accel	Vehicle acceleration
timestamp	Message generation time

III.7.2.3 BSM Transmission Mode

The transmission mode of BSM is broadcast. Below, we define both the broadcast and unicast transmission modes.

- **Broadcast mode:** Broadcast is a type of information transfer where a single sender transmits data to multiple recipients simultaneously. It is often called one-to-many transmission, as the message is sent out to all devices within the communication range.



- **Unicast mode:** This type of information transfer, involving a single sender and a single recipient, is commonly referred to as one-to-one transmission **[37].**

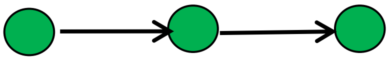


Figure 3.4 Broadcast Mode (a) , Unicast Mode (b)

III.7.3 / Decentralized Environmental Notification (DENM)

III.7.3.1 Definition

DENM is a core message type defined in vehicular networks that enables the rapid and reliable exchange of hazard warnings between vehicles. It enhances road safety by providing timely alerts about potential dangers beyond the line of sight [38].

The DENM packets contains contextual information related to the dangerous event, including:

- Vehicle identifier
- Event identifier
- Vehicle position
- Vehicle speed
- Vehicle acceleration
- Vehicle direction angle
- Severity level
- Transmission timestamp

III.7.3.2 Purpose and Motivation

DENM was developed to meet the need for fast and reliable delivery of safety warnings in vehicular communication networks. Traditional cellular communication depends on network infrastructure and central routing, which can introduce delays and become less effective in situations involving network congestion or limited coverage. Before the emergence of standardized V2X technologies, vehicle safety mainly relied on onboard sensors such as cameras and radar. Although effective, these sensors are limited by their sensing range and cannot detect hazards outside the driver's or vehicle's direct field of view.

The development of DENM was motivated by global efforts to improve road safety through Cooperative Intelligent Transport Systems (C-ITS). As automotive and telecommunications technologies evolved together, V2X communication standards were introduced to allow vehicles to exchange information directly. DENM was designed as an event-driven safety message that is generated only when a relevant event occurs, such as an accident, road obstacle, traffic congestion, or hazardous conditions. By enabling direct communication between vehicles and nearby infrastructure, DENM allows warnings to be delivered quickly [38].

III.8 Conclusion

Routing protocols and safety messages play a key role in making vehicular communication more reliable and effective within intelligent transportation systems. In highly dynamic road environments where vehicles are constantly moving, fast and stable communication becomes essential to improve road safety and traffic management.

Routing protocols help vehicles communicate with each other by ensuring that information is transmitted through the network efficiently. Reliable routing is important because it allows vehicles to exchange data quickly, especially in situations where rapid communication can help prevent accidents or reduce traffic problems.

Safety messages also contribute significantly to driver awareness and safer driving conditions. Messages such as Basic Safety Messages (BSM) allow vehicles to continuously share information like speed, position, and direction, helping drivers better understand the surrounding traffic environment. On the other hand, Decentralized Environmental Notification Messages (DENM) provide alerts about sudden dangers such as accidents, road hazards, or risky situations, enabling faster reactions and safer decisions.

Both, routing protocols and safety messages form an important foundation for connected vehicle technologies. By improving communication between vehicles, they can help reduce accidents, improve traffic flow, and support the development of safer, smarter, and more efficient transportation systems.

Chapter IV

Simulations and Results

IV.1 Introduction

In this work, a comparative performance analysis of three routing protocols: AODV, OLSR, and DSDV, was carried out using UDP (User Datagram Protocol) Unicast CBR (Constant Bit Rate) traffic in an NS-3 simulation environment. The protocols evaluation was based on several Quality of Service (QoS) metrics, including Packet Delivery Ratio (PDR), throughput, average delay, jitter and packet loss, under different vehicle densities (50 and 100 vehicles). The purpose of this study is to determine which routing protocol performs best in highly dynamic vehicular environments. Furthermore, we compared between two safety messages «BSM» and «DENM» in order to enhance road safety.

IV.2 Definition

a) SUMO (Simulation of Urban Mobility): SUMO is an open source, highly portable, microscopic and continuous multi-modal traffic simulation package designed to handle large networks. It can be used to simulate vehicular traffic, from which we can export a trace of vehicle positions that can be used in ns-3 simulations **[39].**

b) TRACI: is a traffic control interface that relies on TCP to interact with the SUMO simulation in real-time **[40]**, allowing for the control and monitoring of vehicles, signals, and pedestrians. It operates according to a client-server model where SUMO is the server, while clients (such as Python scripts) send commands or query data.
TraCI is the bridge that connects traffic simulation in SUMO with network simulation in ns-3.

c) NS-3 (Network Simulator) : (NS-3 is a discrete-event network simulator tailored for research and education in computer networking, enabling detailed modeling of protocols and topologies. Its free, open-source makes it accessible for simulating complex scenarios like VANETs with SUMO integration [41].

d) Netanim: NetAnim is an offline animator based on the Qt toolkit. It animates a previously executed simulation using an XML trace file generated during a simulation **[42].**

IV.3 Simulation parameters of Routing Protocol

The following table summarizes the main simulation parameters used in this study. The experimental setup integrates SUMO and NS-3 through a live TraCI-based coupling mechanism, using a realistic urban map extracted from OpenStreetMap. The simulations employ the IEEE 802.11p standard with UDP CBR safety-like traffic under different vehicle densities and mobility conditions to evaluate the three routing protocols.

Table 4.1 Simulation configuration parameters « Routing Protocols »

PARAMETERS	VALUE
Mobility Simulator	SUMO 1.26.0
Network Simulator	NS-3.46.1
Road Map Source	Openstreetmap(saida city)
Mobility File Format	XML (converted to NS-3 compatible)
Wireless Standard	IEEE 802.11P
Simulation Time	200 seconds
Evalution period	First 180 seconds
Node Speed	10-60km/h
Vehicle Count	50 /100
Traffic pattern	UDP CBR safety-like traffic
Mobility coupling	Live integration using TraCI and TCP socket
Transmission power	33dBm

IV.4 Methodology

a) In the first simulation scenario (figure 4.1), we proceed as flow: We begin with extracting the road map from OpenStreetMap, which is then processed using SUMO's *netconvert* tool to generate the road network file (.net.xml). The mobility scenario is executed in SUMO and connected to ns-3 through the TraCI interface to ensure real-time mobility synchronization. The integrated environment is then configured to form a VANET scenario, where different routing protocols such as AODV, OLSR, and DSDV are implemented, and key performance metrics including Packet Delivery Ratio (PDR), end-to-end delay,etc. Finally, the results are analyzed and compared to evaluate the performance of the routing protocols under the defined scenarios.

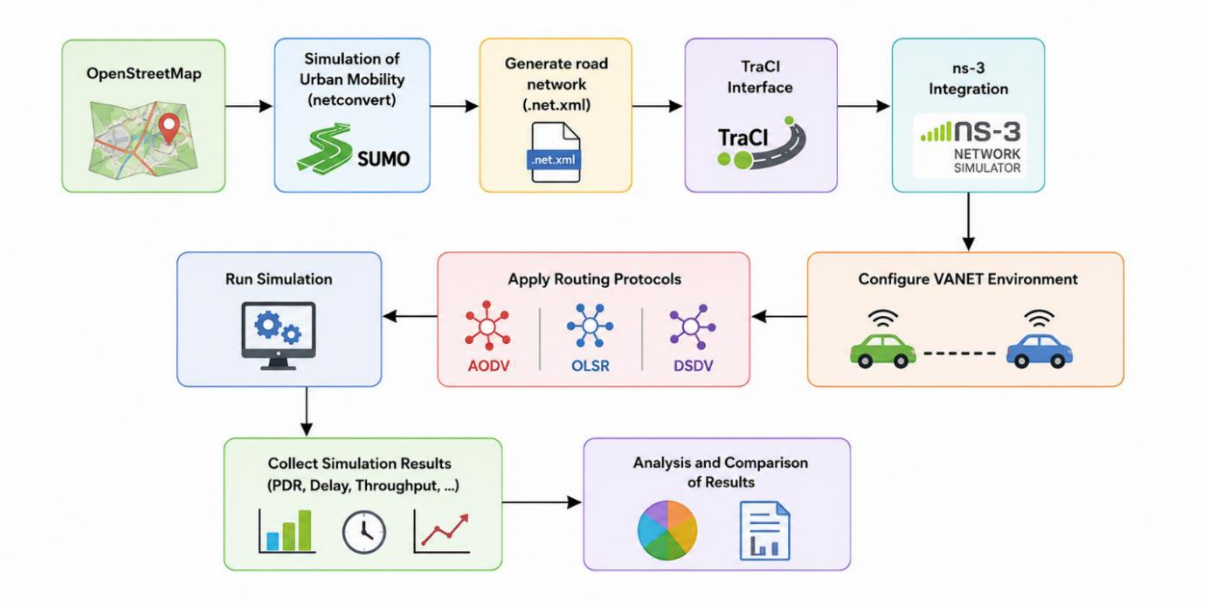


Figure 4.1 First simulation scenario

b) In the second simulation scenario (figure 4.2), the same methodology was followed as in the first scenario. However, routing protocols were removed and the study focused on the comparison between BSM and DENM safety messages under a communication range of 500 m and a transmission power of 30 dBm using unicast communication in a VANET environment.

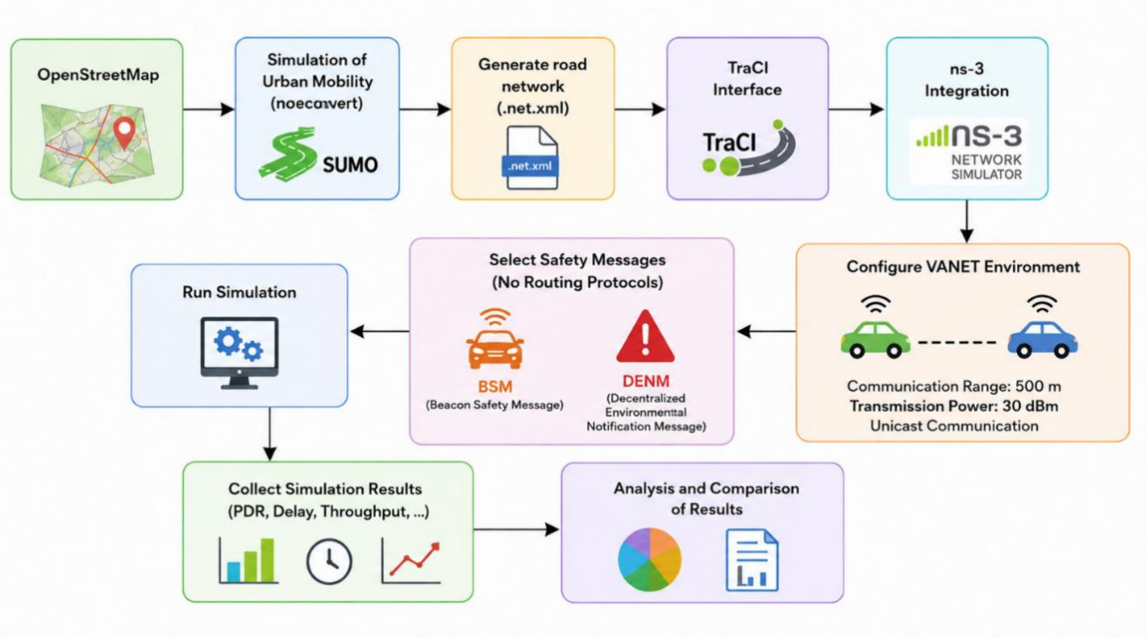
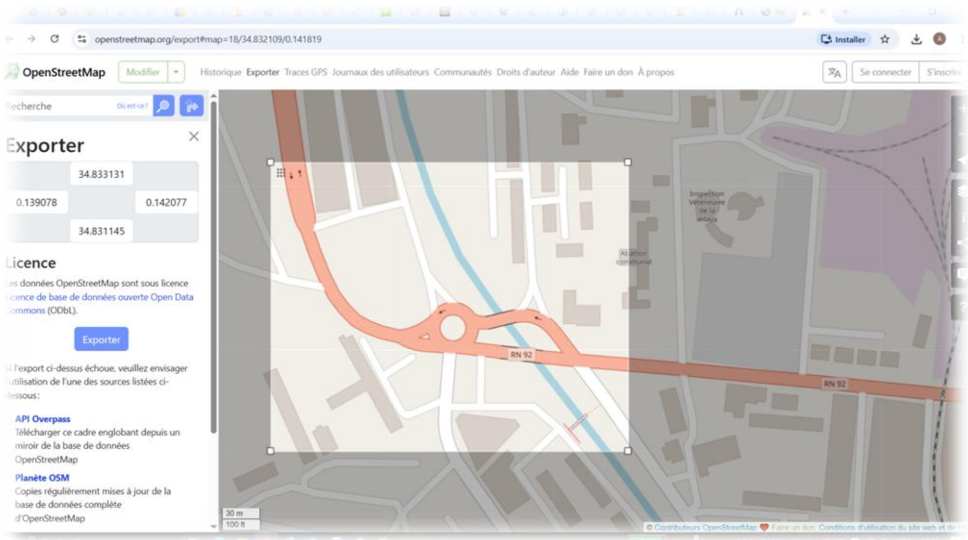


Figure 4.2 Second simulation scenario

Firstly, we extracted a map of the area from OpenStreetMap. An urban area containing several intersections and roads was chosen. (city.osm) [43].

In this work Saida city in Algeria, is used as a case study to reflect real-world traffic conditions (figure 4.3).

Saïda is a city located in western Algeria, approximately 461 km from the capital Algiers. It serves as the administrative center of Saïda Province and represents a typical medium-sized urban environment in Algeria. The city covers an area of approximately 75 km² and exhibits a relatively high population density in its urban center. The city’s road network consists mainly of narrow streets and moderate-capacity roads, which can lead to congestion, especially during peak hours. Additionally, the urban layout reflects typical characteristics of developing regions, including irregular road geometry, limited traffic management infrastructure, and heterogeneous driving behavior. These characteristics make Saïda an appropriate case study for evaluating Vehicle-to-Vehicle (V2V) communication systems under realistic urban conditions. The combination of moderate traffic density, constrained road topology, and dynamic driving patterns provides a challenging environment for routing protocols in Vehicular Ad Hoc Networks (VANETs).



s données OpenStreetMap sont sous licence cence de base de données ouverte Open Data ommons (ODbL).

l'export ci-dessus échoue, veuillez envisager utilisation de l'une des sources listées ci-essous:

Télécharger ce cadre englobant depuis un miroir de la base de données OpenStreetMap

Copies régulièrement mises à jour de la base de données complète d'OpenStreetMap

Figure 4.3 OpenStreetMap (OSM) road network extracted for Saida city region.

Firstly, we converted this map into a road network using netconvert, the resulting file contains « city.net.xml »

- **Roads (edges)**: Defined as <edge> elements with attributes like ID, length, speed limits, lane count, and connectivity, forming the drivable network topology.
- **Intersections (junctions)**: <junction> nodes specify coordinates, traffic rules (priority, right-of-way), and links between incoming/outgoing edges for realistic flow.

Secondly, we create vehicles traffic (movement) using the following SUMO's Python script:

```
python "C:\Program Files (x86)\Eclipse\Sumo\tools\randomTrips.py" -n city.net.xml -r routes.rou.xml -e 200 -p 4 --seed 1 --validate –random
```

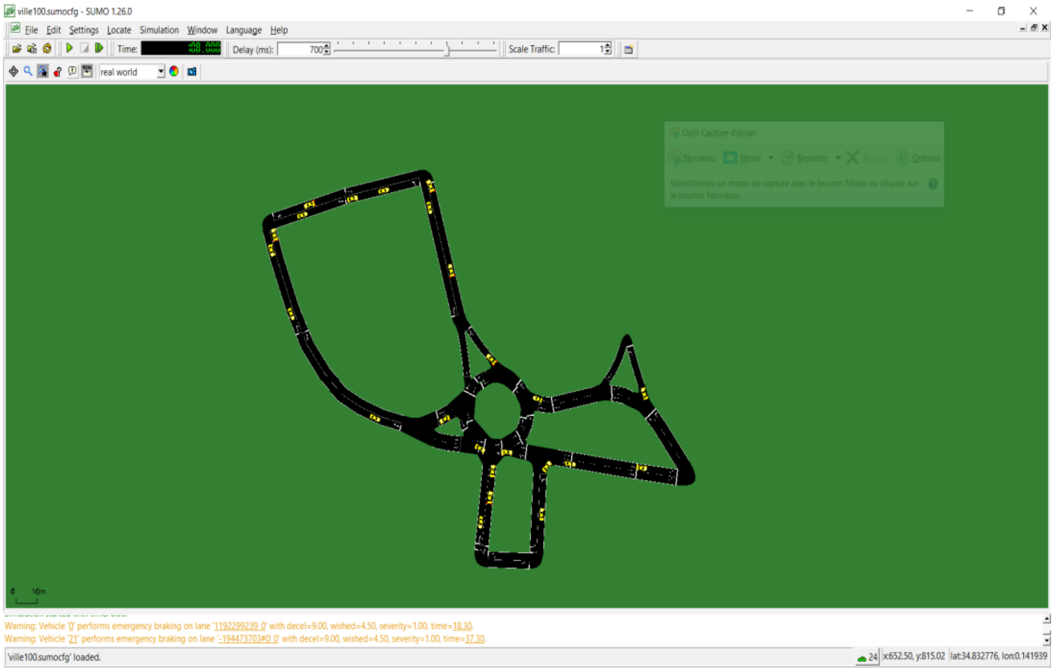
Where:
e : is the end time of simulation.
p : is the period (the time interval between two cars which means how many seconds is needed to create a new vehicle).
In the first simulation step we used 50 vehicles to simulate the road network, and we fixed the simulation end time to 200s, which means that a new vehicle appears every 4 seconds.

$$Periode = \frac{end\ time}{number\ of\ vehicles} \tag{4.1}$$

The resulting file « routes.rou.xml» used to define the traffic behaviour in the simulation. Contains the following information (tag):

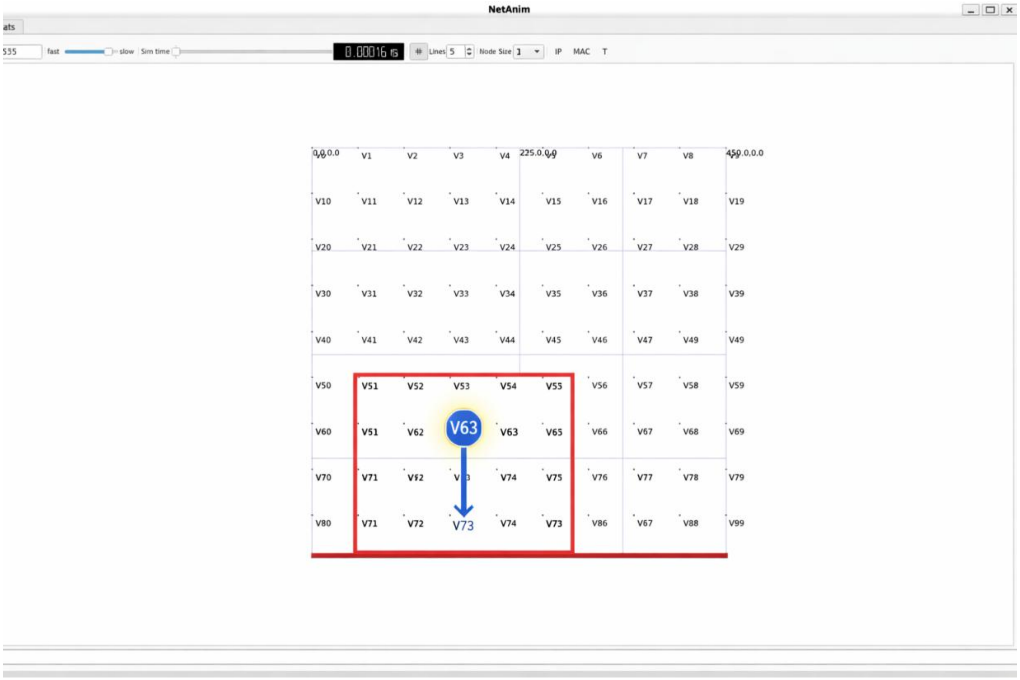
- <vType> definitions of vehicle lengths, speeds, emissions.
- <route> paths as edge sequences (e.g., edge1→edge2→intersection)
- <vehicle> instances with depart times for 50 vehicle.

The following figure present the realistic urban mobility scenario generated using SUMO with OpenStreetMapdata. Figure 4.4 shows a corresponding Netanim interface.



```
Warning: Vehicle '0' performs emergency braking on lane '1192299239_0' with decel=9.00, wished=4.50, severity=1.00, time=18.30.
Warning: Vehicle '21' performs emergency braking on lane '-194473703#0_0' with decel=9.00, wished=4.50, severity=1.00, time=37.30.
'ville100.sumocfg' loaded.
```

(a)



(b)

Figure 4.4 SUMO interface (a) and Netanim interface (b)

IV.5 Part one: performance evaluation of routing protocols

IV.5.1 Simulation performance metrics: In a VANET project using ns-3, metrics are calculated from the statistics provided after the simulation ends, using FlowMonitor.

FlowMonitor in **ns-3** is a built-in tool for collecting and analyzing network performance metrics during and after a simulation. Below we define the key performance metrics used in this work.

- **Packet Delivery Ratio (PDR)**: Percentage of successfully delivered packets per flow.

$$PDR = \left(\frac{Number\ of\ Packets\ Received}{Number\ of\ Packets\ sent}\right) * 100 \qquad (4.2)$$

- **Throughput:** measures the amount of data that actually arrived (RX) per second.

$$\text{Throughput} = \frac{RXbytes*8}{Flow\ duration} \qquad (4.3)$$

Where Flow duration =240-30=210s

- **Delay:** measures the time taken for a data packet to travel across the network from the source vehicle to the destination vehicle. The average delay is given as:

$$\text{Average delay} = \frac{Sum\ delay}{Total\ received\ packets} \qquad (4.4)$$

- **Jitter:** Defines how much that delay varies from one packet to the next:

$$\text{Average Jitter} = \frac{sum\ jitter}{Total\ received\ packets-1} \qquad (4.5)$$

IV.5.2 Results for 50 vehicles

Firstly, we present in the following table the obtained results using 50 vehicles.

Table 4.2 Results for 50 vehicles

PROTOCOL	TX packets	RX packets	LOST packets	PDR	Average Flow Throughput (Mbps)	Avg Delay (ms)	Avg Jitter (ms)
AODV	40000	11134	28866	27.83 %	0.217	151.967	105.135
OLSR	40000	6400	33600	16.00 %	0.124	1.027	0.582
DSDV	40000	3781	36219	9.45 %	0.737	996.201	804.996

IV.5.3 Results for 100 vehicles

Secondly, we present in the following table the obtained results using 100 vehicles.

Table 4.3 Results for 100 vehicles

PROTOCOL	TX packets	RX packets	LOST packets	PDR	Average Flow Throughput (Mbps)	Avg Delay (ms)	Avg Jitter (ms)
AODV	80000	25296	54704	31.62%	0.493	297.266	146.501
OLSR	80000	16439	63871	20.5%	0.320	532.382	377.61
DSDV	80000	3376	76624	4.22%	0.066	1025.28	523.32

IV.5.4 Performance Comparaison Graphs

The graphical representation of the obtained results using 100 vehicles is given in the following figures.

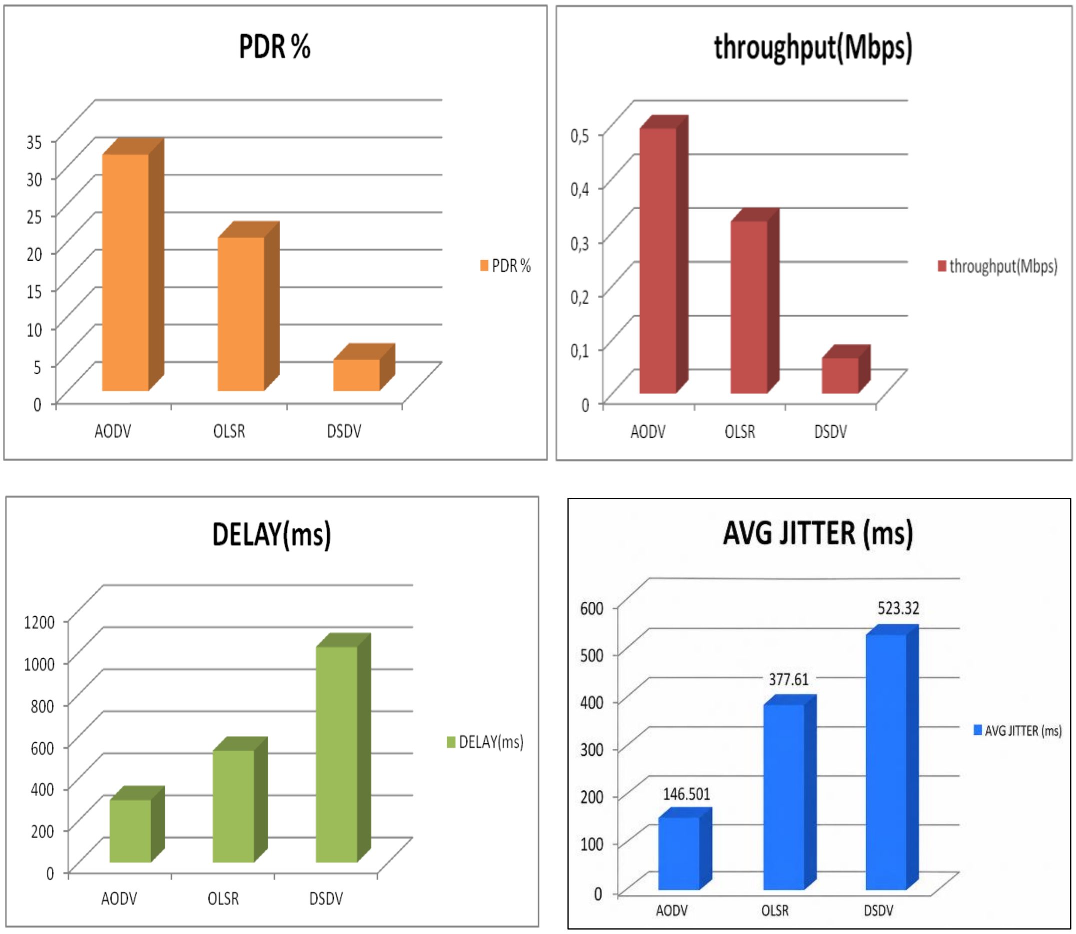


Figure 4.5 Performance Comparison Graphs

IV.5.5 Observation and Interpretation

One of the key observations from the simulation results is that the Packet Delivery Ratio (PDR) values are relatively low for all three routing protocols, however AODV achieved higher results (27.83% for 50 vehicles and 31.62% for 100 vehicles), followed by OLSR (16%) and DSDV (9.45%). Although these values may seem low at first glance, they can be explained by the challenging conditions of an urban VANET environment and further mobility and load traffic conditions:

a) High Vehicle Mobility and Continuous Topology Changes

In this simulation, vehicles moved at speeds between 10 and 60 km/h on a realistic urban road map of Saida City in Algeria. Since vehicles are constantly moving, connections between them change very quickly. As a result, routes become invalid before data transmission is completed. AODV must repeatedly search for new routes, which increases delay, while OLSR and DSDV may continue using routing information that is no longer accurate. This frequent route disruption leads to packet losses and lowers the overall PDR.

b) High Traffic Load (UDP CBR Transmission)

The network generated a large amount of traffic using UDP Constant Bit Rate (CBR): 40,000 packets for 50 vehicles and 80,000 packets for 100 vehicles during only 200 seconds. When many packets are transmitted simultaneously, the wireless channel becomes congested. This increases packet collisions and may overload node buffers, causing some packets to be dropped before reaching their destination.

c) Urban Environment and Signal Limitations

Urban scenarios are naturally more complex than highways. Buildings, intersections, and dense street structures interfere with wireless communication and weaken signal propagation. Even though IEEE 802.11p supports communication up to around 300 meters, obstacles in urban areas often interrupt the connection between vehicles. As a result, more packets are lost during transmission, reducing the Packet Delivery Ratio.

Overall, the relatively low PDR values are not necessarily caused by poor protocol performance alone, but mainly by the combined effects of **vehicle mobility, heavy network traffic, and the challenging urban communication environment**

- **DSDV shows the best** Throughput **with 50 vehicles**

DSDV is a **proactive routing protocol**, meaning it keeps routes updated all the time. With only 50 vehicles, the network isn’t too crowded, so DSDV’s constant updates don’t overload it. Because routes are already known, packets move quickly without waiting for route discovery. That’s why the **data rate (Throughput)** is higher — the protocol spends less time finding paths and more time sending data.

- **OLSR has the lowest** Delay **with 50 vehicles**

OLSR is also proactive but uses **MultiPoint Relays (MPRs)** to reduce unnecessary transmissions. In a medium-density network (like 50 vehicles), MPRs work efficiently, cutting down on redundant messages. This leads to faster packet delivery and less waiting time, giving OLSR the **lowest average delay** among the protocols.

- **AODV achieves the best** PDR **with both 50 and 100 vehicles**

AODV is a **reactive protocol**, which means it creates routes only when needed. This mechanism reduces control overhead and avoids sending packets through broken or outdated paths. As the network grows (100 vehicles), AODV adapts dynamically — it quickly finds new routes when links break. That flexibility helps it maintain the **highest Packet Delivery Ratio (PDR)**, even in larger, more mobile networks.

IV.5.6 Summarize

Among the three evaluated routing protocols, AODV achieved the best overall performance in terms of Packet Delivery Ratio (PDR) and throughput in both network scenarios. Its reactive routing mechanism enables it to adapt efficiently to the frequent topology changes that characterize VANET environments, particularly in the 100-vehicle scenario.

OLSR demonstrated moderate performance. It achieved the lowest delay in the 50-vehicle scenario thanks to its proactive routing strategy and the efficient use of MultiPoint Relays (MPRs). However, its performance degraded as network density increased, leading to higher delay and routing overhead.

DSDV exhibited the weakest performance among the evaluated protocols. Its reliance on periodically updated routing tables makes it less suitable for highly dynamic vehicular environments, resulting in low PDR, reduced throughput, and high delay, especially in dense networks.

Overall, the results indicate that **AODV** provides the best balance between reliability, scalability, and data delivery performance in VANET scenarios. Therefore, reactive routing protocols appear to be more effective than proactive protocols in highly mobile and rapidly changing vehicular networks.

The simulation results indicate that:

- AODV is the most efficient routing protocol among the evaluated protocols for VANET environments.

- OLSR provides acceptable performance and achieves very low delay in medium-density networks, but its efficiency decreases as network density increases.

- DSDV is not well suited for highly dynamic vehicular networks due to its low packet delivery performance and high routing overhead.

IV.6 Part two performance evaluation of safety messages

IV.6.1 Basic Safety Messages (BSM)

In the following table we present the simulation parameters of the BSM on the same road topology and environment described previously.

Table 4.5 BSM Simulation Parameters

PARAMETERS	VALUE
Communication Type	Unicast
Number of Vehicles	100 vehicles
Simulation Time	200 s
Wireless Standard	IEEE 802.11p
PHY Data Rate	6 Mbps
Channel Bandwidth	10 MHz
Communication Range	500 m
Transport Protocol	UDP
Application Type	BSM Safety Messages
Packet Payload Size	200 Bytes
BSM Header Size	52 Bytes
Total Packet Size	252 Bytes
Transmission Interval	0.5 – 0.6 s
Frequency Band	5 GHz
Tx Power	30 dBm

IV.6.1.1 Performance Evaluation of BSM

The performance of the proposed BSM communication system was evaluated using several Quality of Service (QoS) metrics. These metrics are essential for analysing the reliability and efficiency of vehicular safety communications:

- **Packet Delivery Ratio (PDR)**

Packet Delivery Ratio represents the percentage of successfully received BSM packets compared to the total transmitted packets.

- **End-to-End Delay**

End-to-End Delay measures the time required for a BSM packet to travel from the sender vehicle to the receiver vehicle.

$$\text{Delay}=\text{ReceiveTime}-\text{SendTime} \tag{4.6}$$

- **Packet Loss Ratio**

$$\text{PLR}= (\text{LostPackets}/ \text{SentPackets})\times 100 \tag{4.7}$$

- **Throughput**

$$\text{Throughput}=\text{ReceivedData}/\text{SimulationTime} \tag{4.8}$$

IV.6.1.2 Results and interpretation

In contrast to the previous scenario, where only position, speed, acceleration and braking,..etc information's were exchanged and routed over the road network, the current scenario added a critical issue related to driver fatigue (such as drowsiness). This safety-critical information must be efficiently delivered to neighboring vehicles in order to prevent potential accidents.

Table 4.6 Results and interpretation

METRIC	VALUE	INTERPRETATION
Total Transmitted Packets (TX)	35957	Total number of generated BSM packets
Total Received Packets (RX)	35711	Successfully received BSM packets
Lost Packets	246	Packets lost during transmission
Packet Delivery Ratio (PDR)	99.316 %	Excellent delivery performance
Packet Loss Ratio (PLR)	0.684 %	Very low packet loss
Average Delay	0.000771 s (0.771 ms)	Very low communication latency
Minimum Delay	0.000526 s (0.526 ms)	Best communication condition
Maximum Delay	1.00463 s	Rare isolated delay spike
Delay Standard Deviation	0.01173 s	Stable delay behavior
Throughput	363.674 kbps	Stable BSM traffic transmission
Effective Simulation Duration	197.961 s	Active communication duration

In the implemented unicast BSM scenario, each vehicle acted simultaneously as a transmitter and a receiver. Every node periodically transmitted BSM packets to a specific neighboring vehicle while also listening for incoming packets from another vehicle.

The destination mapping followed a circular communication pattern where node (i) transmitted packets to node (i+1), while the last node transmitted to node (0). This design enabled continuous unicast communication across the vehicular network.

The obtained results (table 4.6) demonstrate excellent network performance for BSM unicast communication in the proposed VANET scenario. The Packet Delivery Ratio exceeded 99%, indicating highly reliable communication between vehicles.

The average end-to-end delay remained below 1 ms, which confirms the suitability of the proposed system for real-time vehicular safety applications. Although a few isolated packets experienced delays close to 1 second, these cases were rare and did not significantly affect the global network performance. Moreover, the throughput remained stable throughout the simulation, proving that the network successfully supported continuous BSM transmission under dynamic vehicular mobility conditions.

Overall, the integration of SUMO and ns-3 with IEEE 802.11p achieved efficient and reliable vehicular communication performance.

IV.6.2 Decentralized Environmental Notification (DENM)

In this simulation scenario, a Decentralized Environmental Notification Message (DENM) mechanism was implemented in NS-3 to model driver fatigue warning dissemination in a Vehicular Ad Hoc Network (VANET).

The objective of this scenario is to evaluate the reliability and responsiveness of DENM-based safety message dissemination during driver fatigue situations in VANET environments. Four vehicles were selected to generate fatigue events during the simulation:

- Vehicle 10 at 50 s
- Vehicle 25 at 80 s
- Vehicle 75 at 100 s
- Vehicle 50 at 140 s

Each fatigue event remains active for 10 seconds. During this interval, the corresponding vehicle transmits DENM warning messages every 5 seconds using unicast communication. Each DENM packet contains important contextual information such as vehicle position, speed, acceleration, direction angle, event identifier, event type, severity level, and transmission timestamp. (2 messages for each fatigue events)

The severity level of the fatigue event is dynamically computed according to the vehicle speed:

- Severity 1: speed lower than 10 m/s
- Severity 2: speed between 10 m/s and 20 m/s
- Severity 3: speed greater than or equal to 20 m/s

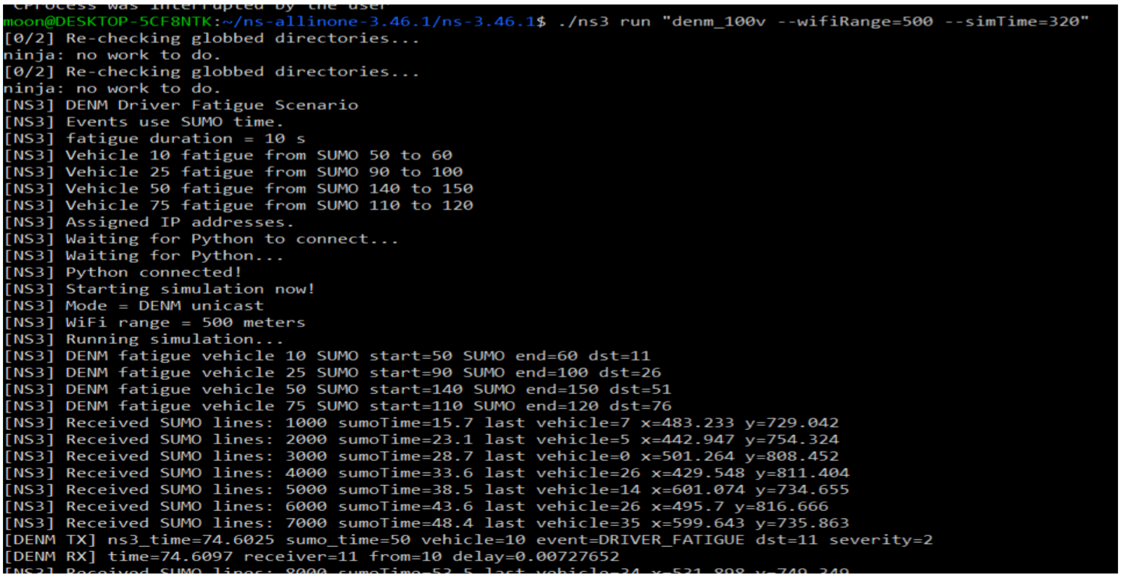
IV.6.2.1 DENM Simulation Parameters and results

In the following table we present the simulation parameters of the DENM on the same road topology and environment described previously.

Table 4.7 DENM Simulation Parameters

PARAMETERS	VALUE
Number of vehicles	100
Simulation time	200 s
Communication type	Unicast
Wireless standard	IEEE 802.11p
Transport protocol	UDP
WiFi range	500 m
Event type	Driver Fatigue
DENM cooldown	5 s
Fatigue duration	10 s

The following figure illustrates the execution of the DENM simulation in ns-3. Driver fatigue events are generated for selected vehicles at predefined times, triggering the transmission of DENM warning messages in unicast mode. The console output shows the interaction between ns-3 and SUMO, as well as message transmission and reception details, including the sender, destination vehicle, event type, and communication delay. These logs confirm the successful dissemination of DENM safety messages during the simulation.



```
moon@DESKTOP-5CF8NTK:~/ns-allinone-3.46.1/ns-3.46.1$ ./ns3 run "denm_100v --wifiRange=500 --simTime=320"
[0/2] Re-checking globbed directories...
ninja: no work to do.
[0/2] Re-checking globbed directories...
ninja: no work to do.
[NS3] DENM Driver Fatigue Scenario
[NS3] Events use SUMO time.
[NS3] fatigue duration = 10 s
[NS3] Vehicle 10 fatigue from SUMO 50 to 60
[NS3] Vehicle 25 fatigue from SUMO 90 to 100
[NS3] Vehicle 50 fatigue from SUMO 140 to 150
[NS3] Vehicle 75 fatigue from SUMO 110 to 120
[NS3] Assigned IP addresses.
[NS3] Waiting for Python to connect...
[NS3] Waiting for Python...
[NS3] Python connected!
[NS3] Starting simulation now!
[NS3] Mode = DENM unicast
[NS3] WiFi range = 500 meters
[NS3] Running simulation...
[NS3] DENM fatigue vehicle 10 SUMO start=50 SUMO end=60 dst=11
[NS3] DENM fatigue vehicle 25 SUMO start=90 SUMO end=100 dst=26
[NS3] DENM fatigue vehicle 50 SUMO start=140 SUMO end=150 dst=51
[NS3] DENM fatigue vehicle 75 SUMO start=110 SUMO end=120 dst=76
[NS3] Received SUMO lines: 1000 sumoTime=15.7 last vehicle=7 x=483.233 y=729.042
[NS3] Received SUMO lines: 2000 sumoTime=23.1 last vehicle=5 x=442.947 y=754.324
[NS3] Received SUMO lines: 3000 sumoTime=28.7 last vehicle=0 x=501.264 y=808.452
[NS3] Received SUMO lines: 4000 sumoTime=33.6 last vehicle=26 x=429.548 y=811.404
[NS3] Received SUMO lines: 5000 sumoTime=38.5 last vehicle=14 x=601.074 y=734.655
[NS3] Received SUMO lines: 6000 sumoTime=43.6 last vehicle=26 x=495.7 y=816.666
[NS3] Received SUMO lines: 7000 sumoTime=48.4 last vehicle=35 x=599.643 y=735.863
[DENM TX] ns3_time=74.6025 sumo_time=50 vehicle=10 event=DRIVER_FATIGUE dst=11 severity=2
[DENM RX] time=74.6097 receiver=11 from=10 delay=0.00727652
```

Figure 4.6 Execution of the DENM simulation scenario in ns-3

Table 4.8 Results

METRIC	**VALUE**
Total DENM transmitted packets	8
Total DENM received packets	8
Packet Delivery Ratio (PDR)	100%
Communication mode	Unicast
Number of fatigue vehicles	4
DENM per vehicle	2
Packet size	264 bytes
Minimum delay	0.000542 s
Maximum delay	0.007276 s
Event type	**DRIVER_FATIGUE**

The obtained results confirm the successful implementation of the DENM driver fatigue scenario in the VANET simulation environment.

A total of 8 DENM packets were transmitted and successfully received during the simulation. The messages were generated only when fatigue events became active, which demonstrates the event-driven nature of DENM communication. Four vehicles generated fatigue events: Vehicle 10, Vehicle 25, Vehicle 50 , Vehicle 75. Each vehicle transmitted two DENM warning messages during the fatigue interval because the fatigue duration was configured to 10 seconds and the DENM cooldown interval was fixed at 5 seconds.

The simulation logs show that all DENM packets were correctly delivered to their intended destinations using unicast communication. Therefore, the Packet Delivery Ratio (PDR) reached 100%, indicating highly reliable communication under the selected network conditions.

The measured end-to-end delay remained very low. Most packets experienced delays close to 0.5 ms, while the maximum observed delay was approximately 7.27 ms. These low latency values demonstrate the ability of IEEE 802.11p to support real-time dissemination of emergency warning messages in vehicular networks. The severity level was dynamically determined according to vehicle speed. Vehicles moving at moderate speeds generated severity level 2, while slower vehicles generated severity level 1.

The obtained results validate the effectiveness of the proposed DENM-based driver fatigue warning mechanism for reliable and timely safety message dissemination in VANET environments.

IV.6.3 Evaluation of BSM and DENM in VANET Simulation

Table 4.9 Comparison: BSM vs DENM in VANET Simulation

METRIC	BSM (Basic Safety Messages)	DENM (Driver Fatigue Scenario)	OBSERVATION
Communication Type	Periodic (continuous)	Event-driven (on demand)	DENM is more selective
Network Load	High	Very low	DENM reduces congestion
Total Packets	Very large (continuous transmission)	8 packets	DENM is lightweight
Packet Delivery Ratio (PDR)	99.31%	100%	DENM slightly more reliable
Average Delay	~0.00077 s	~0.00054 – 0.00727 s	Both very low latency
Maximum Delay	~1.00 s	~0.00727 s	DENM more stable overall
Scalability	Low in dense networks	High scalability	DENM more efficient
Use Case	Continuous monitoring	Emergency detection	Different purposes

As depicted in the above table, BSM and DENM serve two complementary roles in Vehicular Ad hoc Networks (VANETs). BSM ensures continuous situational awareness by periodically forwarding vehicle states, but at the cost of higher network load and bandwidth consumption. In contrast, DENM is highly efficient and optimized for safety-critical events, transmitting messages only when necessary.

The simulation results clearly show that DENM significantly reduces network overhead while maintaining excellent reliability and very low delay. Therefore, a hybrid use of both mechanisms is recommended in real VANET systems: BSM for general awareness and DENM for emergency response scenarios such as driver fatigue detection.

IV.6.4 Conclusion

The simulation results showed that vehicle density has a direct impact on communication performance in VANET environments. As the number of vehicles increased, the network became more dynamic and challenging, affecting the reliability of data transmission and the overall performance of routing protocols.

The routing protocols AODV, OLSR, and DSDV were evaluated using important network metrics such as Packet Delivery Ratio (PDR), throughput, delay, and jitter under traffic densities of 50 and 100 vehicles. Among the studied protocols, **AODV** achieved the best overall performance. It provided a higher Packet Delivery Ratio and more stable communication compared to OLSR and DSDV, especially in highly dynamic traffic conditions. OLSR showed acceptable performance in some scenarios due to its proactive routing mechanism, while DSDV presented lower efficiency because of frequent routing table updates in rapidly changing network environments.

The study also evaluated the role of safety messages in improving vehicular communication and road safety. The evaluation of **Basic Safety Messages (BSM)** and **Decentralized Environmental Notification Messages (DENM)** showed that both messages are important for intelligent transportation systems. However**, DENM** demonstrated better effectiveness in safety-critical situations because it provides event-driven alerts about accidents, road hazards, and dangerous conditions, allowing faster driver reactions. In contrast, BSM ensures continuous awareness by periodically sharing information such as vehicle position, speed, and direction.

Overall, the obtained results confirmed that **AODV** is more suitable for dynamic VANET environments and that **DENM** can provide more efficient support for safety-related applications. Together, efficient routing protocols and intelligent safety messages contribute to improving communication reliability, reducing accidents, and enhancing traffic safety in connected vehicular networks.

General Conclusion

Road traffic has become an important challenge in modern cities due to the continuous increase in the number of vehicles and the growing complexity of transportation systems. Congestion, road accidents, unsafe driving behavior, close distances between vehicles, and driver fatigue are problems that affect both safety and traffic flow every day. These challenges highlight the need for smarter transportation solutions capable of improving road monitoring and helping drivers make safer decisions.

In this work, we focused on Vehicular Ad Hoc Networks (VANETs) and Vehicle-to-Vehicle (V2V) communication technologies as part of Intelligent Transportation Systems. The main idea behind these technologies is to allow vehicles to communicate with each other in real time by exchanging important information about traffic conditions, vehicle movement, and possible dangers on the road. To study this concept, we carried out simulations based on Saida City using SUMO and NS-3. We analyzed and compared three routing protocols—AODV, OLSR, and DSDV—under different traffic densities. The evaluation was based on important performance metrics such as Packet Delivery Ratio (PDR), throughput, delay, and jitter.

From the obtained results, we found that **AODV** achieved the best overall performance compared to OLSR and DSDV. AODV showed better Packet Delivery Ratio and more stable communication, especially in dynamic vehicular environments with changing vehicle density. This demonstrates that reactive routing protocols are more suitable for highly mobile VANET scenarios where maintaining reliable communication is essential for traffic monitoring and safety applications.

We also investigated the role of safety messages in improving road safety by evaluating Basic Safety Messages (BSM) and Decentralized Environmental Notification Messages (DENM). The results showed that both messages play an important role in vehicular communication, but **DENM** proved to be more effective for safety-critical situations because it provides event-driven alerts about accidents, hazards, or dangerous road conditions. This allows vehicles and drivers to react quickly to unexpected events. On the other hand, BSM remains essential for continuous awareness by regularly sharing vehicle information such as speed, direction, and position.

Overall, we demonstrated that connected vehicle technologies can significantly improve road safety and traffic efficiency.

As future work, we can extend this study by evaluating additional routing protocols, larger traffic scenarios, and advanced communication technologies to further improve the reliability and efficiency of intelligent transportation systems and combination of efficient routing protocols such as AODV and intelligent safety messaging systems like DENM to reduce accidents, improve driver awareness, and support smarter transportation systems.

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