FIT Fukuoka Institute of Technology
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DOCTORAL THESIS

Implementation and Performance Evaluation of Intelligent Fuzzy-based Systems and a Testbed for Vehicular Networks

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Abstract

Recently, smart cities and Internet of Things (IoT) applications, such as Vehicular Networks and Opportunistic Networks, have been deeply investigated. However, these kinds of wireless networks have many issues such as network partitioning, network management, information dissemination, security, privacy, and so on. Now, driver assistance systems are used in vehicles and they are saving thousands of lives around the world every day. With the advancement of Vehicular Networking and Artificial Intelligence (AI), the driving support systems will enhance the driving experience and make it safer and convenient.

This thesis focuses on both directions: vehicular networking and driver assistance systems because these technologies can simultaneously coexist and complement each other for road safety. To deal with network partitioning, management, communication, security and driving safety issues in Vehicular Networks, we propose and implement intelligent Fuzzy Logic (FL) based systems considering unique factors, such as vehicle density, speed and mobility, in addition to general aspects like security and trustworthiness. These factors are different and do not correlate with one another, which makes the problem NP-Hard. For this reason, we use FL. The proposed systems can enable efficient and effective modeling of such inherently ambiguous notions as driver's conditions and driving situations.

We evaluate the implemented systems by simulations and experiments. The simulation results show that the proposed systems have a good performance and support the drivers for different driving situations. In order to compare the simulation results, we presented two models for each system. The results indicate that the performance is related to the number of considered parameters and complexity. In order to carry out experiments, we designed and implemented a portable and non-intrusive testbed. By using the testbed, we evaluated the proposed driver monitoring system and gathered critical data for the driving risk management system. We also compared simulation results and experimental results. The comparison results show that the simulation results and experimental results are close to each other.

This thesis contributes to the research field as following: 1) We provide deep insights for vehicular networking and its applications; 2) Proposal, implementation and performance evaluation of a cluster management system based on FL for vehicular networks; 3) Proposal, implementation and performance evaluation of an intelligent fuzzy-based driving monitoring system; 4) Proposal, implementation and performance evaluation of an intelligent fuzzy-based system for driving risk management; 5) Comparison of different models for the proposed intelligent systems; 6) Implementation of a testbed for the proposed intelligent driving-support systems; 7) Comparison of simulation results and experimental results.

The thesis structure is as follows. In Chapter 1 is presented the background, motivation and structure of the thesis. Chapter 2 introduces Wireless Networks. Chapter 3 presents Vehicular Networks. In this chapter, the concepts, applications, radio access technologies, network architectures, data dissemination, security and privacy are explained in detail. Chapter 4 introduces Intelligent Algorithms. Chapter 5 provides basic information underlying FL theory, fuzzy sets and fuzzy systems. Chapter 6 presents the implemented intelligent fuzzy-based systems. In Chapter 7, we discuss the evaluation results of the proposed systems and the implemented testbed. In Chapter 8, we conclude this thesis and give the future work.

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List of Abbreviations

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G-NR	5G New Radio
5GCAR	5G Communication Automotive Research and innovation
5GCARMEN	5G for Connected and Automated Road Mobility in the European UnioN
5GPPP	5G Infrastructure Public Private Partnership
6G	Sixth Generation
ACO	Ant Colony Optimization
AI	Artificial Intelligence
AmI	Ambient Intelligence
ANN	Artificial Neural Network
AP	Access Point
BC	Brakes Condition
BOA	Bisector Of Area
BS	Base Station
BTV	Body Temperature Variation
CAM	Cooperative Awareness Message
CC	Connected Cars
C-ITS	Cooperative-Intelligent Transportation System
COA	Center Of Area
COG	Center Of Gravity
DAS	Driver Assistance System
DENM	Decentralized Environmental Notification Message
DMS	Driver Monitoring System
DRM	Driving Risk Management
DS	Driving Speed
DSA	Driver′s Situational Awareness
DSRC	Dedicated Short Range Communication
DVS	Driver′s Vital Signs
ECG	*Electrocardiogram*
EDGE	Enhanced Data rates for GSM Evolution
EEG	*Electroencephalogram*
EMG	*Electromyogram*
eMBB	Enhanced Mobile Broad-Band
EODS	Enhanced Opposite Direction Search
EOG	*Electro-oculogram*

ET	Environment Temperature
ETC	Electronic Toll Collection
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FCMS	Fuzzy Cluster Management System
FDMS	Fuzzy Driver Monitoring System
FL	Fuzzy Logic
FLC	Fuzzy Logic Controller
FLS	Fuzzy Logic System
FRB	Fuzzy Rule Base
FS	Fuzzy Set
FSDRM	Fuzzy System for Driving Risk Management
GA	Genetic Algorithm
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GUI	Graphic User Interface
HC	Hill Climbing
HR	Heart Rate
HSPA	High-Speed Packet Access
HSPA+	Evolved High-Speed Packet Access
IA	Intelligent Algorithm
ICN	Information-Centric Networking
ICT	Information and Communication Technology
IoT	Internet Of Things
IoV	Internet Of Vehicles
ISM	Industrial, Scientific and Medical
ITS	Intelligent Transportation System
ITU	International Telecommunication Unit
I2N	Infrastructure-to-Network
KM	Karnik-Mendel
LAN	Local Area Network
LTE	Long Term Evolution
MANET	Mobile Ad hoc Network
MeOM	Mean Of Maxima
MF	Membership Function
ML	Machine Learning
mMTC	Massive Machine-Type Communication
MOM	Middle Of Maximum
MSM	Motion Sensor Module
NFV	Network Function Virtualization
NL	Noise Level
NP-hard	Non-deterministic Polynomial-time hard
PERCLOS	Percentage of eyelid closure
PSO	Particle Swarm Optimization
P2N	Pedestrian-to-Network
QoS	Quality Of Service
RC	Road Condition
RH	Relative Humidity

RR	Respiratory Rate
RSU	Road Side Unit
RSUC	Road Side Unit Controller
SA	Simulated Annealing
SAE	Society of Automotive Engineers
SDN	Software Defined Networking
SDNC	Software Defined Networking Controller
SSC	Steering Systems Condition
TC	Tires Condition
TR	Type-Reducer
TS	Tabu Search
T1 FS	Type-1 Fuzzy Set
T2 FS	Type-2 Fuzzy Set
UMTS	Universal Mobile Telecommunications System
URLLC	Ultra-Reliable Low-Latency Communication
VANET	Vehicular Ad hoc Network
VCBV	Volunteer Computing-Based VANET
VCC	Vehicular Cloud Computing
VDC	Vehicle Degree of Centrality
VEC	Vehicular Edge Computing
VET	Vehicle's Environment Temperature
VIE	Vehicle's Interior Environment
VLC	Visible Light Communication
VRLC	Vehicle Remain or Leave Cluster
VRSVC	Vehicle Relative Speed with Vehicle Cluster
VS	Vehicle Security
VT	Vehicle Trustworthiness
VTC	Vehicle's Technical Condition
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-everything
WAVE	Wireless Access in Vehicular Environments
WBAN	Wireless Body Area Network
WC	Weather Condition
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WPAN	Wireless Personal Area Network
WRAN	Wireless Regional Area Network
WRS	Weather-Road-Speed
WSN	Wireless Sensor Network
WWAN	Wireless Wide Area Network

Chapter 1

Introduction

1.1 Background

Road traffic accidents claim approximately 1.35 million lives each year and cause up to 50 million non-fatal injuries, with many injured people incurring a disability of those injuries. And, the fact is, each of those deaths and injuries is preventable [1].

In this regard, industry, governmental institutions, and academic researchers are conducting substantial research to design and build robust systems and proper infrastructure for car accident prevention. The initiatives of many governments for the collaboration of such researchers have concluded on the establishment of Intelligent Transport Systems (ITSs). ITSs deploy intelligent transportation technologies by combining cutting-edge Information and Communication Technology (ICT) to design sustainable information and communication networks based on people, vehicles, and roads.

While there has been a wide variety of benefits provided by the ITSs over the past decades, such as easy trip scheduling and mode selection, and improved public safety, they have not come without a cost. Most ITSs rely on large, expensive centralized infrastructure-based systems that prevent the penetration of such technologies at high rates in low- and middle-income countries.

Vehicular networking has evolved to enhance safety, ease driving, offer convenience, and improve efficiency through intelligent vehicles in expanding the ITSs capabilities with fewer infrastructure costs. To date, networking functions have already been applied in vehicles with several applications and services provided but only to a limited extent due to numerous technical issues that need yet to be entirely addressed.

While some of the challenges are of a similar nature, others are different; thus, the encountered issues are mainly categorized as radio access challenges, issues related to the network architecture, and security issues. The following discusses some of the issues belonging to each category.

Given that vehicular networks are a subset of wireless networks, some challenges are common to other wireless networks, such as limited transmission ranges, finite number of communication channels, and interferences. On the other hand, more challenges come from the unique characteristics of vehicular environments. Large and dynamic topologies, variable capacity wireless links, bandwidth and delay constraints, and short contact durations are some of the features of these networks. These challenges are caused by the high mobility and high speed of vehicles that, on the other hand, come in different densities even within the same area regardless of size. For example, the vehicle density is higher on main streets than on secondary ones, and it changes sharply over time—the same roads are busier during peak hours compared to night hours or other parts of the day.

The research in wireless access technologies aims to provide new ways that improve the usage of wireless resources in terms of the allocated spectrum, communication channels, power management, and so forth. Various radio technologies have emerged over the past few years with more under development in this regard, e.g., Dedicated Short Range Communication (DSRC), WiFi, Bluetooth, 4G/5G/6G, TV white space, microwave, millimeter-wave, and Visible Light Communications (VLCs). Each one of these radio technologies has the potential of solving several radio access issues while simultaneously being a full complement of one another. However, new network architectures are needed to integrate these heterogeneous technologies and enable interoperation in the harmony of multiple coexisting wireless networks.

Software Defined Networking (SDN), Network Function Virtualization (NFV), Network Slicing, Cloud Computing, Edge/Fog Computing, and Information-Centric Networking (ICN), among others, are some of the approaches and paradigms that not only promise to enable the required interoperation but also offer new ways on dealing with the massive data information of the ever-increasing number of Vehicle-to-everything (V2X) services. However, finding the best approach that can address routing and data dissemination-related problems that the network meets the demands of Quality of Service (QoS) of all possible applications remains a complex task to be solved.

Various Artificial Intelligence (AI) approaches, including Fuzzy Logic (FL), Machine Learning (ML), and search algorithms, are actively being used in the abovementioned approaches and technologies to analyze massive data and find the underlying structures that assist in decision-making tasks. These AI approaches are also used to address the security issues in these networks. Many tools and techniques based on AI can autonomously identify and respond to potential attacks or threats based on similar or previous activity. The diversity of services comes with many security, trust, and resiliency requirements; thus, many operations must be standardized first.

Every encountered challenge is a complex research topic, and careful attention is needed to effectively address all the identified issues so that proper solutions are provided. Although a more detailed overview of the mentioned challenges is given in the following chapters, the main objective of the work presented in this thesis is to deal with the problems described in the following, with the rest of the areas left for future work.

1.2 Motivation and Objectives

The state-of-the-art technologies in vehicular networking are paving the way not only for a complete deployment of the Connected Cars (CC) technology but also for reaching a bigger goal, that of putting the fully autonomous vehicles on the roads.

Although the highly competitive and rapidly advancing autonomous vehicle race has been on for several years now, the current advances fall only between the Level 2 and 3 of the Society of Automotive Engineers (SAE) levels [2].

However, even if the automotive companies do all that it takes on their end to make fully automated cars, there will still be one big obstacle, the infrastructure. Building the proper infrastructure for autonomous cars might take decades, even in the most developed countries. And yet, since 93% of the world's road fatalities occur in low- and middle-income countries [1], it is crucial to seek faster alternatives that have the potential of reducing these alarming rates.

Driver Assistance Systems (DASs) were once the pride of the biggest car manufacturers, but now they seem mostly as a shadow of their former selves. They are still, however, saving thousands of lives around the world every single day. And, with the advancement Internet of Things (IoT) and AI applications, vehicular networking, and Ambient Intelligence (AmI) in particular, DASs can get the push they need for a comeback once more as the game-changer.

Therefore, this thesis focuses on both directions—vehicular networking and driving-support systems—given that these technologies can simultaneously coexist and complement each other, and most importantly, converge at their respective ultimate goal, achieving road safety.

In this regard, the following immediate objectives were identified:

- Provision of deep insights for nehicular networking and its applications.
- Proposal, implementation, and performance evaluation of a cluster management system based on FL for vehicular networks.
- Proposal, implementation, and performance evaluation of an intelligent fuzzy-based driving monitoring system.

- Proposal, implementation, and performance evaluation of an intelligent fuzzy system for driving risk management.
- Comparison of different models for the proposed intelligent systems.
- Implementation of a testbed for the proposed intelligent driving-support systems.
- Comparison of simulation results and experimental results.

The following paragraphs describe the scientific contributions of this thesis.

The first contribution of this thesis is the proposal and implementation of a secure and trustworthy intelligent fuzzy-based system for clustering in vehicular networks. The results of this work were presented in the *33rd International Conference on Advanced Information Networking and Applications (AINA-2019)*, which was held in Matsue, Japan. An extended version of this research work consisting of a comparison study of two intelligent fuzzy cluster management system models was published in the 55th Volume of *Cognitive Systems Research, Elsevier* [j1]. The proposed system models are presented in Section 6.2 and evaluated in Section 7.1.

The second contribution is the proposal of a fuzzy-based approach for driver condition monitoring and its implementation in a laboratory testbed. We implemented two models based on the proposed approach, and the preliminary results for each model were presented in the *13th International Conference on Complex, Intelligent, and Software Intensive Systems (CISIS-2019)* and the *22nd International Conference on Network-Based Information Systems (NBiS-2019)*, held in Sydney, Australia, and Oita, Japan, respectively. The paper presented in *CISIS-2019* received the "Best Paper Award" at the conference. The research work conducted in this regard concluded to the publication of all simulation/experimental results and all the findings in a thorough paper, published in *Future Generation Computer Systems - the International Journal of e-Science, Volume 105, Elsevier* [j2]. The details of the proposed approach and the implemented testbed are described in Section 6.3. The evaluation results are commented in Section 7.1.

The third contribution is the proposal and implementation of an integrated fuzzy-based driving-support system for real-time risk management in vehicular networks, which is presented in Section 6.4.1 and evaluated in Section 7.3. This contribution is published in *Sensors, Volume 20, Number 22, MDPI* [j3]. This contribution is an outcome of several presentations given at different International Conferences held in Taiwan, Belgium, Japan, Poland, and Canada (see International Conferences section). We express our gratitude to all the researchers for the valuable discussions we had after each presentation. We also thank the reviewers of all submitted papers for their comments. The discussions and well-received comments led us to the finalization of this contribution.

The fourth contribution of this thesis is the proposal, design, and performance evaluation of an extended version of the fuzzy-based driving risk management system, which additionally considers the vehicle's technical condition for the evaluation of the driving risk. This version was proposed as an alternative for the low-income countries where the old vehicles outnumber the new ones, and the vehicle-related problems cause many accidents. This contribution was published in the 11th Volume of *Internet of Things, Elsevier* [j4], and it is discussed between Sections 6.4.3 and 7.3.3 of this thesis.

1.3 Thesis Organization

This thesis is organized into eight chapters, and a flowchart representing its structure is given in Figure 1.1. This chapter, Chapter 1, conveys the focus of the thesis, the definition of the problems and identified objectives, the contributions, and the thesis' organization. A synopsis of the following chapters is as follows.

Chapter 2 gives an introduction to Wireless Networks and to the technologies that enable them to meet the demands of emerging applications. The concept of IoT and its enablers are also discussed in this chapter because they are the cornerstone of smart cities and vehicular networks.

Chapter 3 presents Vehicular Networks. The network architectures, the applications, the radio access technologies, the data dissemination, and the most important aspects of security and privacy, are among the main covered topics. The chapter explains in detail the technologies behind recent developments because not only are these emerging technologies the enablers of the state-of-the-art of vehicular networks but they also enable full implementation of our proposed system

Chapter 4 takes an overview of Intelligent Algorithms, which includes the principle of each algorithm, the advantages and disadvantages of their use, and several respective applications.

Chapter 5 provides fundamental information regarding FL theory, fuzzy sets, and fuzzy systems. The concept of a linguistic variable, of fuzzy operators, of Membership Functions (MFs), that of a fuzzy rule, and the inference engine process, are described in detail for a comprehensive understanding of the application of FL presented in this thesis.

Chapter 6 introduces the implemented intelligent fuzzy-based systems. It includes a description of the proposed systems concerning the objectives and motivation and gives all the implementation details one must know in order to obtain the same (simulation) results.

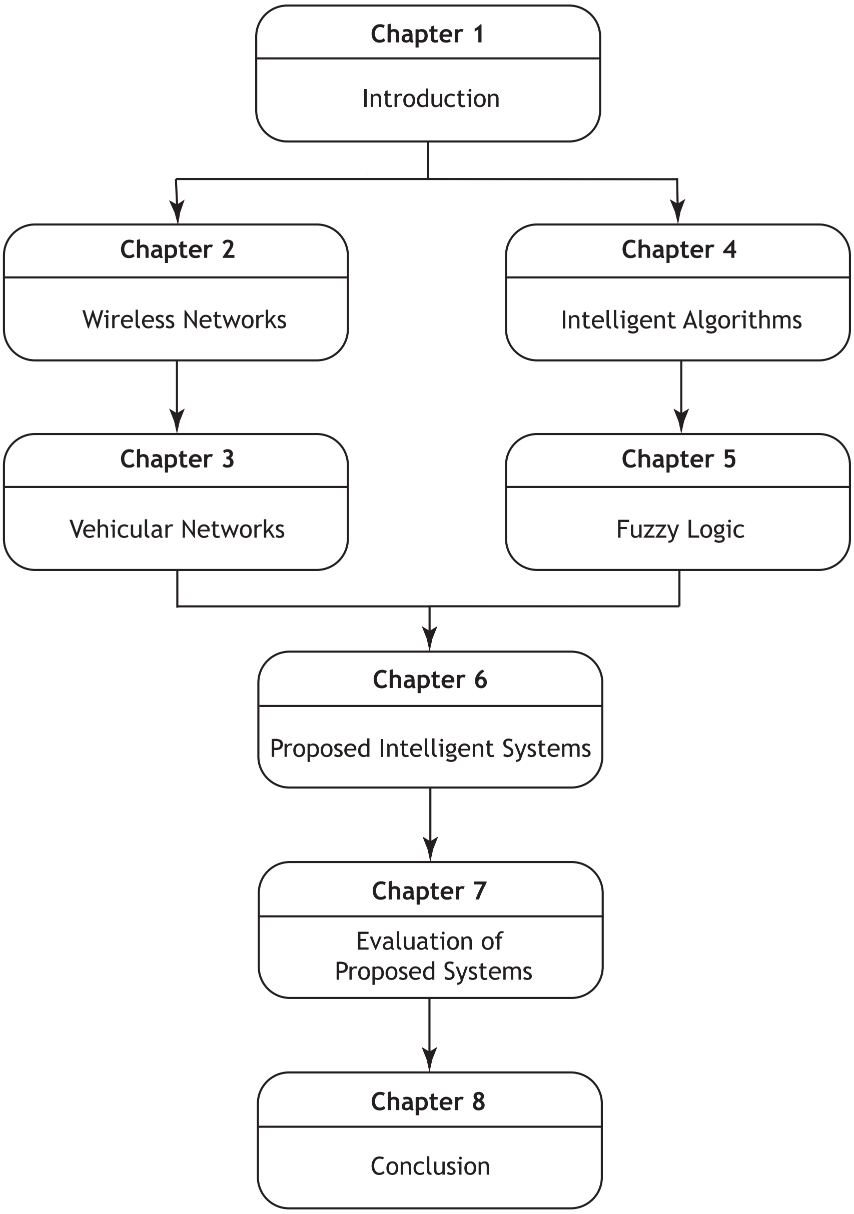

FIGURE 1.1: Thesis structure.

Chapter 7 discusses the evaluation results of the proposed systems and the implemented testbed. An analysis of the simulation results for each of the proposed systems is presented with the examination of the experimental results of the implemented testbed to follow. A comparison between relevant systems and between the simulation and experimental results is also drawn.

The last chapter, Chapter 8, concludes the thesis, summarizing the main research findings and future research directions.

Chapter 2

Wireless Networks

The last decades have seen an unprecedented growth of wireless networks, and this trend is set to continue without cease. These networks have a great impact on the way we live and the impact is expected to grow exponentially looking at how wireless systems are revolutionizing today's industries and applications while simultaneously giving shape to concepts of futuristic societies.

The focus of this chapter is on the wireless networks and technologies that are the cornerstone of a complete and widespread deployment of vehicular networks. This chapter begins with a classification of wireless networks in terms of the network architecture, to continue with a discussion over Mobile Networks (also known as Cellular Networks) and Mobile Ad hoc Networks (MANETs) as these networks are important to put vehicular networks into context. Then, it reviews important concepts and technologies such as IoT, Wireless Sensor Networks (WSNs), Cloud, Fog, and Edge computing, and SDN since these technologies are the driving force behind the successful implementation and management of vehicular networking applications. The chapter ends with a short section that presents the architecture of vehicular networks comprising all those components.

2.1 A Brief Overview

Wireless networks can be defined as networks whose communication is free of the need of using any wires, using the free space instead as the communication medium. Guglielmo Marconi gave the first demonstration of radio communication in 1897, by using radio waves to provide continuous contact with ships sailing across the English Channel. Since then, wireless communications have evolved remarkably and have become part of our everyday life. Garage door openers, radios, cellular communications, free-to-air TV, navigation and tracking, wireless security cameras, WiFi, hot spots, and contactless payments are some of the most notable examples of wireless communication systems. As the demand for connectivity is continuously increasing, many new applications ranging from smart cities and advanced intelligent

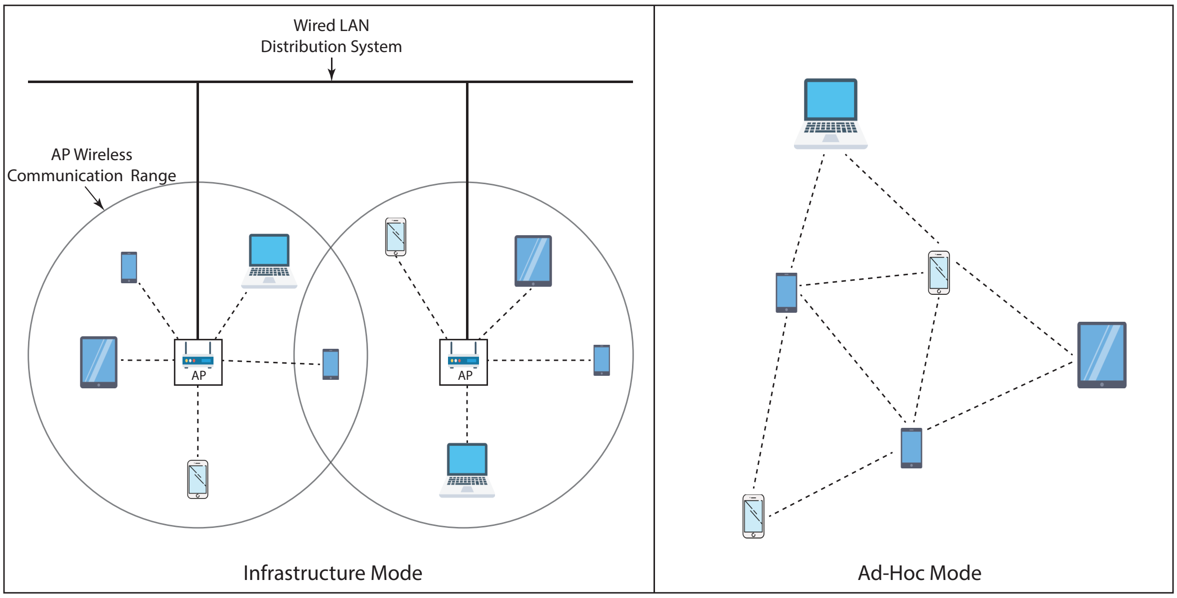

FIGURE 2.1: Simple illustration of the architecture of infrastructure-based and infrastructureless networks.

transportation systems to fully automated factories and remote telemedicine are emerging from research concepts to concrete applications.

The success of these applications is attributed to the capability of wireless networks to provide reliable connectivity between two distant terminals regardless of the distance separating them. Based on the communication distance, the wireless networks are mainly classified as Wireless Body Area Networks (WBAN), Wireless Personal Area Networks (WPAN), Wireless Local Area Networks (WLAN), Wireless Metropolitan Area Networks (WMAN), Wireless Regional Area Networks (WRAN), and Wireless Wide Area Networks (WWAN). Another way of classifying wireless networks would be based on their architecture. Although digging deep into architectures works for detailed classification, a simple classification categorizes the wireless networks into two main groups: infrastructure-based and ad hoc networks. A simple illustration of these two network architectures is given in Figure 2.1. In the following sections, we describe these architectures and explain the most common types for each group.

2.2 Infrastructure-Based Wireless Networks

Wireless networks emerged as a way to extend the coverage of a wired network in areas where installing wires was seen as impossible or as inefficient for some reason. Nowadays, wireless networks are more than just an alternative to wired networks, supporting high mobility and offering flexibility, convenience, and enhanced experiences. Wireless networks providing huge capacities, faster rates, and reliable connectivity are typically based on a fixed infrastructure (called backbone network for large-scale networks) to ensure the establishment of a communication link between any two mobile terminals at any time. In this type of architecture, even two mobile terminals close to one another cannot communicate directly; instead, communication is realized through a specialized terminal, called Access Point (AP) or Base Station (BS). The terminology to refer to this unit may differ between technologies because they offer distinguishable features, but its fundamental concept remains the same in all infrastructure-based wireless networks. In the following, we discuss Mobile Networks and WLANs as they are the most prominent types of such networks and are considered technologies that have ignited the wireless revolution.

2.2.1 Mobile Networks

Mobile networks are by far one of the most successful communication technologies that have had widespread use shortly after their appearance. The current generation of cellular networks has almost no similarity with the technology that its earliest predecessor used, and only a few principles, such as the concept of dividing the area into cells, have remained the same; however, in order to put current advances into context, we will begin this section with a short review of how these networks have changed over the last four decades.

Initially, cellular systems were designed for mobile devices inside vehicles with antennas installed on their roofs. The first generation of mobile networks (1G) had base stations covering large cells and which did not use the available radio spectrum efficiently, so their capacity was very small compared to today’s standards. In addition, the mobile devices were large and expensive, and affordable only by business users.

It was the development of digital wireless technologies that made it possible for cellular networks to have the services delivered to the masses through the development of the Global System for Mobile Communications (GSM). This technology marked the launch of the second generation of mobile networks (2G), which introduced increased voice capacity and smaller mobile cellphones. An enhancement of 2G networks came with the deployment of General Packet Radio Service (GPRS) technology, providing packet data capabilities over these networks, which supported new, data-oriented services and applications. Further enhancements of these networks arrived with the implementation of Enhanced Data rates for GSM Evolution (EDGE) that improved the data transmission rates of GPRS. Nevertheless, the mobile data was only in the beginning, and voice calls still dominated the traffic in 2G networks.

The growth of mobile data was slow even with the deployment of first commercial third generation (3G) networks—also known by the name Universal Mobile Telecommunications System (UMTS)—which were introduced in the early 2000s, but in the years leading up to 2010, its use started to increase considerably [3]. Two factors were behind this growth: the availability of enhanced 3G communication technologies, namely High-Speed Packet Access (HSPA) and Evolved HSPA (HSPA+), and the introduction of smartphones that supported numerous applications. Shortly after, the smartphones were everywhere, generating increased traffic, demanding more capacities, and requiring a reduced end-to-end latency. These issues drove the mobile networks to move to their fourth generation (4G), with the Long Term Evolution (LTE) technology denoting the first version of this generation.

Although the current research trend is focused on the fifth generation (5G), and even beyond it, we will also provide in this section a brief introduction to 4G/LTE, since the current standard of 3rd Generation Partnership Project (3GPP) for the deployment of vehicular networks is based on this technology.

4G/LTE

Whilst at the beginning was debated whether LTE should be considered a 4G technology, the controversy no longer exists because later International Telecommunication Union (ITU) gave consent to the use of term 4G to describe technologies whose performance is substantially better than the performance of 3G systems. For comparison, the peak data rates of LTE reach 300 Mbps in the downlink and 75 Mbps in the uplink under ideal signal conditions, as opposed to the last improvement of HSPA+, which delivered 84.4 Mbps and 23 Mbps in the downlink and uplink, respectively. The LTE-Advanced, which came as an improvement of LTE, took these figures to a different level, with downlink rates up to 3000 Mbps and uplink rates up to 1500 Mbps [3]. Moreover, this technology reduced the end-to-end latency in the network to even less than 5ms, proclaiming its feasibility of supporting vehicular communications in real-world scenarios. The standard for supporting vehicular communications was finally specified in 3GPP Release 14 [4], and it also includes the specifications of the LTE-Advanced Pro, which was first introduced in the previous release. LTE-Advanced Pro exceeds the limits of its predecessor, and it is considered a Pre-5G technology.

5G

What 4G has delivered is impressive, but there is more to come from 5G. There have been many use cases and applications whose technical requirements exceed the capabilities of 4G systems introduced over the last years, and 5G is expected to support them with ease. The ITU-R M.2083 [5] classifies them into three usage scenarios:

- enhanced Mobile Broad-Band (eMBB) which addresses the human-centric applications for a high-data-rate access to mobile services, multi-media content, and data. This scenario fosters new services and applications over smart devices (smartphones, tablets, and wearable electronics). It emphasizes wide-area coverage to provide seamless access and high capacity in hot spots.
- Ultra-Reliable Low-Latency Communications (URLLC) which opens the possibility for mission-critical connectivity for new applications such as automatic vehicles, Smart Grid, and Industry 4.0, which have stringent requirements on reliability, latency, and availability.
- massive Machine-Type Communications (mMTC) that supports dense connectivity with a very large number of connected devices typically deployed in IoT scenarios. The devices such as sensors are low-cost, low-power consumption but typically transmitting a low volume of delay-tolerant data.

The current standard, 5G New Radio (5G-NR), is required to reach peak data rates of 20 Gbps in downlink and 10 Gbps in uplink, but further improvements may reach even higher peak data rates. The technical performance requirements that ITU has set in the ITU-R M.2410-0 report [6] also include a minimum requirement for user plane latency of 4 ms for eMBB and 1 ms for URLLC and support for high-speed vehicular applications up to 500 km/h.

2.2.2 Wireless Local Area Networks

WLANs enable users to establish wireless connections within a local area, forming a Local Area Network (LAN) in limited areas such as within homes, coffee shops, corporate or campus buildings, or in public spaces such as parks and airports.

WLANs provide flexible data communication systems in temporary offices or other spaces where the installation of extensive cabling would be prohibitive or to supplement an existing LAN so that users can work at different locations within a building at different times.

Typical WLAN implementations include 802.11 (Wi-Fi) and Hiperlan2. Under the latest approved standard, 802.11ax (Wi-FI 6), data can reach transmission speeds between 135 Mbps to 1.2 Gbps per stream based on the channel used. The APs are the core of such networks, and the communication of two terminals is realized through these APs. The infrastructure mode illustrated in Figure 2.1 depicts how these networks are established to cover multiple users.

2.3 Infrastructureless Wireless Networks

Infrastructureless wireless networks are self-organizing networks formed by a set of independent nodes which do not rely on a pre-fixed infrastructure [7]. The nodes communicate directly with the other nodes inside their communication range and forward the necessary information in a multi-hop manner throughout the network, without a central administration. In other words, data dissemination is performed by the nodes by relaying the packets from one node to another until the data reach their destination. As an autonomous self-configuring network, they can be fully deployed in any environment/location without the need for a BS or AP. In the following, we discuss two prominent classes of these networks, MANETs, and WSNs since these networks are closely related to vehicular networks.

2.3.1 Mobile Ad Hoc Networks

MANETs were initially implemented in the military in 1970, with the aim to improve communication in devastated areas and difficult terrains [8]. A multi-hop communication was the solution to provide resilient connectivity beyond the line of sight in such a dynamic environment, in which a pre-established communication infrastructure was impossible to have. Since then, the advancements in MANET research have offered great potential even beyond the military domain.The attractive features such as redundancy, flexibility, no single points of failure, easy deployment, and low-cost installation make them appealing for several practical scenarios. Moreover, supported by standardized technologies like IEEE 802.11, HiperLAN2, Bluetooth, and ZigBee, their range of applications has significantly expanded to commercial use, from small size static networks suffering from power resources to large scale dynamic networks [9]. Examples of an application include environmental surveillance, natural disaster relief, and emergency services [10].

MANETs can operate either independently or cooperate with other networks. For example, for devices in close proximity, when the communication through a BS or an AP is inefficient, MANET is used to perform data exchange between these devices or those inside a personal area networking. An illustration of this scenario can be derived if the architectures presented in Figure 2.1 are merged. Another application is a sensor network deployed in a difficult terrain where the network infrastructure is impractical or too costly to be developed. MANETs also enable wireless communication of process plants in a distributed control system in biotech, mining, pharmaceuticals, and other industrial fields, which offer low reconfiguration and maintenance costs. Even though MANET can be deployed in a large-scale heterogeneous network covering a large surface, much remains to be done to ensure

QoS requirements, reduce interferences from outside signals, support high data rates, and overcome power constraints.

MANETs are considered to have much potential in the domain of vehicles and ITSs too. The application of MANETs capabilities in the vehicles has resulted in the conception of Vehicular Ad hoc Networks (VANETs), which on the other hand, have seen numerous challenges coming from their unique features. Compared to MANETs, VANETs have an increased number of network nodes that also move much faster, which, in turn, changes the topology more frequently. These frequent changes result in more contact opportunities, which is a positive aspect, but they also make the network suffer from intermittent connectivity [11]. Because of these particular features, vehicular networks are no longer considered a subset of MANETs but are now studied as a different type on their own.

2.3.2 Wireless Sensor Networks

Sensors offer significant help in various social problems by converting real-world events into digital data that can be processed, analyzed, stored, and acted upon. A WSN consists of a large number of sensor nodes that operate together to monitor a particular process. These sensor nodes are typically low-cost and can be deployed even in remote and rough terrains beyond human reach. A sensor node is typically composed of a power unit, a sensing module, and a low power transceiver used for data dissemination, in addition to the storage and processing capabilities that help to store, analyze, and fuse the gathered data [12]. The sensors communicate with one another and with BSs through one hop and multi-hop communications using very little power in order to increase the longevity of the network, which has the power consumption its critical challenge.

The advances of wireless communications and semiconductors have helped in increasing the network lifetime leading to widespread use of such networks. Nowadays, WSNs are deployed to monitor and model different phenomena like volcanic activity, structural health condition of tunnels and bridges, heritage buildings conservation, agriculture productivity, forecast flooding, and environmental pollutants, industrial automation process, and many more. Despite their huge potential in many applications, current WSN must deal with challenges such as limited storage and processing capability, limited communication bandwidth, and single-purpose design [13].

WSN will continue to give momentum to many new applications due to the features it provides. In ITSs and vehicular networks, WSNs are seen as a key component of heterogeneous systems cooperating along with other technologies employed in vehicular scenarios; especially, due to the little installation and maintenance costs

[14]. They can be deployed along urban roads and highways, intersections, and in parking areas to constantly obtain information and inform the driver beforehand about the weather and road condition, the traffic state, and so forth. Moreover, by connecting the sensed data to the Internet, WSN will enable numerous applications in the IoT, enhancing interaction between humans and the environment.

2.4 Emerging Concepts and Enabling Technologies

In the following section, we review concepts and technologies such as IoT, Cloud, Fog, and Edge computing, and SDN since these technologies are the driving force behind the successful implementation and management of vehicular networking applications.

2.4.1 Internet of Things

IoT refers to the network of everyday objects connected to the Internet to generate data that aim at enhancing the quality of life. These objects range from household tools and equipment to industrial machines and even humans. Everything traditional will be transformed into smart by integrating animate and inanimate objects into the information networks via embedded devices, actuators, sensor networks, communication technologies, etc. IoT will enable these devices to connect to the Internet, share information, communicate with each other and other networks free from human intervention.

Enterprises and consumers alike will profit from the large-scale deployment of IoT as this will enable a broad spectrum of services that will deliver efficient solutions to many issues. Consumers will have a better quality of life due to the capability of IoT to improve health monitoring through wearable sensors, boost home security, time efficiency, and comfort, prevent unreasonable energy consumption, advance education, and provide many other benefits. Whereas enterprises will have more profits, will offer increased service quality, and will create new business opportunities by understanding the customers' needs, boosting productivity, ameliorating decision-making in the manufacturing process, preventing malfunctions, improving transportation and logistics, and so on.

However, these benefits will not come without a cost. In order to successfully deliver applications, many requirements must be first satisfied. For example, services related to safety and healthcare are time-critical, but they do not necessarily need high bandwidth. On the other side, surveillance systems do require high bandwidth to transmit videos, but most of the time do not need the data to be transmitted in real-time. The network must identify the service needs and must be flexible to give

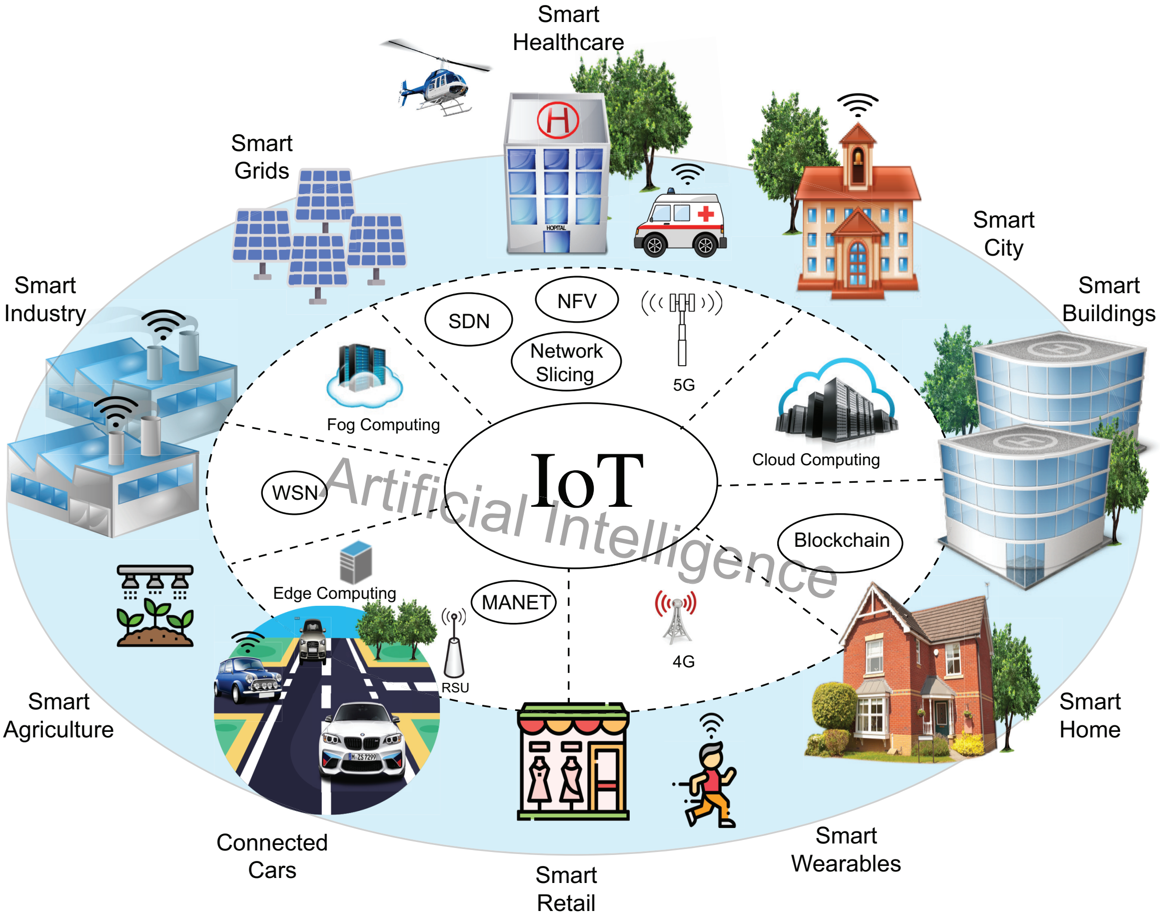

FIGURE 2.2: IoT applications and enabling technologies.

primacy to high-priority applications. Other important issues that IoT faces include interoperation with different types of systems, network data congestion, geo-fencing, and location accuracy.

Smooth interoperation of all the components participating in IoT, including Cellular Networks, MANETs, WSNs, and other enabling technologies such as Software Defined Networking, Cloud, Fog, and Edge Computing, is recognized as the feasible solution to these issues. We illustrate this conceptualization in Figure 2.2. Vehicular networks will be a crucial component of this concept as not only will vehicles use the information made available from the other integrated components but they will also share their resources and provide their information to the IoT, helping to better manage traffic, cut pollution, make better use of infrastructure and enable citizens to stay safe and clean [15].

2.4.2 Cloud, Fog, and Edge Computing

Fog computing is a highly virtualized platform that has many features that make it an appropriate platform to deliver numerous services in safety, traffic support, infotainment, and analytics: geographical distribution (across cities, and along roads, and highways), low latency, mobility support, and location awareness, among others [16]. However, despite its great attributes, it does not exclude the necessity of Cloud computing in vehicular networks. Given the significant increase in the amount of data generated by the ever-increasing number of sensors, devices, and, more importantly, vehicles; Cloud computing will continue to have its crucial role in these networks as it provides the necessary resources for big data management and analytics.

Edge computing in vehicular networks, or the so-called Vehicular Cloud Computing (VCC), Volunteer Computing-Based VANET (VCBV), Vehicular Edge Computing (VEC) or whatever this technology is named as it is roughly the same thing, consists of vehicles equipped with resources and services of networking, computing, storage, and control capabilities, which are used to process a considerably amount of data at/through the vehicles, therefore offloading massive traffic flows from core networks. If that data is sent back across a long network link to be analyzed, logged, and tracked, that takes much more time than if the data is processed at the edge, close to the source of the data [17].

2.4.3 Software Defined Networking

The core concept of SDN is the decoupling between the control plane and data plane, which provides dedicated mechanisms for resources and connectivity management. The first one is used for network traffic control and the latter for data forwarding. This separation will simplify network management that becomes extremely complicated when the number of nodes increases and the topology changes dramatically [18]. SDN can provide different applications simultaneously and adapt to changing applications' requirements and conditions in delay, propagation, and bandwidth, i.e., prioritizing safety-related applications. In addition, they support heterogeneity of wireless interfaces for better computation, storage, and high efficiency with fewer costs [19]. By reforming the data transmission rules on the network, they select different interfaces for different applications depending on their requirements [19].

Since vehicular networks are characterized by heterogeneous and dynamic environments, the traditional routing mechanisms have poor performance, causing high latency and bandwidth waste. The incorporation of SDN into these networks will increase the intelligence and flexibility to offloading communications by storing and forwarding data with low latency and by exploiting all available resources. Moreover, it will offer a centralized hybrid paradigm and provide a global view of the network. This awareness allows efficient administration and management of the network, making better routing decisions based on vehicles congestion, weather and roads conditions, jitter, packet loss rate, and other significant performance parameters [20].

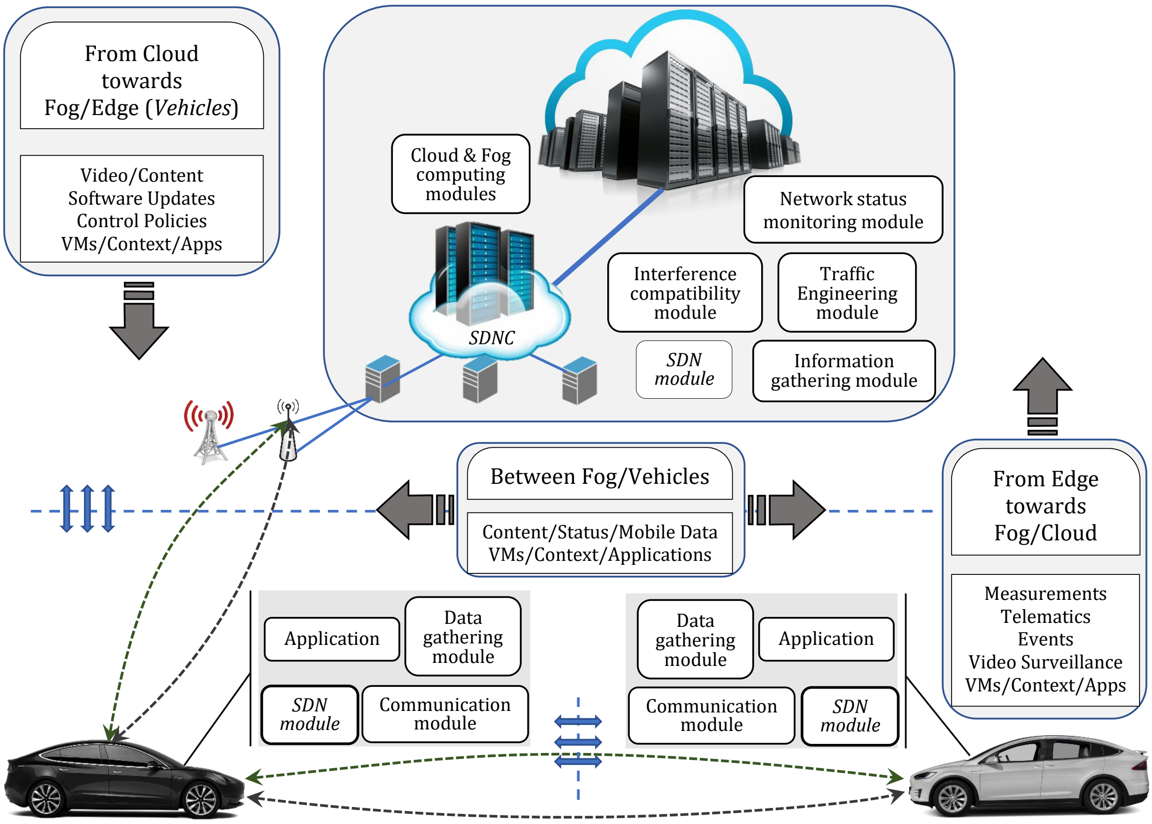

FIGURE 2.3: Cloud-Fog-Edge Computing and SDN integrated within vehicular networks and the content flow in this novel architecture.

2.5 5G SDN Vehicular Networks

The integration of all the aforementioned technologies within vehicular networks creates a hybrid system between centralized and distributed computing/network-control [21]. The basic components of this network architecture with the content distribution are given in Figure 2.3.

Certainly, vehicles constitute the key component of this integrated architecture as most of the information that flows in the network will pass through them at some point, i.e., vehicles can be at the same time a source of information, a relay node, or a destination point of the information, which, on the other hand, can be comprised of only raw data, only processed, or both of them. In addition, although different types of sources are used to acquire the same type of information, different types of information serve the same destination/application. Nonetheless, the other components—data centers, fog servers, SDN Controllers (SDNC), 5G base stations, Road Side Units (RSUs), and RSU Controllers (RSUCs)—are almost as important as vehicles because the traditional VANETs architecture, which was based only on the vehicles, has failed to meet the demands.

The sensors installed along the roads monitor the driving environment (e.g., traffic density, weather condition, the type and condition of the road) and send the sensed data to the nearest RSU. In this process, the vehicles moving nearby can also help by working as relay/processing nodes, so the sensors do not waste energy to send the generated data farther. Vehicles, which also monitor the driving environment through their sensors and cameras, can help in the processing operation if they possess the required resources. Otherwise, Cloud or Fog resources will do all the processing tasks depending on the application requirements. For instance, if the processing is needed in real-time, the resources to be used are those of Fog. Cloud servers are used as a repository for software updates, control policies, and data that need long-term analytics and are not delay-sensitive. SDNC does, by all means, the orchestration of all the processes and components involved in this architecture [20].

The implementation of this architecture promises to provide numerous services for drivers and passengers, and it will set the scene for future autonomous and connected cars.

Chapter 3

Vehicular Networks

The basic concept of vehicular networking is straightforward: take the widely adopted communication technologies used to connect mobile devices to each other and to the Internet and, with some adjustments, apply them to the domain of vehicles. Certainly, if it were that straightforward, the researchers would have never cared to develop new vehicular communication technologies, the research work presented in this thesis would likely never have been conducted, and this thesis would have never been written, or it simply would not have been focused on such networks. Vehicular networks face unique challenges caused by the high mobility and high speed of vehicles, which, on the other hand, come in different densities, even within the same areas. They also have unique requirements in terms of latency, bandwidth, coverage, availability, and so forth.

In this regard, the research community is actively developing new technologies and methods to address all the identified issues while trying to predict challenges that may come with the deployment of these technologies. But, as technologies evolve, so does the terminology related to them. Therefore this chapter focuses on different concepts of vehicular networks, details the technical aspects of some existing and emerging network architectures, describes various applications enabled through the network communications applied in vehicles, and outlines aspects related to the security and privacy of such networks. The first section aims to shed light on the distinction between several architectures of vehicular networks widely used by many researchers. The following sections are dedicated respectively to applications, radio access technologies, information dissemination in these networks, and users' security and privacy.

3.1 Network Architectures

In the following, we describe the most popular terms in literature that researchers use to describe different vehicular networks architectures.

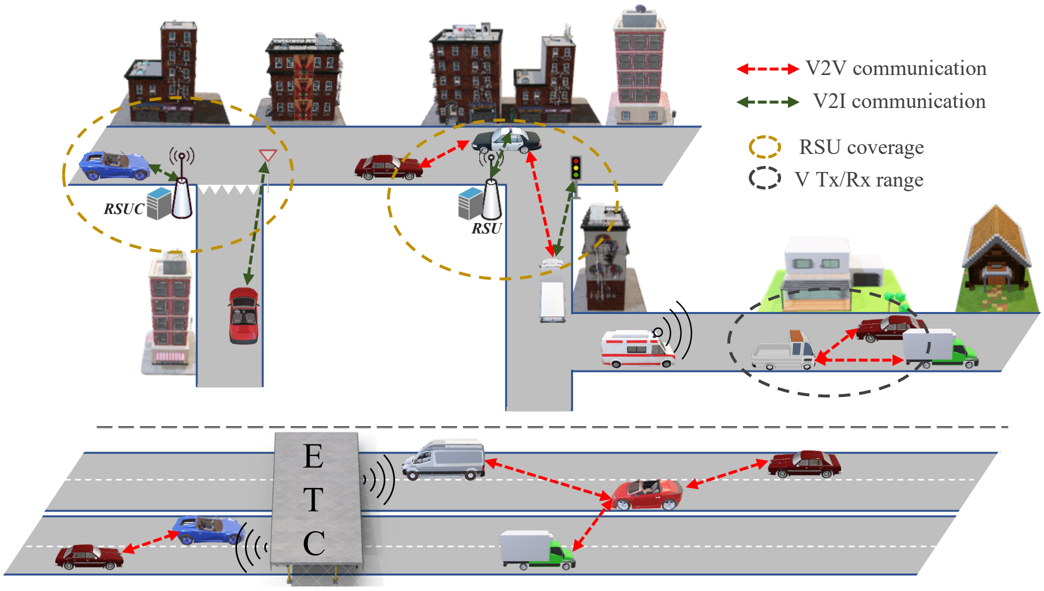

FIGURE 3.1: Illustration of a typical vehicular ad hoc network.

3.1.1 Vehicular Ad Hoc Networks

It has been two decades since VANETs were first mentioned, and they have been of chief interest to many researchers ever since. VANETs were proposed as a case of MANETs but with the distinctive characteristic that the mobile nodes are vehicles, which, on the other hand, have high mobility and tend to follow organized routes instead of moving randomly.

Two types of communications take place in VANETs: vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. The infrastructure includes RSUs, road signs, traffic lights, Electronic Toll Collection (ETC), among others. We illustrate the typical VANET communication scenarios in Figure 3.1. These types of communications support many applications spanning from road safety and traffic optimization to rural and post-disaster scenarios connectivity.

3.1.2 Internet of Vehicles

The advances in vehicle manufacturing and communication technology have made it possible for vehicles to be equipped with various sensing platforms, computing facilities, storage, and control units while being connected to any entity (surrounding vehicles, RSUs, pedestrians, network, cloud, and so on) via vehicle-to-everything (V2X) communications. With all these entities connected through vehicles, and with many of them being designed for other purposes as well, the term ad hoc was considered obsolete by many researchers as it does not comprehensively cover the wide range of the technologies integrated within/connecting these entities. Driven by IoT, researchers gave rise to the concept of Internet of Vehicles (IoV) as a broader

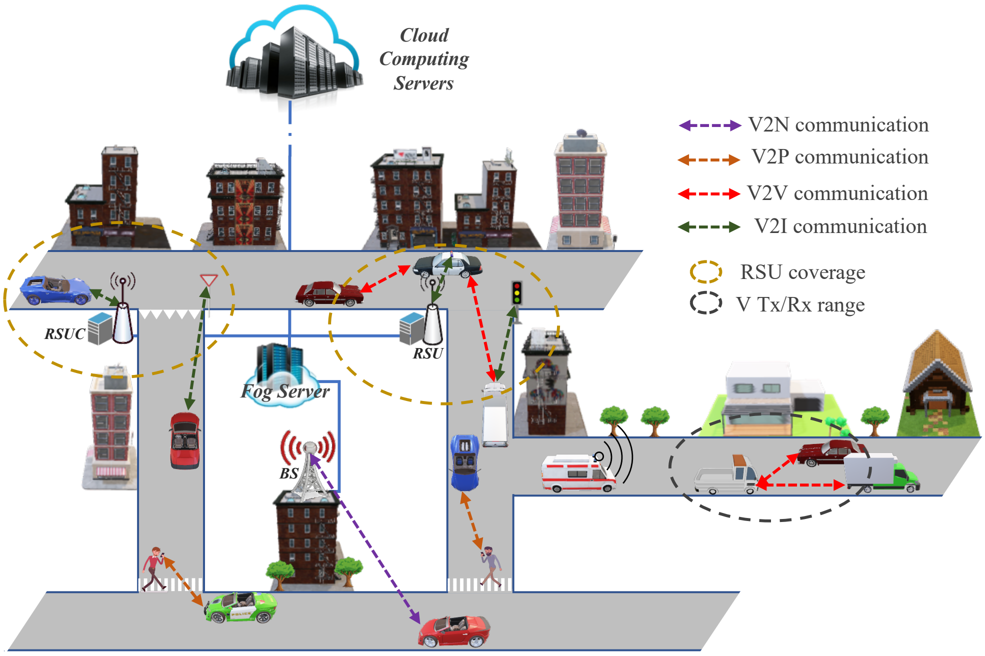

FIGURE 3.2: Illustration of a typical IoV scenario.

concept to better represent the new era of vehicular networks.[1] While there are many types of communications envisioned in IoV, only V2V, V2I, Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N) have made their way to get standardized by far. We illustrate these communications with a typical IoV scenario in Figure 3.2.

3.1.3 Cellular V2X

V2X has evolved from just a concept referring to communication types that take place in vehicular networks to a vehicular communication system that is analogous to these networks on its own. As described above, the former concept relates to the connection of vehicles to all nearby nodes that are equipped with networking functions. The latter represents the technology that can offer a multitude of services characterized by divergent requirements, ranging from a fully automated vehicle traveling in a smart city to streaming 8K videos on an in-vehicle infotainment system. This technology provides an integrated operation between V2V, V2I, V2P, and V2N by leveraging the infrastructure of Cellular Networks, e.g., 4G/LTE, 5G [4], [22], [23]. A counterpart communication technology of C-V2X was IEEE 802.11p [24], but it reached a dead-end in the US as U.S. Federal Communications Commission (FCC) decided to move on from DSRC [25].

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[1] However, it should be noted that many researchers still use the term VANETs while detailing the differences between conventional and novel VANETs architectures, with the latter being equivalent to IoV.

The Connected Vehicles Concept

Connected Vehicles or *Connected Cars* is a very popular term used in the commercial world to express the new generation of cars that can provide all the services described above. In essence, this term is equivalent to the Internet of Vehicles or C-V2X since all these three terms refer to the concept of new cars that can connect and interact with their surroundings while offering a myriad of practical applications and services that bring safety and ease to our daily life.

3.2 Applications

The technology of vehicular networking has seen growth not only in the number of available applications but also in the features they provide, and yet it seems to be an even more enormous potential development ahead. These applications have been seeking to find certain features that can be provided in some particular situations with specific purposes. While the technology to support many use cases of these applications is already available, many other use cases need yet to be supported properly. In addition, new concepts for new applications come along continually as the society is eager for innovation and change.

We surveyed the work of different standardization bodies, including 3GPP [4], [22], [26], ITU [27], European Telecommunications Standards Institute (ETSI) [28], and other launched projects of The 5G Infrastructure Public-Private Partnership (5GPPP) such as Fifth Generation Communication Automotive Research and innovation (5GCAR) [29] and 5G for Connected and Automated Road Mobility in the European UnioN (5GCARMEN) [30] to make an up-to-date list of the applications and use cases that have emerged over the years.

The applications are loosely classified for discussion in this thesis into three main use case groups: 1) Road safety and advanced vehicle control, 2) Advanced traffic management, and 3) Comfort and infotainment services. There is some overlap between the three groups of applications because some use cases have features that belong to more than one of the groups; that is why we differentiate them by considering their primary purpose.

3.2.1 Road Safety and Advanced Vehicle Control

Road safety and advanced vehicle control applications and use cases are presented in Table 3.1. Their purpose is to reduce the risk of driving and save the lives of road users either by directly/indirectly preventing collisions or by mitigating the severity of the accident if for any reason that accident cannot be avoided.

TABLE 3.1: Road safety and advanced vehicle control use cases.

No.	Use Case	Source
1	Vehicle Platooning	3GPP/ETSI
2	Automated cooperative driving for short distance grouping	3GPP
3	Cooperative collision avoidance of connected automated vehicles	3GPP
	Longitudinal collision avoidance	ITU-R/ETSI
4	Changing driving-mode	3GPP
5	Emergency trajectory alignment	3GPP
6	Cooperative lane change of automated vehicles / Lane merge	3GPP/5GCAR
7	Road safety services / V2X Road safety service via infrastructure	3GPP
8	Curve Speed Warning	3GPP
9	Enhancing Positional Precision for traffic participants	3GPP
10	Teleoperated support	3GPP
11	eV2X Remote driving	3GPP
	Remote driving for automated parking	5GCAR
12	V2V Emergency Stop / V2I Emergency Stop	3GPP
	Stationary vehicle - vehicle problem	ETSI
13	Emergency notification and personal security/SOS service	ITU-R/ETSI
14	Forward Collision Warning	3GPP
15	Intersection safety information provisioning for urban driving	3GPP
	Intersection collision avoidance	ITU-R/ETSI
16	Collective perception of environment	3GPP
17	Cooperative Adaptive Cruise Control	3GPP/ETSI
18	Video data sharing for assisted and improved automated driving	3GPP
	See-through	5GCAR
	Vision Enhancement Systems	ITU-R
19	V2V Emergency vehicle warning	3GPP
	Back-situation awareness of an emergency vehicle arrival	5GCARMEN
	Emergency vehicle management	ITU-R/ETSI
20	Wrong way driving warning	3GPP/ETSI
21	Pre-crash Sensing Warning / Pre-crash restraint deployment	3GPP/ITU-R
22	Control Loss Warning	3GPP
23	Warning to Pedestrian against Pedestrian Collision	3GPP
24	Vulnerable Road User Safety	3GPP
25	Pedestrian Road Safety via V2P awareness messages	3GPP
	Network assisted vulnerable pedestrian protection	5GCAR
	Vehicle-pedestrian accident avoidance	ITU-R
26	Motorbike awareness	5GCARMEN
	Motorcycle approaching indication	ETSI
27	Event horizon	5GCARMEN
28	Lateral collision avoidance	ITU-R
29	Mixed Use Traffic Management	3GPP
	Vehicle sensors and state sharing	5GCARMEN
	Safety readiness	ITU-R
	Decentralized floating car data	ETSI
30	Public travel security	ITU-R
31	Slow vehicle indication	ETSI
32	Signal violation warning	ETSI
33	Roadwork warning	ETSI

TABLE 3.2: Advanced traffic management use cases.

No.	Use Case	Source
1	Sensor and state map sharing / Map download and update	3GPP/ETSI
	High definition local map acquisition / Route guidance	5GCAR/ITU-R
2	Queue Warning	3GPP
3	V2N Traffic Flow Optimization	3GPP
	Traffic network monitoring and control	ITU-R
4	3D video composition for V2X scenario	3GPP
5	Green Driving	5GCARMEN
6	Travel demand management	ITU-R
7	Incident detection and management	ITU-R
8	Emissions testing and mitigation / Environment analysis	ITU-R/5GCARMEN
9	Electric zones	5GCARMEN
10	Dynamic Speed Limit	5GCARMEN
11	Pre-trip travel information	ITU-R
12	En-route transit information	ITU-R
13	Dynamic ride sharing / Ride matching and reservation	3GPP/ITU-R
	Car rental/sharing assignment/reporting	ETSI
14	Public transportation management	ITU-R
15	Pedestrians route guidance	ITU-R
16	Regulatory/contextual speed limits notification	ETSI
17	Traffic light optimal speed advisory	ETSI
18	Limited access warning, detour notification	ETSI
19	In-vehicle signage	ETSI
20	Vehicle and RSU data calibration	ETSI

3.2.2 Advanced Traffic Management

The main objective of advanced traffic management applications presented in Table 3.2 is to optimize traffic flow and provide more efficacy for the road systems for the vehicles, pedestrians, and commuters using public transportation. However, these applications may offer secondary benefits, which are not directly associated with traffic management; but, as stated earlier in this section, the classification is made by considering their primary purpose. Correspondingly, several applications belonging to road safety and advanced vehicle control group might as well be listed here as advanced traffic management applications since they indirectly, often even directly, facilitate traffic management, too.

3.2.3 Comfort and Infotainment Services

The purpose of comfort and infotainment services is to enrich the travel experience by providing on-demand information to the drivers and passengers. Applications such as vehicle/service life cycle management and other applications that are intended to improve the efficiency and productivity of commercial vehicle operations are also included in this group of use cases. All the applications that fall into this definition are presented in Table 3.3.

TABLE 3.3: Comfort and infotainment services use cases.

No.	Use Case	Source
1	Automated Parking System	3GPP
	Parking management	ITU-R/ETSI
2	Video streaming	5GCARMEN
3	En-route driver information	ITU-R
4	Personalized public transportation	ITU-R
5	Vehicle administration	ITU-R
6	Fleet management	ITU-R/ETSI
7	Vehicle preclearance	ITU-R
8	Automated roadside safety inspections	ITU-R
9	Electronic payment services / Electronic toll collect	ITU-R/ETSI
10	Point of Interest notification	ETSI
11	Insurance and financial services	ETSI
12	Media downloading	ETSI
13	Remote diagnosis and just in time repair notification	3GPP/ETSI
14	Vehicle software/data provisioning and update	ETSI
15	Stolen vehicle alert	ETSI
16	Tethering via Vehicle	3GPP
17	Personal data synchronization	ETSI

3.3 Radio Access Technologies

Every application has its own QoS requirements to be satisfied in order to run smoothly and serve its purpose. The exponential growth of the proposed applications has proportionally increased the complexity of meeting their QoS demands due to the limited allocated radio spectrum. Various radio access technologies have been proposed over the past years to exploit every single slot of the allocated radio spectrum, and more are under development. The radio access technologies range from WiFi and DSRC to cellular networks and cognitive radio and are discussed in the following subsections.

3.3.1 Short-Range Radio Technologies

For many years short-range radio technologies were considered to be the right track for successfully deploying vehicular networking applications. Not only were technologies such as WiFi [31], Bluetooth [32], Zigbee [33] that use the Industrial, Scientific and Medical (ISM) frequency bands put forward for such purpose, but there was also a dedicated spectrum for vehicular communications known as DSRC spectrum for Wireless Access in Vehicular Environments (WAVE). DSRC/WAVE is defined in IEEE 802.11p [34] and in the IEEE 1609 family of standards [35], and in the last two decades, it was seen as one of the wireless technologies that could potentially meet the low latency requirement for safety applications. However, this technology saw its end in the United States as FCC decided to split the 75 MHz of

DSRC spectrum (5.850 - 5.925 GHz), allocating the lower 45 MHz of the band for Wi-Fi and other unlicensed uses and the upper 30 MHz for ITS that must use C-V2X technology [25]. Europe, on the other hand, did not abolish this technology. Instead, they adopted a technology-neutral approach that supports both Cooperative ITS (C-ITS) and C-V2X [36].

3.3.2 Cellular Networks

Although the use of cellular networks infrastructure for vehicular networks was proposed since when 3G was becoming a reality, or even earlier when GSM made its appearance and some basic applications such as tracking of stolen vehicles were believed to be successful by leveraging this technology, it is just recently that cellular networks have come into play as a true game-changer in enabling present and future vehicular networking applications. The shift started with the LTE and with 5G now, it is closer than ever. This technology is named C-V2X and is specified in the 3GPP Release 14 [37] for LTE, whereas the support of 5G and the specification of the service requirements are specified in the 3GPP Release 15 [38]. While the releases provide necessary technical details for the deployment of this technology, 5GAA is the player making indispensable efforts to make it a reality.

C-V2X supports both short- and long-range communications. The former is known as the direct mode or Sidelink and uses the PC5 interface, whereas the latter is known as network mode or UP/Downlink and is implemented over the Uu interface for LTE and 5G NR Uu URLLC [26]. Direct mode is essentially V2V, V2I, and V2P, while network mode is V2N communication[2]. These communication modes are introduced at the beginning of this chapter and illustrated in Figure 3.2.

3.3.3 White Spaces and Cognitive Radio

White spaces usually refer to the band of frequencies of the radio spectrum that are unused due to technical reasons, such as the purpose of acting as a guard band between used radio bands to avoid interference. However, this term refers to all the unutilized radio bands, including the radio which has never been used or other frequency bands left unused due to technical changes, e.g., abolition of some radio communication technology.

TV white space, for instance, which is the 470-790 MHz frequency band in the European Union, is currently unused because of abandoned TV channels and is considered for wireless broadband access since it holds rich potential for expanding

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[2] Network mode also includes other types of communications where the vehicles are not a factor, such as Pedestrian-to-Network (P2N) and Infrastructure-to-Network (I2N).

broadband capacity due to superior propagation characteristics and large penetration performance. The use of TV white space is also investigated for vehicular networks, and the research results promote it as a way forward for the development of connected vehicles [39]–[43].

Cognitive radio is another promising idea envisioned to solve the problem of scarce spectrum. It is a radio technology that allows dynamic programming, configuration, and management of the radio spectrum to enable users to communicate through the best radio channels in their vicinity while avoiding interferences and congestions. The novel approaches and the research challenges associated with the use of cognitive radio technologies in vehicular networks are surveyed and presented in several research papers [44]–[46].

3.4 Information Dissemination

When vehicles are within the range of cellular antennas, communication is done via the network. However, as we mentioned in the above sections, vehicles can also communicate with one another or with other entities directly, especially when there is no possibility of connecting to a BS. The communication is done via the PC5 interface following the 3GPP specification. This communication type is considered ad hoc mode, and as such, it requires communication protocols that can provide the resiliency and robustness requested in the information dissemination process.

Many communication methods and protocols are proposed over the years, grouped mainly according to the strategy of transmitting the information to the desired destination. For example, these methods can be distinguished as transmitting data from a single source to a single destination node, to a set of nodes inside an area, or to all nodes in the network. These transmission strategies are known as unicast, multicast/geocast, and broadcast, respectively.

- The unicast strategy refers to point-to-point communications, which means that data is transmitted from a single source to a single destination node. This strategy is achieved through a hop-by-hop greedy forwarding mechanism that relays the information immediately or a carry-and-forward mechanism that stores the data in case of a lack of continuous connectivity and forwards it when a decision is made.

- The multicast/geocast strategy is used to deliver data from a single node to a set of nodes that lie within a specific geographical region, also known as zone of relevance. Geocast is considered among the most feasible approaches for safety-related applications in vehicular networks since it can inform all nodes traveling close to the event location. Beacon messages with Cooperative

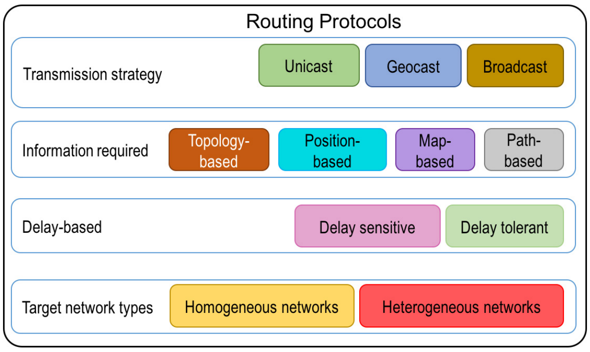

FIGURE 3.3: Taxonomy of routing protocols in vehicular networks adopted from [50].

Awareness Message (CAM) [47] and Decentralized Environmental Notification Message (DENM) [48] are typical examples. The former provides periodical information of a vehicle to its neighbors about its presence, position, speed, etc. whereas the latter is an event-triggered message delivered to alert road users of a hazardous event.

- Broadcast strategy disseminates information to all vehicles in the network without exception. This approach can be used for data sharing, weather information, road condition, traffic, entertainment, and advertisement announcements.

The classification based on the transmission strategy is the most common way to distinguish the communication protocols, yet it is not the only manner. Cheng et al. [49] present other categories of routing protocols based on different perspectives such as the information required, delay-based information, and the network type target. A summary of these classification manners is given in Figure 3.3. The information required category is based on the type of information required to perform routing, which can be information related to topology, position, path- or map-based. Delay-based information disseminates data in real-time for critical applications or uses a carry-and-forward mechanism that stores the data in the buffer and transmits it once a vehicle comes within the transmitter's communication range. Whereas, the target network can be categorized as homogeneous network where the communication relies on single network architecture and heterogeneous network which includes various radio access technologies.

3.5 Security, Privacy and Trust

Developing and implementing security, privacy, and trust management solutions is a challenging task for all kinds of computer networks and doing so for vehicular networks is no exception. In fact, the unique characteristics of these networks make

TABLE 3.4: Recent surveys related to security, privacy, and trust.

Survey	Aspect(s)	Contribution	Year
[51]	Privacy	Comprehensive overview of existing privacy-preserving schemes	2015
[52]	Trust	An adversary-oriented survey of different trust models and their evaluation against cryptography	2016
[53]	Security	Overview of security challagenges and requirements, and a novel classification of different attacks along with their corresponding solutions	2017
[54]	Security	A review of services, challenges and security threats evolving from the software-defined approach	2018
[55]	Security, Privacy, Trust	A Survey covering well-studied topics of security, authentication schemes, location privacy protection mechanisms, and existing trust managements models	2019
[56]	Security	Deep analysis of various security aspects such as requirements, challenges, and attacks together with the evaluation of their respective solution	2019
[57]	Security, Privacy	A comprehensive review of various research works that address privacy, authentication and secure data dissemination	2020
[58]	Security, Privacy	Introduces security and privacy aspects of C-V2X, and discusses open security challenges and issues	2020
[59]	Trust	A review, analysis, and comparison of current trust establishment and management solutions, and a discussion of future opportunities	2021

the development and implementation of these solutions an even more challenging issue. Many authors have researched different methods that meet the needs of security, privacy, and trust management of vehicular networks. Several surveys covering vehicular networks' requirements, challenges, existing and possible types of threats, and corresponding solutions have been published over the years. These surveys are listed in Table 3.4 for further reading since the goal of this section is to provide basic notions related to security, privacy, and trust rather than a deep analysis of research conducted in this direction.

3.5.1 Security

Secure communication between all involved entities in vehicular networks is of the utmost importance since any successful attack from a malicious hacker could result in a traffic accident. Therefore, a good security framework must consider the basic security requirements in terms of authentication, availability, confidentiality, integrity, non-repudiation, etc., and protect these services from different threats and attacks. There are different ways to classify the attackers and the attacks. The attackers are classified as, for example, active/passive, malicious/rational, insider/outsider, or local/extended attacker. Attacks, on the other hand, can be grouped based on the targeted service, based on the communication mode they hit (V2V, V2I, V2P, V2N), or even based on the entities (hardware or software, authorities, vehicles, infrastructure, or other members) they affect. Some of the most hazardous attacks in vehicular networks are Denial of Service, Distributed Denial of Service, Sybil attack, Black and Gray Hole, Wormhole, Injection of erroneous messages, Replay, and Eavesdropping. Details of these attacks, their respective solutions, and also many other identified attacks can be found in the surveys presented in Table 3.4.

3.5.2 Privacy

Only dedicated individuals should have the right to access and control the vehicle information and decide what will be communicated to others. One of the most common methods to protect the privacy of individuals is anonymity. Anonymity is defined as the state of being not identifiable within a set of subjects, which can be provided by employing an authentication scheme. Based on the cryptographic mechanisms, the following categories of anonymous authentication schemes can be identified: public-key infrastructure, symmetric cryptography, identity-based, group, and certificateless signatures.

3.5.3 Trust

Trust management deals with the trustworthiness of the received information and the trustworthiness of the vehicles that have sent that information. There are three popular trust management models: entity-centric, data-centric, and combined trust models. In order to establish an effective trust management model, some properties need to be considered, such as decentralization, real-time constraints, information sparsity, scalability, and robustness. Looking at the growth and feasibility of blockchain technology, perhaps vehicular networks are not that far from establishing the long-awaited trust model that addresses those existing challenges [60].

3.6 Related Work

The highly competitive and rapidly advancing autonomous vehicle race has been on for several years now, and it is a matter of time until we have these vehicles on the roads. However, even if the automotive companies do all that it takes on their end to create fully automated cars, there will still be one big obstacle, the infrastructure. In addition, this could take decades even in the most developed countries. Moreover, 93% of the world's fatalities on the roads occur in low- and middle-income countries [1], and considering all these facts, driver-support systems should remain the focus of interest for the foreseeable future.

Driver-support systems can be very helpful in many situations as they do not depend on the infrastructure as much as driverless vehicles do. Furthermore, they can provide driving support with very little cost, thus help in low- and middle-income countries in the long battle against car accidents. Most of these systems concentrate on maintaining the driver's attention and intervene when they seem incapable of driving safely. There are different ways to detect the driver's inattention: monitoring the driver directly, analyzing the driving performance, and combining the first two.

Such systems have been in the focus of many researchers of the automotive industry and academia for many years, and their work has been paying off given the continuous improvement of such systems. In [61], authors review several projects executed by some major automotive companies such as Toyota, Nissan, BMW, Mercedes-Benz, Saab, and Volvo, and by companies such as Veoneer, Seeing Machines, and SmartEye, which are specialized only at the research and development of these systems. These projects have driver inattention (coming from fatigue, drowsiness, and distractions) in their focus, for which they use smart cameras to track several facial features and then process the acquired data using computer vision algorithms. There are also many researchers from academia that are engaged in the development of these systems. In [62], authors implement a vision system for monitoring driver's vigilance by integrating the facial features of the eyes, mouth, and head. In Ji et al. [63], the authors deal with driver fatigue, for which they propose a probabilistic model by considering head, eyelid, and gaze movement along with the driver's facial expressions. There are also many other research works that use such behavioral measures to detect driver inattention. These include the percentage of eyelid closure (PERCLOS) [64], [65], eye blinking [64], [66], [67], pupils' motion [68], yawning [69], as well as other facial expressions—jaw drop, lip/mouth stretch, inner/outer brow raise, and such [70], [71]. The authors communicate interesting results and good performance of their systems. However, since they use facial feature extraction and vision-based approaches, their systems encounter many limitations. Vision-based approaches require a long moving-averaged window to track slow changes in the driver's vigilance. Furthermore, they experience several illumination issues, especially during night-times. Infrared illumination techniques can be very effective in such cases [64], [72], [73], but in the case of light reflection (sunlight or reflections from glasses), the performance declines by 30% [64].

Other researchers use driver's biological signals e.g., *electrocardiogram (ECG)*, *electroencephalogram (EEG)*, *electromyogram (EMG)*, and *electro-oculogram (EOG)*, to detect his/her drowsiness and report that these biopotentials can be used to detect drowsiness with a high accuracy [61], [74]. Heart rate also varies considerably between the different stages of drowsiness, such as alertness and fatigue [75], [76]. In addition to heart rate, respiratory rate can be used as an indicator of mental stress [77].

Driving performance measures are proven to be an effective way of detecting driver inattention as well, since changes in the mental state while driving are reflected in the driving performance. To detect driver fatigue, Zhong et al. [78] performed a localized energy analysis on the vehicle state information, such as steering angle and trace profile. They conclude that the localized energy changes with the driver's mental state. In [79], the authors estimate driver fatigue through steering motion. They apply chaos theory to explain the change of steering-wheel motion, and by analyzing the chaos characteristics they can detect signs of possible fatigue episodes. Other research works consider different parameters, including the steering-wheel position, accelerator pedal position, forces on the pedals, lane boundaries, upcoming road curvature, and vehicle velocity [80]–[83]. The aforementioned research works detect driver inattention based on driver-vehicle interaction, which can be effective in many cases, yet it requires modifications of the vehicle structure, which is inappropriate in real-world assessments [84].

On the other hand, there are several research papers that are in line with our research work regarding the method used to determine the driver's situation. In [64], authors use PERCLOS, eye closure duration, blink frequency, fixed gaze, frontal face pose, and nodding frequency as input parameters to a fuzzy inference system. They reported that their system detects driver fatigue with 98% accuracy. Nevertheless, the performance of the system is severely affected by the light reflections, which cause a 30% decline in detection accuracy. A more straightforward fuzzy system considering the following inputs: head-nodding frequency, posture adjustment frequency, slouching frequency, and PERCLOS is implemented in [85]. Even though authors consider fewer input parameters for the implementation of the system, they report that it runs slow, and state that an implementation of the system using C language in place of Matlab could facilitate it to run much faster. Thorough work in regard to the diversity of considered inputs is presented in [84]. Vehicle speed, PERCLOS, heart rate, blood pressure, and temperature are the parameters that authors consider for their driver monitoring system. They design a Fuzzy Bayesian framework that analyzes the condition of the considered variables and then determines whether the driver can drive safely. Although authors report good resolution and flexibility of the system, they also state a high computational complexity which is determined by the number of fuzzy members in each MF and by the number of nodes in the Bayesian network.

Chapter 4

Intelligent Algorithms

For centuries, human beings have been trying to understand nature in its simplicity and complexity, so they could perceive the way the elements of nature interconnect with each other, as an example that would allow them to better adapt to the changing environments. Naturalists, biologists, physicists, and all kinds of scientists have observed and explained numerous phenomena related to their respective fields. But in the second half of the last century, we saw a different trend: the emergence of interdisciplinary fields that would foster many successful applications in the upcoming years. Engineers and computer scientists followed this trend too. They began observing existing natural systems and their natural evolution and designed different artificial systems that work on the same principles and others capable of doing the same job. For instance, engineers built the plane looking at how birds fly; they invented the submarine observing fish, the radar from bats, new kinds of sonars from dolphins, and so on.

Computer science saw the rise of Intelligent Algorithms (IAs) that would lay the foundation of today's Artificial Intelligence (AI) systems, and this is attributed to bionics as well. Fuzzy Logic (FL), Genetic Algorithms (GAs), swarm intelligence techniques such as Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO), and Artificial Neural Networks (ANNs) are some of the approaches and methods commonly referred to as IA that are motivated by bionic ideas. FL, for example, is an approach that is inspired by the intuitive way in which humans think and interact. ANNs mimic somewhat the biological neural networks of animal brains. GAs, on the other side, are inspired by the scientific theory of evolution by natural selection conceived by Charles Darwin. ACO is inspired by the foraging behavior of ant colonies, PSO comes from the bird flocks and fish shoals, and so forth.

While the bionic ideas continued to give rise to more successful variants of these intelligent methods, the researchers did not focus only on natural systems. They have broadened the family of IAs even with solutions that have never appeared in nature. Hill Climbing (HC), Tabu Search (TS), and Simulated Annealing (SA)[1], for instance, are local search methods that have no inspiration from nature, and yet are ranked among the most prominent IAs.

These IAs emerged as a need for practical alternative techniques that can tackle and solve various challenging engineering problems. For instance, fuzzy-based systems can be used to make intelligent decisions when there is a need to contend with high levels of imprecision and uncertainty. GAs are ideal techniques to solve optimization and allocation problems. ANNs, on the other side, can be applied to recognition problems or rule learning. In this chapter, we investigate these intelligent algorithms by taking an engineering approach to the design, analysis, and implementation of the intelligent systems that make use of such algorithms. FL, as the main method used in the design and implementation of our proposed systems, is discussed in detail in the following chapter.

4.1 Artificial Neural Networks

ANNs mimic somewhat the biological neural networks that constitute animal brains. ANNs are based on artificial neurons, also known as nodes, which are collections of small, individually processing units that are interconnected by means of links that enable the information to pass between them. These nodes can be classified into a least three layers: one layer composed of input nodes, one comprised of the output nodes, and a third layer consisting of (layers of) hidden nodes which are placed in between the input and output layer. A typical neural network is illustrated in Figure 4.1. The input layer nodes take the input data, perform processing operations on them, and pass the results to the nodes of the next layer. This process continues until the output layer nodes are passed all the processed data.

ANNs begin by assigning random values (weights) to the links connecting each node. These weights need then to be adjusted to numbers that are relevant to the task that needs to be performed. This process may seem straightforward, but finding proper weights gets very complicated when the network is composed of multiple layers and thousands of nodes.

This is the part where the process of training the ANNs takes place. An example data set is used first as the input to allow the algorithm to adjust the weights based on the known pattern. The more training examples provided, the better the neural network can adjust its weights to map each input to the correct outputs.

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[1] Although SA did find inspiration from the annealing technique in metallurgy, which is the process of slow cooling of metals, this practice is not considered as a natural process because the algorithm mimics the technique itself rather than the physical processes happening as result of its application.

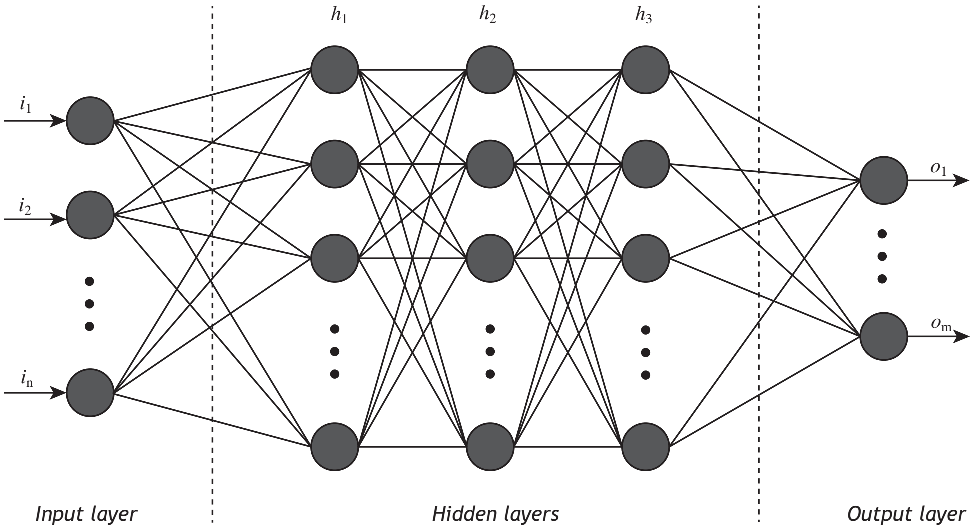

FIGURE 4.1: Illustration of the architecture of a typical ANN composed of multiple layers.

Once the training process is done, the ANNs can perform classification and prediction tasks even on new data patterns that are messy or unstructured. These data patterns can come from real systems or physical models, computer programs, or other sources. The application of ANNs has seen success in a variety of fields such as telecommunications, transportation, automotive manufacturing, economics, medical research, and electronics.

4.2 Genetic Algorithms

GAs are metaheuristic search algorithms that are inspired by the process of evolution of living things. Similar to the living things, which evolve over generations through the natural selection process in order to adapt to the changing environments, GAs select the fittest individuals of the population in order to have a reproduction process yield stronger offspring for the next generation. The algorithms start with an initial population of possible solutions (individuals) to a problem that undergoes a series of repetitive processes of recombination (crossover) and mutation, producing better offspring over time. The flow of these processes is given in the flowchart shown in Figure 4.2.

Each individual is assigned a proper fitness value through an objective (fitness) function following the logic that fitter individuals should be given higher chances to mate and produce in order to increase the chances of obtaining fitter offspring. However, assigning the proper fitness values to each individual is not a straightforward task. The formulation of objective function should be carried out properly and with careful attention because a flawed function can lead to worthless results. And, it is not only the formulation of the fitness function that leads to such results. The use of population size, the choice of mutation rate, that of crossover rate, and the criteria upon which the new population is selected also need to be planned carefully.

FIGURE 4.2: Flow diagram of a classic GA.

Despite these drawbacks, many advantages make GAs a powerful problem-solving technique and have made these algorithms successful in a wide range of applications. They contend with high complexity and are ideal for parallelism implementation [86]. The former is attributed to the fitness function, which can be continuous or discrete, linear or nonlinear, stationary or non-stationary, or random noise. The latter corresponds to the ability of multiple individuals to act as independent agents, allowing the subgroups of the population or the entire population itself to explore the search space in many directions simultaneously.

4.3 Swarm Intelligence

Swarm intelligence is a population-based problem-solving approach that takes inspiration from the behavior of social insects, such as ants and bees, of flocks of birds, and of other animals that are highly interactive with the members of their kind. An aspect of interest of social behavior is communication, which allows these animals to forage, mate, establish dominance, defend their territory, coordinate group behavior, and care for their offspring. It is the process of foraging that the techniques of swarm intelligence mimic in particular. These animals share information related to their surroundings continually while in search of food in order to explore the environment and find favorable paths through which they all can find food or safely transport the food back. Correspondingly, these techniques explore the search space (the set of all possible solutions) to find approximate solutions, or ideally, best solutions, to solve hard optimization problems. In the following, we explain two of the most known swarm intelligence optimization techniques, ACO and PSO.

4.3.1 Ant Colony Optimization

The ACO is an algorithm that was initially proposed in 1992 [87]. Since then, many successful variants of ACO algorithms have been introduced, although all these variants share essentially the same idea.

Similar to real ants, which explore the environment and trail pheromones to direct other ants to the discovered food resources (Figure 4.3 illustrates this process), the artificial ants (simulation agents) explore the search space and record their coordinates and the quality of solutions they have found to enable more ants to locate better solutions in later simulation iterations.

The ACO algorithm needs the optimization problem be first transformed into a weighted graph whose possible paths would mark the set of solutions to the problem. Then, the artificial ants can explore the search space and find their solutions by moving on the graph. The solutions are built incrementally through the modification of a set of parameters that are associated with one of the graph components (nodes or edges). The best path found at the end of all iterations is the solution that the algorithm proposes to the problem.

ACO algorithms have resulted to be an effective technique for solving a wide range of optimization problems. While this approach was initially applied to solve mainly NP-hard problems, it has also been applied to deal with routing problems in telecommunication networks and to provide solutions to many industrial problems, with all these applications marking the success of this approach [89].

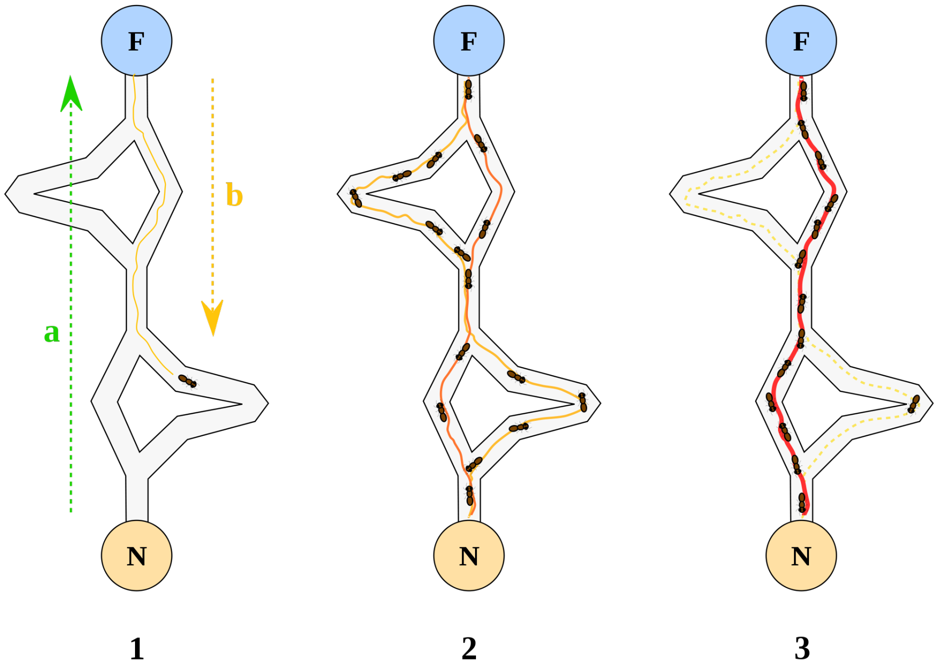

FIGURE 4.3: Ants trailing pheromones to direct other ants toward the discovered food resources through the shortest path found [88].

4.3.2 Particle Swarm Optimization

Given that PSO and ACO are both swarm intelligence techniques, their approach to the given problems can be considered to share a few similarities. For example, both techniques are population-based methods that optimize the given problem by improving the candidate solutions (simulation agents) over many iterations according to a given measure quality. However, PSO does not require the problem be transformed into a weighted graph, but instead has the simulation agents, here called dubbed particles, move around to find good solutions in the search space based on simple formula over their position[2] and velocity. In the initialization phase, each particle is given a random position in the search space and a random velocity to move in it. Each particle memorizes the best position they have found in that iteration. In the next iterations, the velocity of each particle is updated based on the particle's own experience and based on the experience of its adjacent particles. The experience of a single particle refers to the best local position the particle itself has found so far, while the experience of other particles refers to the best position in the search space found by other particles. As illustrated in Figure 4.4, by updating the velocities after each iteration, the algorithm expects the swarm to move toward the best solutions [90].

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[2] Although the particles are referred to as candidate solutions, it is their position in the search space that corresponds to a solution to the given problem.

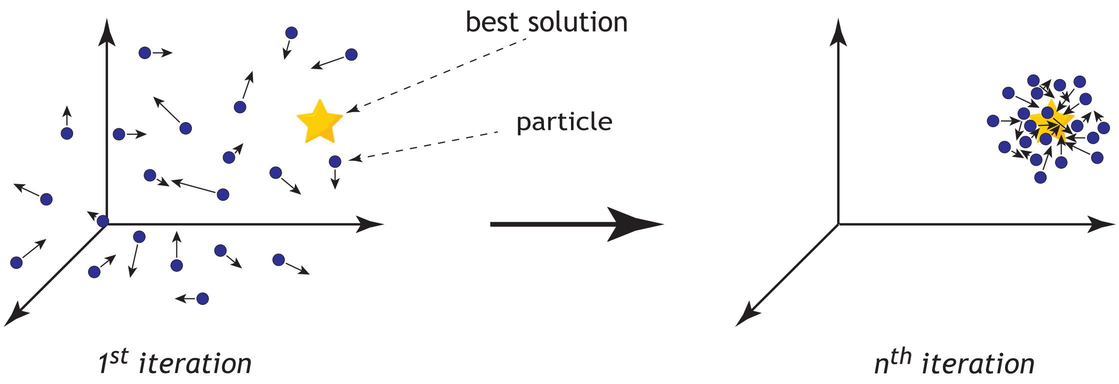

FIGURE 4.4: Arbitrary movement of particles placed at random positions in the first iteration and expected convergence of the algorithm after many iterations.

PSO has been successfully applied to many engineering problems, including fuzzy control, function optimization, artificial neural network training, and pattern classification [91]–[93].

4.4 Local Search Methods

Local search methods are heuristic methods that find use in problems that need not necessarily be provided with an optimal solution. Instead of focusing on finding the optimal solution, the local search algorithms iteratively improve the candidate solutions by maximizing a certain criterion during a given time frame. That is, these algorithms move from solution to solution in the search space by applying local changes, until a sufficiently good solution is found or a time-bound is elapsed.

Local search algorithms are applied successfully to a variety of NP-hard problems, including problems from mathematics, operations research, bioinformatics, computer science, and engineering. In the following, we explain three of the most used local search methods that can be found in literature: Hill Climbing, Tabu Search, and Simulated Annealing.

4.4.1 Hill Climbing

HC is an algorithm that makes incremental changes to the solutions provided after each of its iterations in an attempt to find better solutions to the given problem. First, the algorithm is given an arbitrary solution (which is generated randomly) and then it makes an incremental change to that solution. When that incremental change results to be a better solution, the new solution becomes the current solution for the next iteration. The algorithm continues with the incremental changes over iterations until no further improvements can be found. For this reason, HC often finds only

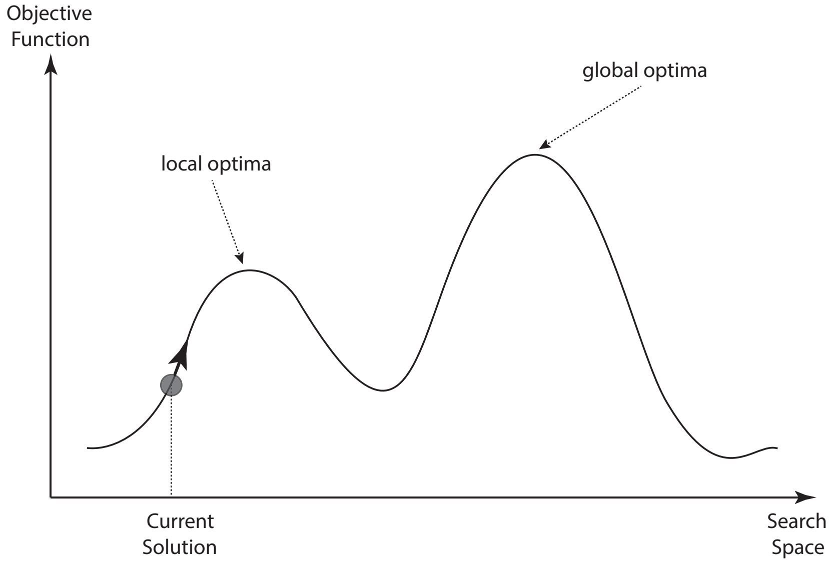

FIGURE 4.5: Graphical representation of search space of possible solutions to a given problem and algorithm's dependence on initial solution.

the local optima, that is, the best solution among the neighbor solutions, when in fact, a global optimum—the best solution in the search space—is possible. Figure 4.5 explains the dependency of the algorithm on the initial solution.

There have been attempts to improve the original HC algorithms, and newer variants with lower probabilities of becoming trapped in local optima are now available. *Hill climbing with random restart*, for example, uses a strategy that involves multiple random restarts to allow the algorithm to explore more than one peak [94]. With this strategy, the algorithm can reach all the peaks in the search space, enabling better solutions to be discovered.

4.4.2 Tabu Search

In contrast to HC, which accepts only better solutions, TS can replace the current solution with a less efficient solution if no improvements are available in that area. This move can be considered flexible because it allows the algorithm to escape from getting stuck at a local optimum. The algorithm then selects a new search movement by forbidding itself from going back to recently-visited solutions in order to allow other new regions of the search space to be visited. To store all the prohibited solutions, the algorithm uses a "tabu" list which is checked every time a new solution is evaluated. The algorithm continues to explore the search space until a stopping criterion forces the algorithm to end, e.g., an attempt limit has been reached, or a score threshold has been satisfied. The steps of the algorithm are shown in Figure 4.6.

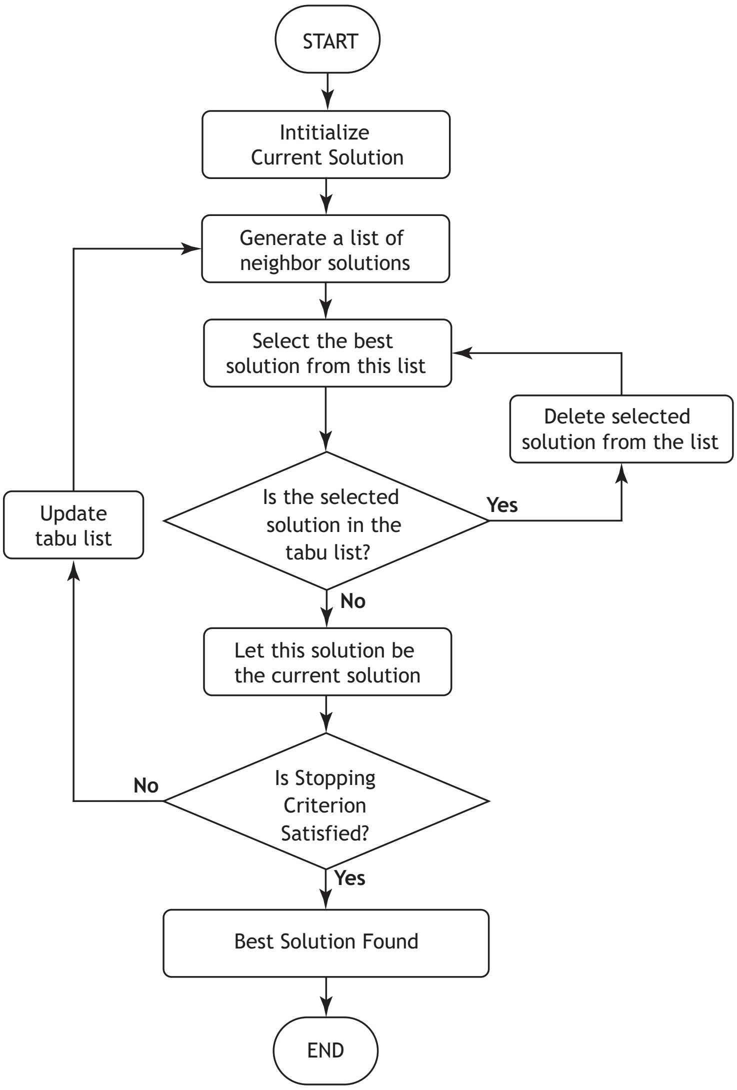

FIGURE 4.6: Flowchart of a simple TS algorithm.

4.4.3 Simulated Annealing

SA is an algorithm that attempts to locate the best solution possible, usually a near-optimal solution, by making arbitrary adjustments to the current solution. These adjustments correspond to the other solutions in the current solution's neighborhood. At each iteration, the algorithm evaluates these candidate solutions coming from the arbitrary adjustments and assigns an acceptance probability to each of them. Then, based on the acceptance probability of the candidate solution, the algorithm decides whether to accept it or to stay in the current solution. Even if the adjustments result in a less efficient solution, the algorithm still evaluates it as a candidate solution while assigning an acceptance probability that decreases with these adjustments [95]. As it can be seen from Figure 4.7, it is the acceptance of these less efficient solutions, that similarly to TS, make SA escape the local optima to seek better solutions.

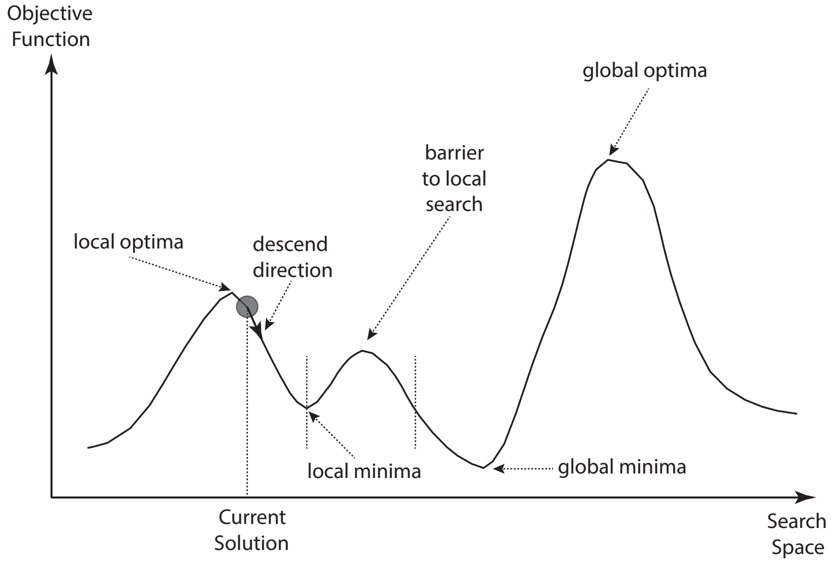

FIGURE 4.7: Search space diagram of a problem with multiple peaks and algorithm's capability to escape barriers and explore all solutions.

4.5 Hybrid Methods

While each technique takes an interesting approach to the problem, the implementation of a single method often comes with disadvantages. When certain limitations are identified from the implementation of a single method, a hybrid method can be considered a good alternative to ensure high accuracy, resiliency, and robustness. Hybrid methods consist of methods that combine two or more techniques to perform a task or solve a problem that cannot be dealt with properly by a single method. Based on the way they solve the given problems, hybrid methods are distinguished as methods that integrate two or more techniques to perform the same task or methods that have these techniques perform separate tasks of the same problem.

For instance, neuro-fuzzy controllers use FL and ANNs and sometimes even search techniques, to perform the same task, e.g., to control a process. In another hybrid system, genetic algorithms may be used to optimize the network topology, the learning rate, and initial weights of neural networks, which then are used to recognize patterns or make predictions. On the other hand, hybrid systems that use the techniques to perform separate tasks may have, for example, the genetic algorithms perform a task, i.e., find an optimum solution using the output of a previously completed task, such as the task of deriving some parameters, performed, for example, by a neural network.

Although there are many benefits to the use of a hybrid method over a single method, the outcome is not always a success. The design of a hybrid system should be carried out with careful attention because the application of hybrid methods usually results in higher computational costs and requires a relatively considerable amount of time to provide an output.

Chapter 5

Fuzzy Logic

This chapter provides basic and concise introduction of Fuzzy Logic (FL) Theory, detailed enough to enable the reader to better understand its application presented in the subsequent chapters of this thesis. The chapter begins with a description of FL in regards to the traditional logic, continues with a short introduction of fuzzy sets, concept from which FL starts, to end then with a more detailed description of the systems that are based on FL and therefore use fuzzy sets.

5.1 Introduction to Fuzzy Logic

In recent years, a myriad of fuzzy-based applications is encountered, with most of the applications coming from Japanese companies. The applications range from consumer products such as vacuum cleaners, cameras, washing machines, and microwave ovens to decision-support systems, automotive systems, industrial process control, and medical instrumentation, among many other fields [96]–[98].

The idea of FL dates back to 1965 when Mr. Lotfi Zadeh, a computer scientist and electrical engineer working as a professor at the University of California, Berkeley, published "Fuzzy Sets" [99] in which he put forth his ideas that could close the gap between mathematics and the intuitive way that humans talk, think and interact with the world.

FL is a multi-valued logic that allows intermediate values to be defined between conventional evaluations such as true-false, cold-hot, bad-good, slow-fast, etc.

For example, humans can so easily identify, say, a car moving at a high speed even if they are not given a specific speed. Computers on the other hand, can as well identify easily which cars are moving fast—if programmed to do so—but a specific speed, that would work as border limit up to which a car is considered as moving slowly, must be predefined. In traditional logic, all the cars would be categorized as moving slowly or fast based on this border. Similarly, one can add other borders to distinguish the cars moving very fast or very slow, but this does not mean one is applying FL because adding sharp boundaries to define the value of the words is far from programming computers in a humanlike way of thinking.

To better understand the applications of FL,it is first important to understand the concept of FL since it has two different meanings on its own. One in a narrow sense, FL_n, and another in a wider sense, FL_w. In the former aspect, FL is defined as a logical system viewed as an extension of multi-valued logic. In the latter, FL is synonymous with fuzzy set theory, a theory that relates to classes of objects with indistinct boundaries in which membership is a matter of degree. From this point of view, FL in the former aspect is a branch of the latter [100].

Besides FL_n, there are many other branches of FL_w—fuzzy arithmetic, fuzzy graph theory, fuzzy probability theory, and fuzzy topology to name a few. These branches derive from the fuzzification of their respective field. In fact, it is important to state that any field X and any theory Y can be fuzzified by replacing the concept of a crisp set in X and in Y with that of a fuzzy set [97]. Examples of the application of fuzzification to applied fields such as neural pattern recognition, network theory, mathematical programming, and stability theory lead to fuzzy pattern recognition, fuzzy neural network theory, fuzzy mathematical programming, and fuzzy stability theory. The application of fuzzy sets to these fields and theories brings greater generality and higher expressive power, making them able to model real-world problems through the exploitation of the tolerance for imprecision and uncertainty. Most importantly, what is gained through their application is a methodology that enables robustness, tractability, and lower solution cost above all.

Despite the attributes it offers, FL should not be used when conventional control theory yields an acceptable result, and an adequate and solvable mathematical model already exists or can easily be created. Thus, it is noteworthy to consider the application of FL when the problem to be dealt with is a non-deterministic polynomial-time hard (NP-hard) problem. In such cases, there is no algorithm or mathematical model available that can provide a solution in polynomial time, let alone if we need to handle certain problems in real-time.

The application of FL presented in this thesis considers FL in its broad sense. The basic ideas underlying it are explained in the following sections. The concept of a fuzzy set, of logical operations, of a Membership Function (MF), that of a linguistic variable, and of a fuzzy rule are among the concepts to be described. We delineate most of these concepts in Section 5.3 to enable the reader to understand all the steps of the implementation of Fuzzy Logic Systems (FLSs) just by reading the section alone.

5.2 Fuzzy Sets

FL begins with the concept of fuzzy sets, which is the class of objects with a continuum of grades of membership.

To understand what a fuzzy set is, let us first review the definition of a classical set[1]—also referred to as a 'crisp' set so it can be distinguished from a fuzzy set. A crisp set is then a container that presents a dichotomy between individuals in some given universe of discourse. The universe of discourse, which could be considered as a fancy term for such a simple concept, refers to the input space of values that a certain variable is allowed to take value.

A set A is a crisp set in a given universe of discourse U when for any member of U, it can be said that A includes all members of U that meet a certain condition and excludes the rest of the members. A is defined as:

$$A = \{\, x \mid x \text{ meets a certain condition}\},\ \forall x \in U$$

Other mathematical expressions which derive from the definition are:

$$\overline{A} = \{\, x \mid x \notin A\},\ \forall x \in U$$
$$A \cup \overline{A} = U$$
$$A \cap \overline{A} = \emptyset$$

Alternatively, we can introduce a zero-one MF (differently named as characteristic function) for A as below:

$$A \Rightarrow \begin{cases} \mu_A(x) = 1, & \text{if } x \in A \\ \mu_A(x) = 0, & \text{if } x \notin A \end{cases}$$

Let us consider, for example, the set of weather types given in Figure 5.1. The set wholly includes sunny, cloudy, windy, rainy, and snowy, while it wholly excludes the other elements (beach, mountain, museum, historic, and so on). Everything falls into either one category or the other. There is no element that is both a type of weather and not a type of weather.

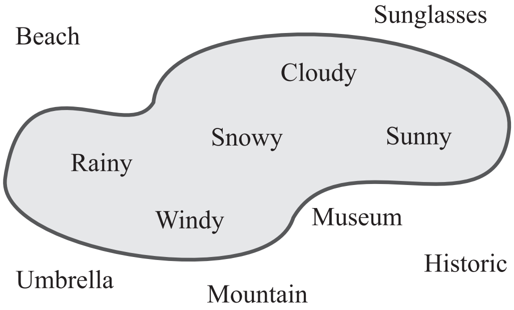

FIGURE 5.1: Set of weather types.

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[1] This type of set is called a classical set because it has been around for a long time. It was Aristotle who first formulated the Principle of the Excluded Middle, which states that for any proposition, either that proposition is true or its negation is true.

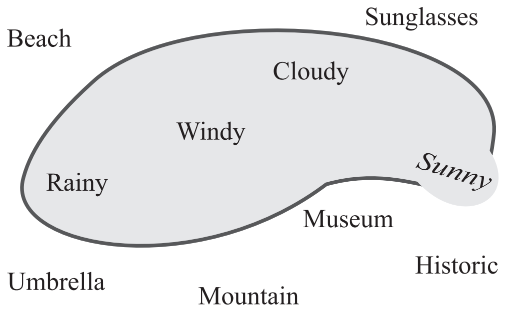

FIGURE 5.2: Set of weather conditions on a certain day.

Let us now consider the set of the weather condition on a certain day. The weather condition is subject to change as the weather does not just stay in one place but moves and changes from hour to hour or day to day. The diagram showed in Figure 5.2 attempts to classify conditions of the weather during the day. For the sake of the example, let us further assume about the weather on that hypothetical day. The clouds cover the sky, the wind blows from different directions, and it rains almost all day. However, every now and again during the day, the rain stops, and the sun comes out. The question stands then, should we include *sunny* as a weather condition for the day, or should we just ignore that the day had those moments of sunshine, or perhaps a bit of both.

By the definition of the crisp set, an element can only be or not be a part of the set. It cannot be both. But, if we were to assign a degree of membership to our concept of sunny, say, 1 to a cloud cover of 0%, 0.75 to a cloud cover of 25%, and 0 to a cloud cover 75%, then we could include sunny to our set of the weather condition to a partial degree of membership.

5.2.1 Type-1 Fuzzy Sets

The term fuzzy set, in fact, comprises all the sets that are not crisp, which brings the necessity of a clarification.

First, when Prof. Zadeh introduced the fuzzy sets back in 1965 [99], he introduced a framework which, as he would say, "*naturally deals with problems in which the source of imprecision is the absence of sharply defined criteria of class membership, rather than the presence of random variables*". This framework would use fuzzy sets, later known as type-1 fuzzy sets (T1 FS)[2], which, in other words, are sets whose elements have grades of membership that are crisp. That is, the characteristic function of these sets can take any value (crisp) between zero and one.

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[2] After the introduction of type-*n* fuzzy sets, it became necessary to make it clear that the previously introduced *fuzzy sets* are a special case of type-n fuzzy sets.

A definition of a *T1 FS* with its membership (as opposed to zero-one MF defined earlier) is as follows:

The MF $\mu_A(x)$ of a fuzzy set A is a function $\mu_A : U \rightarrow [0, 1]$
So, every element x in U has a degree of membership in [0, 1]: $\mu_A(x) \in [0, 1]$
A is completely determined by the set of tuples: $A = \{(x,\ \mu_A(x)),\ x \in U\}$

5.2.2 Type-2 Fuzzy Sets

A type-2 fuzzy set (T2 FS) is, by definition, a fuzzy set whose membership values are T1 FSs on [0, 1]. In other words, T2 FS has grades of membership that are fuzzy, so if we can use the popular term *fuzzy sets* again for T1 FS, a T2 FS then could be termed a “fuzzy-fuzzy set.”

A type-*n* fuzzy set is then a fuzzy set in U whose membership values are type *n - 1*, $n > 1$ fuzzy sets on [0, 1].

From a practical point of view, such type-*n* fuzzy sets for large n (even for $n \geq 3$) are hard to deal with, and it is extremely difficult or even impossible to apply them in real-world applications. Thus, when the term fuzzy sets with MFs is used, it refers to the T2 FSs.

The fuzzy sets with fuzzy MFs were first introduced in 1975 by Prof. Zadeh because the previously proposed fuzzy sets did not address the fact that words can mean different things to different people. In [101], pp. 241, he writes, "*The consideration of fuzzy sets with fuzzy membership functions is motivated by the close association which exists between the concept of a linguistic truth with truth-values such as true, quite true, very true, more or less true, etc., on the one hand, and fuzzy sets in which the grades of membership are specified in linguistic terms such as low, medium, high, very low, not low, and not high, etc., on the other.*"

5.2.3 Why Choose T1 FS Over T2 FS

Not only have fuzzy sets with MFs been around since 1975, but they also have been successfully implemented in many applications, especially in the last two decades. These types of fuzzy sets and the systems that use them are used when there is a need to contend with high levels of uncertainties.

It is a fact that T2 FLSs have demonstrated better abilities to handle uncertainties than their T1 counterparts in many applications; however, there are three main reasons why we use T1 FLSs over T2 FLSs.

First, because T2 FLSs are slower than T1 FLSs. The T2 FLSs use, in most cases, a *type-reducer* (TR), which maps a T2 FS into a T1 FS as most of the applications require a crisp number at the FLS output. A TR uses the iterative Karnik-Mendel (KM) algorithms for its computations, which add a delay (there is a time delay associated with any iterative algorithm) to the application. Although the enhanced opposite direction search (EODS) algorithms are the fastest enhancement to the KM algorithms, the T2 FLSs that use them are still about three times slower than the T1 FLSs [102]. And, if the TR and KM algorithms are not used, but the minimax uncertainty bounds[3] are used instead, the T2 FLSs lose in accuracy. The total computational time of the T2 FLS varies in the range of seconds, and, in our applications, this is non-acceptable. Safety applications in vehicular networks require systems and solutions that run strictly in real-time.

Second, they have a very high computational cost which goes against the objective of our work. The extra computations require more powerful processors, which increases the cost of the overall system.

And third is that T1 FLS have proven themselves that they can adequately solve real problems. Thus, when there are no/some uncertainties, the benefits of using T1 FLSs are twofold, and the aspects where T1 FLSs win over T2 FLSs are aspects that we cannot make a trade-off.

5.3 Implementation Details of an FLS

IIn the previous sections, we provided basic definitions of FL and fuzzy sets, which, as we stated at the beginning of this chapter, serve the purpose of understanding the implemented application presented in this thesis. There is certainly not an intention of explaining the fuzzy set theory here in this chapter. We try to keep it simple because we do not want to cause any confusion by discussing abundant mathematical definitions of the features of fuzzy sets. There are no fancy concepts or principles that comprise the fuzzy set theory either. Many research papers and books are available for this purpose [96]–[98].

The same can be stated for the FLSs. There are a plethora of different applications which use different types of FLSs. On the one hand, there are T2 FLSs that use general T2 FSs; different kinds of interval T2 FLSs: interval singleton T2 FLS, interval T1 non-singleton T2 FLS, and interval T2 non-singleton T2 FLS. On the other hand, there are even T1 FLSs that differ in the inference process, with Mamdani, Sugeno, and Tsukamoto being among the most used ones (though the latter is not as commonly used as the first two). And, these are just a few glimpses of what is taking place in the research of fuzzy sets and fuzzy systems.

Thus, in this section, we describe in detail only the concepts associated with Multiple Input Single Input T1 FLSs (hereinafter will be referred to as just FLSs) based on a Mamdani inference engine, which, again, is the case of the implemented systems

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[3] also known as Wu-Mendel uncertainty bounds.

presented in this thesis. In this case, it is to state that we explain the motivation of selecting a particular method over other available methods.

5.3.1 Linguistic Variables

A basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words or sentences in a natural or artificial language. For instance, *Environment Temperature* is a linguistic variable if its values are words rather than numbers, i.e., very cold, cold, not cold, hot, not hot, not very hot etc., rather than -3, -2, -1, 0, 1, 2, 3,...°C. Although words are inherently less precise than numbers, their use is closer to human intuition.

"*The concept of a linguistic variable provides a means of approximate characterization of phenomena which are too complex or too ill-defined to be amenable to description in conventional quantitative terms.*" L. A. Zadeh, 1975, pp. 199 [101].

Note that later in the description of the proposed fuzzy systems, the set of values that a linguistic variable takes is identified with the terminology *term set*.

5.3.2 Membership Functions

An MF is a curve that specifies the degree to which a given input belongs to a set. It assigns to each object a grade of membership between 0 and 1. In other words, it defines how each point in the universe of discourse U is mapped to a membership value, and it is often associated with the notation $\mu : U \rightarrow [0, 1]$. As also mentioned in the previous sections, an MF itself is known by the designation of the symbol μ, and we will use the same symbol to represent the MFs in the following chapter.

MFs are used in the fuzzification and defuzzification steps of an FLS to map the non-fuzzy input values to fuzzy linguistic terms and vice versa.

Features of MFs

Since many features apply to all kinds of MFs, it is useful to describe a few important ones. These features are visualized in Figure 5.3, and the concepts are described shortly below.

Core: The region of U that is characterized by complete and full membership. That is, all elements x of U such that $\mu(x) = 1$.

Support: The region of U that is characterized by non-zero degree of membership. That is, all elements x of U such that $\mu(x) > 0$.

Boundary: The region of U that is characterized by the elements that have a nonzero membership but not complete and full membership. That is, all elements x of U such that $0 < \mu(x) < 1$.

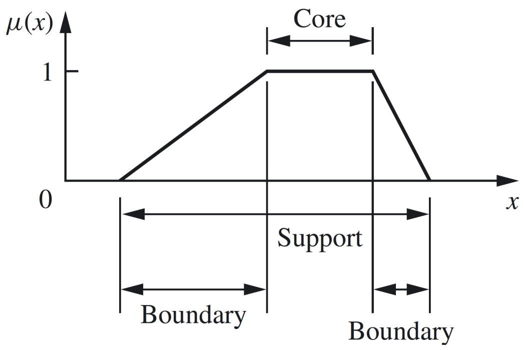


FIGURE 5.3: Core, support, and boundaries of a MF.

Another characteristic to be considered is *completeness*, denoted by ϵ. This parameter is very important since it is related to the overlapping of the fuzzy sets that comprise a linguistic variable (every linguistic value of a linguistic variable is characterized by a fuzzy set and therefore is represented by an MF). Overlapping is one of the strengths of every fuzzy controller in practical applications as it controls the robustness of the controller. We illustrate this parameter in Figure 5.4.

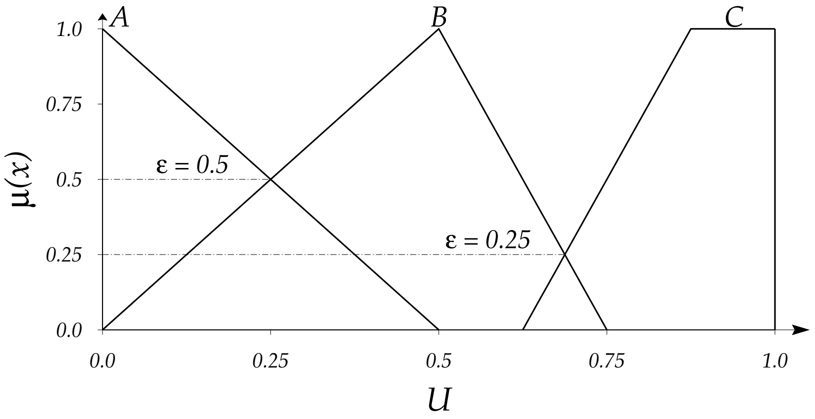
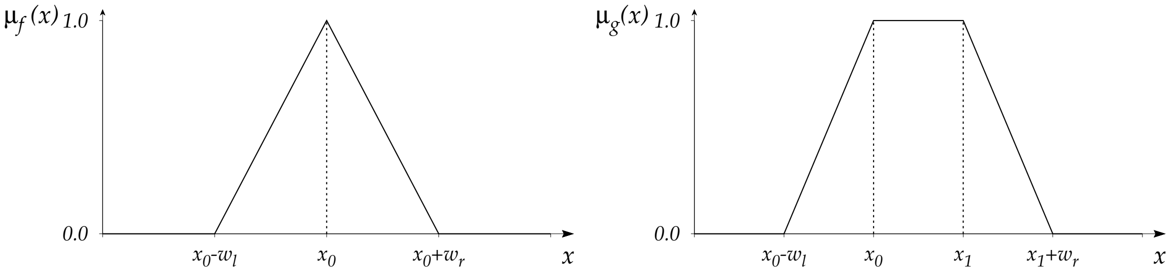


FIGURE 5.4: Example of *completeness* for some overlapping MFs.

In In general, when ϵ decreases, more regions in U are characterized by a low maximal truth degree of the rules they activate, which has the risk of an inefficient control. On the other hand, when epsilon ϵ, there are more redundancies. Studies from different authors suggest that a minimum value of 0.25 and an average of 0.5 should be considered to guarantee an efficient and robust control [103], [104].

Types of MFs - Triangular and Trapezoidal MFs

There are different curve types of MFs such as, triangular, trapezoidal, piece-wise linear, Gaussian, singleton, sigmoidal, and quadratic and cubic polynomial. However, we use only the first two types as these forms of MF are the most suited types for real-time operation.



(a) Triangular MF.

(b) Trapezpodal MF.

FIGURE 5.5: Triangular and trapezoidal MFs.

Let us explain the triangular and trapezoidal MFs in respect to Figure 5.5.

A triangular MF, denoted with $\mu_f(x)$, is defined by the element x_0 which is the only element of the *core*, a left width (left boundary) w_l and a right width (right boundary) w_r.

$$\mu_f(x; x_0, w_l, w_r) = \begin{cases} 0, & \text{if } x \leq x_0 - w_l \\ 1 - \frac{x_0 - x}{w_l}, & \text{if } x_0 - w_l < x \leq x_0 \\ 1 + \frac{x_0 - x}{w_r}, & \text{if } x_0 < x < x_0 + w_r \\ 0, & \text{if } x \geq x_0 + w_r \end{cases}$$

A trapezoidal MF, denoted with $\mu_g(x)$, is defined by the elements x_0 and x_1 which are the edge elements of the *core*, a left width (left boundary) w_l and a right width (right boundary) w_r.

$$\mu_g(x; x_0, x_1, w_l, w_r) = \begin{cases} 0, & \text{if } x \leq x_0 - w_l \\ 1 - \frac{x_0 - x}{w_l}, & \text{if } x_0 - w_l < x < x_0 \\ 1, & \text{if } x_0 \leq x \leq x_1 \\ 1 + \frac{x_1 - x}{w_r}, & \text{if } x_1 < x < x_1 + w_r \\ 0, & \text{if } x \geq x_1 + w_r \end{cases}$$

5.3.3 *IF-THEN* Rules

Similar to expert systems, the *IF-THEN* rules are the heart of an FLS. The *IF-THEN* rules—or just fuzzy rules—have the advantage of storing knowledge in a form that is easy to visualize, providing an effective way to control the overall system. They express the input-output relations by involving linguistic variables in both "IF" and "THEN" clauses, such as:

IF x is A **and** y is B THEN z is K

The former is called the antecedent or premise while the latter is called the consequent or conclusion. In general, variables x and y express the inputs and z the output. A, B, and K, on the other hand, are the linguistic values for x, y, and z, respectively, which as previously mentioned, are expressed by FSs.

In most applications, as in the example case, the antecedent of a rule comprises multiple parts. In this case, a ***logical operator*** is applied to the multiple parts, which would be the operator ***and*** in the example case. In binary logic, if we take the same rule for example, z is True only when both x and y are True. Considering that, in FL, the truth of any statement is a matter of degree, the Boolean operator is replaced by a fuzzy operator, that would include AND operator (*min* function or *product*), OR operator (*max* function or *probabilistic OR*), *T-norm* and *T-conorm* among others. For the construction of the fuzzy rules we use in our implemented systems, we use only the AND operation (*min* function) since it is simple, very effective, and widely used. In addition, most of the parameters we use in our systems are equally important; therefore, we choose the *min* operator over *max*, which is a widely used operator as well.

5.3.4 Fuzzy Inference Process

All rules are evaluated in parallel, and the order of the rules is not important. The parallel nature of the fuzzy rules is an important aspect of FLSs. Instead of switching sharply between modes based on breakpoints, the logic flows smoothly from regions where one rule or another dominates[4].

The evaluation of the rules is just one of the parts of the fuzzy inference process, which essentially is a method that interprets the input parameter values, and based on the fuzzy rules, it assigns values to the output parameter.

The fuzzy inference process involves all we have described so far, from linguistic variables and MFs to fuzzy rules and operations. It consists of the following steps:

1. Step 1: Fuzzification of the input parameters
2. Step 2: Application of the AND operation in the antecedent
3. Step 3: Implication from the antecedent to the consequent
4. Step 4: Aggregation of the consequents across the rules
5. Step 5: Defuzzification

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[4] Recall the example included at the beginning of the chapter with the idea of identifying the cars traveling at a high speed and that adding sharp boundaries to classify the cars is not a human-like way of thinking.

The first three steps are used to interpret the fuzzy rules (each rule is interpreted separately), producing a fuzzy set for each involved rule. The fourth step is then performed to aggregate the output fuzzy sets for each rule into a single output fuzzy set. The last step is used to transform that fuzzy set into a crisp number. We describe these steps in detail in the following.

Fuzzification

The first step is to determine the degree to which a given value of every involved input parameter, a crisp numerical value, belongs to their respective appropriate fuzzy sets. It is done through the MFs of each linguistic variable and the fuzzification method (which is the singleton method for T1 FLSs). No matter what the input linguistic variables describe, the fuzzification process always yields an output within the interval between 0 and 1.

Fuzzy Operator

This step is always performed in our implemented systems because our proposed systems include more than one input parameter; the fuzzy rules have antecedents comprised of multiple parts.

Through fuzzification, a number between 0 and 1 is obtained for each part of the antecedent. If rules have antecedents, consisting of, say, four parts, this means that there are four numbers between 0 and 1 that need to be resolved into a single number. It is done by applying the fuzzy operation; AND operation (*min* function) in our case. The single number obtained from this stage is called the degree of support for the rule.

Implication

It is the final part of the rule interpretation process and the third of the five-step inference process. It is the modification of the consequent through the application of the result of the antecedent. There are many ways to modify the consequent, but two are most common: the *min* (*minimum*) function or *prod* (*product*) function. While both methods can be used in a Mamdani system, in a Sugeno system only the *prod* method can be used in this step.

Since the consequent of a rule in a Mamdani system is a fuzzy set, the degree of support for the rule modifies that fuzzy set to the degree it specifies. We use *min* method as it is the most common way to modify the output set. The output of this step is a fuzzy set truncated by the degree of support for the rule.

Aggregation

It is the step where two of the most used inference processes, Mamdani and Sugeno, actually differ from one another. While the output of the *Implication* step in a Mamdani system is a reshaped fuzzy set for each fired rule (because the antecedent of the rule itself is represented by a fuzzy set), in a Sugeno system, the output is a single number as it uses singleton output membership functions (the antecedent part of rules in a Sugeno system is explained by a polynomial with respect to input variables).

Moreover, when a linguistic variable involves MFs that overlap for some values of U, which is very common, if not always, the input values from those regions belong to more than one fuzzy set. This means that more than a rule will be fired (activated) at the same time; therefore, the rule outputs must be combined in some manner.

And, aggregation is the process by which these rule outputs are combined into a single fuzzy set. The most used functions are *max* (maximum), *probabilistic OR* and *sum* (sum of the rule output sets). We use the *max* method because it is more straightforward and widely accepted.

Defuzzification

It is the final step of the inference process by which the output of the aggregation process, which is a fuzzy set, is mapped to a crisp number, and it is called defuzzification.

There are many defuzzification methods such as *Center of Gravity* (COG), also known as *centroid*, *Center of Area* (COA)[5], *Bisector of Area* (BOA), *Middle of Maximum* (MOM), *Mean of Maxima* (MeOM), and so on. We use COG, also known as the *centroid* method, as it is the most popular defuzzification method in the literature. COG computes the center of the gravity of the area under the aggregate fuzzy set.

5.4 FuzzyC Simulation Tool

Although the Fuzzy Logic Toolbox provided by MATLAB works well for analyzing, designing, and simulating FLSs, we use FuzzyC as a simulation tool for our proposed systems. FuzzyC is software written in C language that enables modeling of different FLSs with ease and accuracy, just like the MATLAB Fuzzy Logic Toolbox. It is developed in our laboratory—Information Networking and Applications (INA) Laboratory—and is maintained and improved throughout the years.

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[5] These two methods, COA and COG, are often confused together. Some authors [97], [105], would refer to them as a single method known with two different names; whereas, other authors [96], [106] would even categorize them into different defuzzification techniques (some methods derive from other methods, thus are classified as the same technique).

FuzzyC includes fuzzification, fuzzy operators, implication, aggregation, and defuzzification methods needed along the inference process. Even though there is not a Graphic User Interface (GUI) available for it yet, the design of the FLSs is easy and convenient. Moreover, it can work with the same file generated by the MATLAB Fuzzy Logic Toolbox, which allows a FLS designed in the latter to be executed in FuzzyC and vice versa.

There are three main reasons why we use FuzzyC over MATLAB Fuzzy Logic Toolbox. The first is that FuzzyC is more computationally efficient. It does not need powerful processors to run into, which facilitates the design of different testbeds. Second, it is faster than its counterpart, which is an aspect worth making use of in our real-time implemented systems. Last but not least, it can be integrated easily with other systems working with different intelligent algorithms; therefore, it is practical for building hybrid intelligent systems.

5.5 Summary

In this chapter, we provided basic concepts that make possible an adequate comprehension of Fuzzy Logic, Fuzzy Sets, and Fuzzy Logic Systems. All the components involved in the implementation of an FLS were described, andthe most important aspects and features were briefly analyzed. Different terms and methods associated with FL and FLSs were introduced, and literature recommendations were given through citations. More attention was paid to the implementation details of a FLS that correspond to the case of our proposed and implemented systems, which will be presented in the next chapter. Along the sections, we gave the motivation behind the selection of the techniques and methods we use over other available techniques and methods.

To recall the most important ones: We use Type 1 Fuzzy Sets because they are faster, have lower (computational) costs, and are adequate for our implemented systems' needs.

We use Mamdani over Sugeno because Mamdani systems have more widespread acceptance for decision support applications due to the intuitive and interpretable nature of the *IF-THEN* rules. Moreover, determining the parameters of polynomials in the antecedent of Sugeno fuzzy rules is inefficient and less straightforward than defining the output fuzzy sets for Mamdani inference.

The methods selected along the inference process are: AND operation (*min* method) as *Fuzzy Operator*, *min* method for the *Implication* step, *max* as the *Aggregation* method, and *Center of Gravity* for defuzzification process. These methods are the most used methods in literature due to the simplicity, efficacy, and performance they offer.

Chapter 6

Proposed Intelligent Systems

This chapter describes the proposed intelligent systems concerning the motivation, objectives, and implementation details. The first section may be considered a continuation of the previous chapter, although the topics covered here relate to the design of Fuzzy Logic Systems (FLSs), rather than to the implementation steps of the inference process. It discusses, in a general way, the issues we encountered during the design of the proposed systems to make known what it takes to design FLSs. The remainder explains in detail three intelligent FLSs. The first FLS consists of an intelligent system that deals with network management issues in vehicular networks in terms of communication and data processing, while the other two FLSs are categorized as driving-support systems. Each of the sections introducing the FLSs begins with a description in respect to the objectives and motivation of the system it introduces, to continue with all the implementation details one must know to obtain the same (simulation) results. The details include, more specifically, the explanation of the parameters (linguistic variables) of the implemented systems, the term set (the set of linguistic values) for each parameter, the chosen Membership Functions (MFs), and the Fuzzy Rule Base (FRB) of every Fuzzy Logic Controller (FLC) comprising the proposed FLSs.

6.1 Implementation Issues

We use FL to implement the proposed systems because the problems we have to deal with involve many uncorrelated parameters, and such problems are classified as NP-hard problems. Different approaches can be used to deal with such problems, but FL is the most efficient approach in solving decision-making and control problems in real-time. Selecting the proper type of fuzzy sets and methods—the methods used for the processes of fuzzification, implication, aggregation, and defuzzification—that suit the application requires experience and knowledge, and this is only the first step of the design of an FLS (see Chapter 6).

The next big step after the identification of the challenges is the conception of the approach that can solve those challenges. To design the best problem-solving approach, all the factors that are a cause of a problem should be pointed out and taken into consideration. In our case, the factors have to be, in some kind of way, an input of the system, with the system output having the ability to control the desired outcome. While this stands for all kinds of areas and problem-solving methods, it is necessary to mention this in the design of FLSs for the following reasons.

First, when only a factor or two are a cause of the problem, a solvable mathematical model can easily be created, and therefore there is no need for an FL approach.

Second, as opposed to the case of very few inputs, there should not be many inputs in a single FLC either because this increases the complexity.

Third, one may not want to have many separate FLSs, with one FLS solving only some issues, since that would lead to the emerging of different problems. For example, a simple question stands to the fact that if we should implement only one system, only some, or all systems at the same time. If the decision is not to implement all the proposed systems, then some issues will not be covered since one cannot predict what will the problem be and implement it right away before it happens. On the other hand, if all the systems are implemented, the systems that cover similar issues could interfere with each other. Moreover, there might be a need to solve several issues at a time, and therefore there should be a way to coordinate all the implemented systems, which is certainly not an easy task.

Once all these factors are taken into consideration (the input parameters are decided), there are other important issues to be resolved, such as:

1. Determining the suitable number of the linguistic terms for both input and output parameters,
2. Finding the appropriate type of MF that represents better its linguistic term,
3. Deciding the proper range of numerical values (granularity) for each term set,
4. Constructing a flawless rule base that can control the system in the best way.

Sorting out all these issues to construct the ideal FLS is practically impossible; however, a satisfactory, near-optimum solution is most of the time acceptable, and that could be provided with some effort. These efforts include the process of tuning all the above components until the desired results are achieved.

In our systems, as mentioned in Section 5.3.2, we use triangular and trapezoidal MFs since they are suitable for real-time operation. We carried out many simulations to decide the number of the terms for each parameter (input and output) and the granularity for each term set—which includes the core and the support for each MF. For a linguistic parameter x, the set of its linguistic values is denoted by $T(x)$,

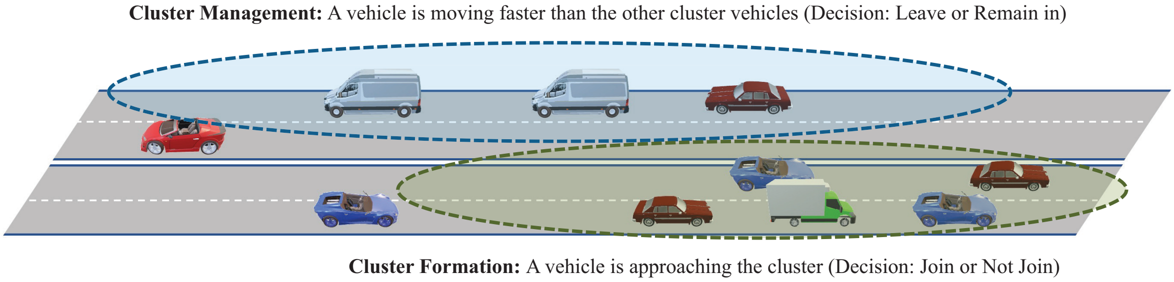


FIGURE 6.1: Illustration of case scenarios for clusters of vehicles.

and the number of the linguistic values by $\mid T(x) \mid$. The set of the MFs associated with the term set of the parameter x is represented by $M(x)$. Based on the linguistic description of input and output parameters, we then construct the FRB. The FRB of each FLC that a FLS is comprised of forms a fuzzy set of dimensions equivalent to $\mid T(x_1) \mid \times \mid T(x_2) \mid \times \cdots \times \mid T(x_n) \mid$, where $\mid T(x_i) \mid$ is the number of terms on $T(x_i)$ and n is the number of input parameters.

6.2 Fuzzy Clustering Management System

In this section, we present an approach that can be used in vehicular networks for better network management. Vehicular networks create large-scale networks composed of numerous mobile nodes (vehicles). While big connected networks are created in dense environments like cities, highways, and rural areas, the created networks are of all kinds of topologies, and on top of that, the topologies change frequently. In Figure 6.1, we illustrate two possible case scenarios of clustering in vehicular networks: cluster formation and cluster management. We consider the latter scenario for which we propose a Fuzzy Cluster Management System (FCMS) that can manage the created networks in a more efficient way. We present and compare two system models, FCMS1 and FCMS2. The parameters used for the implementation of each model, together with the implementation details are given in the following.

The proposed system models are shown in Figure 6.2. For FCMS1, we consider three linguistic input parameters: Vehicle Relative Speed with Vehicle Cluster (VRSVC), Vehicle Degree of Centrality (VDC), and Vehicle Security (VS) to decide the Vehicle Remain in or Leave Cluster (VRLC) possibility output parameter. For FCMS2, we consider four parameters: three parameters are the same as FCMS1 parameters, and a new parameter is added, which is called Vehicle Trustworthiness (VT). The input parameters are as follows.

VRSVC: This is an important parameter in vehicular networks when considering cluster techniques for network management. A vehicle should be close to the Cluster

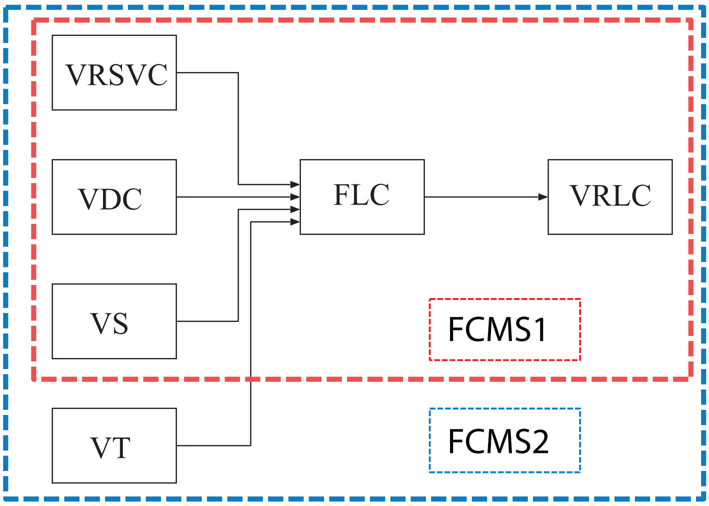


FIGURE 6.2: Diagram of proposed FCMS models.

Head, and in order to remain in the cluster, it should move at the same speed as other cluster vehicles. Otherwise, it will leave the cluster.

VDC: The number of connections the vehicle has to other vehicles in the cluster is an important parameter to decide if this vehicle will remain in or leave the cluster.

VS: In vehicular networks, security is a critical issue. A vehicle is secure if it has the proper safeguard techniques or mechanisms to keep the communication and involved devices protected from malicious intentions.

VT: It is important for vehicles to be trustworthy. Trust is defined as a value assigned to a vehicle based on the services it received and actions performed by the other vehicle. A trustworthy vehicle is a vehicle that has been given a high trust value by other vehicles and can deliver high-quality services to other vehicles in the network.

The term sets of input parameters, *VRSVC*, *VDC*, *VS*, and *VT*, are defined respectively as:

$$\begin{aligned}
T(VRSVC) &= \{Slower\ (Sl),\ Same\ (Sa),\ Faster\ (Fa)\}; \\
T(VDC) &= \{Little\ Important\ (LI),\ Medium\ Important\ (MI),\ Very\ Important\ (VI)\}; \\
T(VS) &= \{Low\ (Lo),\ Medium\ (Me),\ High\ (Hi)\}; \\
T(VT) &= \{Low\ (Lw),\ Middle\ (Md),\ High\ (Hg)\}.
\end{aligned}$$

The MFs for input parameters are defined as:

$$\begin{aligned}
\mu_{Sl}(VRSVC) &= g(VRSVC;\ Sl_0,\ Sl_1,\ Sl_{w_l},\ Sl_{w_r}); \\
\mu_{Sa}(VRSVC) &= f(VRSVC;\ Sa_0,\ Sa_{w_l},\ Sa_{w_r}); \\
\mu_{Fa}(VRSVC) &= g(VRSVC;\ Fa_0,\ Fa_1,\ Fa_{w_l},\ Fa_{w_r}); \\
\mu_{LI}(VDC) &= g(VDC;\ LI_0,\ LI_1,\ LI_{w_l},\ LI_{w_r}); \\
\mu_{VI}(VDC) &= f(VDC;\ MI_0,\ MI_{w_l},\ MI_{w_r}); \\
\mu_{VI}(VDC) &= g(VDC;\ VI_0,\ VI_1,\ VI_{w_l},\ VI_{w_r});
\end{aligned}$$

TABLE 6.1: FCMS parameters and their term sets.

Model		Parameter	Term Set
FCMS2	FCMS1	VRSVC	Slower (Sl), Same (Sa), Faster (Fa)
		VDC	Little Important (LI), Medium Important (MI), Very Important (VI)
		VS	Low (Lo), Medium (Me), High (Hi)
		VT	Low (Lw), Middle (Md), High (Hg)
FCMS1 & FCMS2		VRLC	Leave(Le), Weak Leave (WL), Very Weak Leave (VWL), Neither Remain Nor Leave (NRNL), Very Weak Remain (VWR), Weak Remain (WR), Remain (Re)

$$\begin{aligned}
\mu_{Lo}(VS) &= f(VS;\ Lo_0,\ Lo_1,\ Lo_{w_r});\\
\mu_{Me}(VS) &= f(VS;\ Me_0,\ Me_{w_l},\ Me_{w_r});\\
\mu_{Hi}(VS) &= f(VS;\ Hi_0,\ Hi_1,\ Hi_{w_l});\\
\mu_{Lw}(VT) &= g(VT;\ Lw_0,\ Lw_1,\ Lw_{w_l},\ Lw_{w_r});\\
\mu_{Md}(VT) &= f(VT;\ Md_0,\ Md_{w_l},\ Md_{w_r});\\
\mu_{Hg}(VT) &= g(VT;\ Hg_0,\ Hg_1,\ Hg_{w_l},\ Hg_{w_r}).
\end{aligned}$$

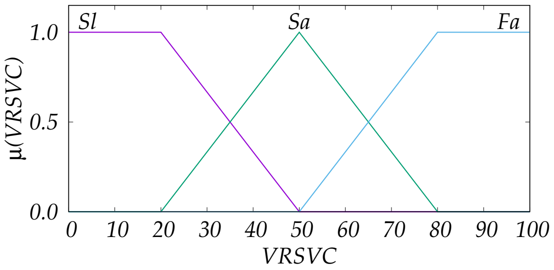
The small letters w_l and w_r mean the left and right width, respectively, and are better explained in Section 5.3.2 in respect to Figure 5.5.
The term set for the output parameter $VRLC$ is defined as:

$$VRLC = \begin{pmatrix} Leave \\ Weak\ Leave \\ Very\ Weak\ Leave \\ Neither\ Remain\ Nor\ Leave \\ Very\ Weak\ Remain \\ Weak\ Remain \\ Remain \end{pmatrix} = \begin{pmatrix} Le \\ WL \\ VWL \\ NRNL \\ VWR \\ WR \\ Re \end{pmatrix}.$$

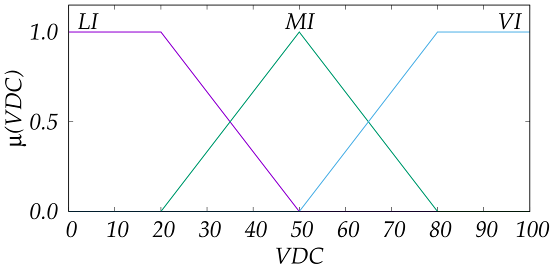
The MFs for the output parameter are defined as:

$$\begin{aligned}
\mu_{Le}(VRLC) &= g(VRLC;\ Le_0,\ Le_1,\ Le_{w_l},\ Le_{w_r});\\
\mu_{WL}(VRLC) &= f(VRLC;\ WL_0,\ WL_{w_l},\ WL_{w_r});\\
\mu_{VWL}(VRLC) &= f(VRLC;\ VWL_0,\ VWL_{w_l},\ VWL_{w_r});\\
\mu_{NRNL}(VRLC) &= f(VRLC;\ NRNL_0,\ NRNL_{w_l},\ NRNL_{w_r});\\
\mu_{VWR}(VRLC) &= f(VRLC;\ VWR_0,\ VWR_{w_l},\ VWR_{w_r});\\
\mu_{WR}(VRLC) &= f(VRLC;\ WR_0,\ WR_{w_l},\ WR_{w_r});\\
\mu_{Re}(VRLC) &= g(VRLC;\ Re_0,\ Re_1,\ Re_{w_l},\ Re_{w_r}).
\end{aligned}$$

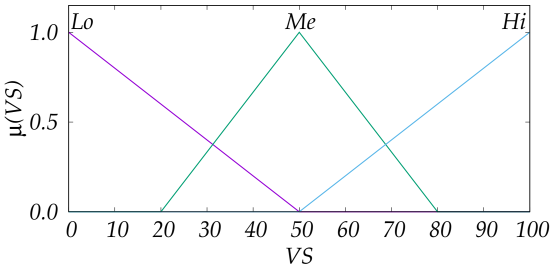
The FCMS1 and FCMS2 linguistic parameters and their term sets are recapped in Table 6.1. The MFs that we use in our system models are shown in Figure 6.3. In Table 6.2 (Table 6.3), we show the FRB of FCMS1 (FCMS2), which consists of 27 (81) rules.



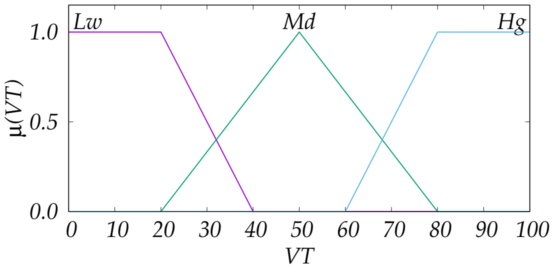
(a) Vehicle Relative Speed with Vehicle Cluster



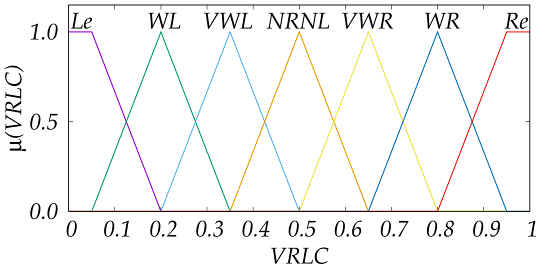
(b) Vehicle Degree of Centrality



(c) Vehicle Security



(d) Vehicle Trustworthiness



(e) Vehicle Remain or Leave Cluster

FIGURE 6.3: MFs for parameters of FCMS.

TABLE 6.2: Fuzzy Rule Base of FCMS1.

Rule	**VRSVC**	**VDC**	**VS**	**VRLC**	**Rule**	**VRSVC**	**VDC**	**VS**	**VRLC**
1	Sl	LI	Lo	Le	14	Sa	MI	Me	WR
2	Sl	LI	Me	WL	15	Sa	MI	Hi	Re
3	Sl	LI	Hi	VWL	16	Sa	VI	Lo	WR
4	Sl	MI	Lo	Le	17	Sa	VI	Me	Re
5	Sl	MI	Me	VWL	18	Sa	VI	Hi	Re
6	Sl	MI	Hi	NRNL	19	Fa	LI	Lo	Le
7	Sl	VI	Lo	WL	20	Fa	LI	Me	WL
8	Sl	VI	Me	NRNL	21	Fa	LI	Hi	VWL
9	Sl	VI	Hi	VWR	22	Fa	MI	Lo	Le
10	Sa	LI	Lo	NRNL	23	Fa	MI	Me	VWL
11	Sa	LI	Me	VWR	24	Fa	MI	Hi	NRNL
12	Sa	LI	Hi	WR	25	Fa	VI	Lo	WL
13	Sa	MI	Lo	VWR	26	Fa	VI	Me	NRNL
					27	Fa	VI	Hi	VWR

TABLE 6.3: Fuzzy Rule Base of FCMS2.

Rule	**VRSVC**	**VDC**	**VS**	**VT**	**VRLC**	**Rule**	**VRSVC**	**VDC**	**VS**	**VT**	**VRLC**
1	Sl	LI	Lo	Lw	Le	41	Sa	MI	Me	Md	WR
2	Sl	LI	Lo	Md	Le	42	Sa	MI	Me	Hg	Re
3	Sl	LI	Lo	Hg	WL	43	Sa	MI	Hi	Lw	WR
4	Sl	LI	Me	Lw	Le	44	Sa	MI	Hi	Md	Re
5	Sl	LI	Me	Md	WL	45	Sa	MI	Hi	Hg	Re
6	Sl	LI	Me	Hg	NRNL	46	Sa	VI	Lo	Lw	NRNL
7	Sl	LI	Hi	Lw	WL	47	Sa	VI	Lo	Md	VWR
8	Sl	LI	Hi	Md	VWL	48	Sa	VI	Lo	Hg	Re
9	Sl	LI	Hi	Hg	VWR	49	Sa	VI	Me	Lw	WR
10	Sl	MI	Lo	Lw	Le	50	Sa	VI	Me	Md	Re
11	Sl	MI	Lo	Md	Le	51	Sa	VI	Me	Hg	Re
12	Sl	MI	Lo	Hg	VWL	52	Sa	VI	Hi	Lw	WR
13	Sl	MI	Me	Lw	WL	53	Sa	VI	Hi	Md	Re
14	Sl	MI	Me	Md	VWL	54	Sa	VI	Hi	Hg	Re
15	Sl	MI	Me	Hg	VWR	55	Fa	LI	Lo	Lw	Le
16	Sl	MI	Hi	Lw	VWL	56	Fa	LI	Lo	Md	Le
17	Sl	MI	Hi	Md	NRNL	57	Fa	LI	Lo	Hg	WL
18	Sl	MI	Hi	Hg	WR	58	Fa	LI	Me	Lw	Le
19	Sl	VI	Lo	Lw	Le	59	Fa	LI	Me	Md	WL
20	Sl	VI	Lo	Md	WL	60	Fa	LI	Me	Hg	NRNL
21	Sl	VI	Lo	Hg	NRNL	61	Fa	LI	Hi	Lw	WL
22	Sl	VI	Me	Lw	VWL	62	Fa	LI	Hi	Md	VWL
23	Sl	VI	Me	Md	NRNL	63	Fa	LI	Hi	Hg	VWR
24	Sl	VI	Me	Hg	WR	64	Fa	MI	Lo	Lw	Le
25	Sl	VI	Hi	Lw	NRNL	65	Fa	MI	Lo	Md	Le
26	Sl	VI	Hi	Md	VWR	66	Fa	MI	Lo	Hg	VWL
27	Sl	VI	Hi	Hg	WR	67	Fa	MI	Me	Lw	WL
28	Sa	LI	Lo	Lw	WL	68	Fa	MI	Me	Md	VWL
29	Sa	LI	Lo	Md	VWL	69	Fa	MI	Me	Hg	VWR
30	Sa	LI	Lo	Hg	VWR	70	Fa	MI	Hi	Lw	VWL
31	Sa	LI	Me	Lw	NRNL	71	Fa	MI	Hi	Md	NRNL
32	Sa	LI	Me	Md	VWR	72	Fa	MI	Hi	Hg	WR
33	Sa	LI	Me	Hg	WR	73	Fa	VI	Lo	Lw	Le
34	Sa	LI	Hi	Lw	VWR	74	Fa	VI	Lo	Md	WL
35	Sa	LI	Hi	Md	WR	75	Fa	VI	Lo	Hg	NRNL
36	Sa	LI	Hi	Hg	Re	76	Fa	VI	Me	Lw	VWL
37	Sa	MI	Lo	Lw	VWL	77	Fa	VI	Me	Md	NRNL
38	Sa	MI	Lo	Md	VWR	78	Fa	VI	Me	Hg	WR
39	Sa	MI	Lo	Hg	WR	79	Fa	VI	Hi	Lw	NRNL
40	Sa	MI	Me	Lw	VWR	80	Fa	VI	Hi	Md	VWR
						81	Fa	VI	Hi	Hg	WR

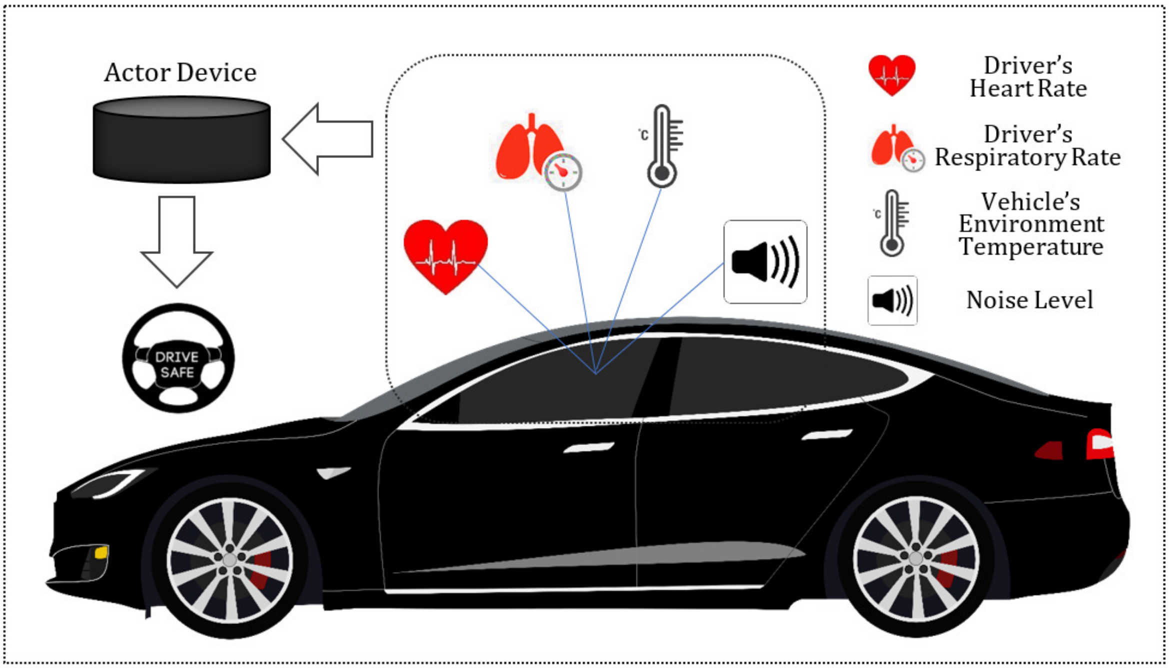


FIGURE 6.4: Visualization of FDMS architecture.

6.3 Fuzzy Driver Monitoring System

Fully autonomous vehicles still have a long way to go, but driving support technologies are becoming widespread, even in everyday cars. The goal is to improve driving safety and performance by relying on the measurement and recognition of the inside/outside environment and their reflection on steering operation. In Section 3.6, we gave a review of driving-support technologies existing in the literature. Considering the advantages and limitations of the existing systems, we present and implement two driving-support systems, one for driver monitoring and another for driving risk management. The proposed systems are non-complex and non-intrusive intelligent systems that can detect danger or a risky situation in real-time and then warn the driver about the danger.

6.3.1 FDMS Design

Since the fuzzy rule expression is close to an expert natural language, it allows the modeling of such inherently ambiguous notions as driver situations in an efficient and effective way [98], [107]–[111].

The proposed Fuzzy Driver Monitoring System (FDMS) determines the driver's situation in real-time by considering different types of parameters. The considered parameters include environmental factors and the driver's vital signs that can influence his actual condition. A visualized model of our proposed system is given in Figure 6.4. We present and compare two models of FDMS, whose design is given

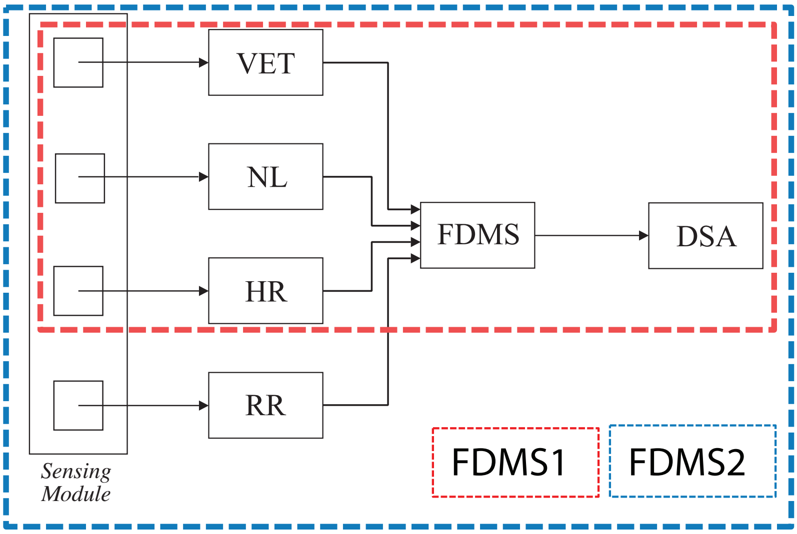


FIGURE 6.5: Diagram of proposed FDMS models.

below. We also implement both models in a testbed with the experiment setup details to follow the system design.

The structure of the proposed FDMS models is shown in Figure 6.5, with the red and blue frame showing FDMS1 and FDMS2, respectively. For the implementation of FDMS1, we consider three input parameters: Vehicle's Environment Temperature (VET), Noise Level (NL), and Heart Rate (HR) to determine the Driver's Situational Awareness (DSA). For FDMS2, the Respiratory Rate (RR) is taken into consideration as an extra parameter to determine the same output, with some modifications on the term sets and MFs used for its defuzzification.

The term sets of input parameters are defined respectively as:

$$\begin{aligned} T(VET) &= \{Low\ (L),\ Medium\ (M),\ High\ (H)\}; \\ T(NL) &= \{Quiet\ (Q),\ Noisy\ (N),\ Very\ Noisy\ (VN)\}; \\ T(HR) &= \{Slow\ (S),\ Normal\ (No),\ Fast\ (F)\}; \\ T(RR) &= \{Slow\ (Sl),\ Normal\ (Nm),\ Fast\ (Fa)\}. \end{aligned}$$

The MFs for input parameters are defined as:

$$\begin{aligned} \mu_L(VET) &= g(VET;\ L_0,\ L_1,\ L_{w_l},\ L_{w_r}); \\ \mu_M(VET) &= g(VET;\ M_0,\ M_1,\ M_{w_l},\ M_{w_r}); \\ \mu_H(VET) &= g(VET;\ H_0,\ H_1,\ H_{w_l},\ H_{w_r}); \\ \mu_Q(NL) &= g(NL;\ Q_0,\ Q_1,\ Q_{w_l},\ Q_{w_r}); \\ \mu_N(NL) &= f(NL;\ N_0,\ N_{w_l},\ N_{w_r}); \\ \mu_{VN}(NL) &= g(NL;\ VN_0,\ VN_1,\ VN_{w_l},\ VN_{w_r}); \\ \mu_S(HR) &= g(HR;\ S_0,\ S_1,\ S_{w_l},\ S_{w_r}); \\ \mu_{No}(HR) &= g(HR;\ No_0,\ No_1,\ No_{w_l},\ No_{w_r}); \\ \mu_F(HR) &= g(HR;\ F_0,\ F_1,\ F_{w_l},\ F_{w_r}); \end{aligned}$$

$$\begin{aligned}
\mu_{Sl}(RR) &= g(RR;\, Sl_0,\, Sl_1,\, Sl_{w_l},\, Sl_{w_r});\\
\mu_{Nm}(RR) &= g(RR;\, Nm_0,\, Nm_1,\, Nm_{w_l},\, Nm_{w_r});\\
\mu_{Fa}(RR) &= g(RR;\, Fa_0,\, Fa_1,\, Fa_{w_l},\, Fa_{w_r}).
\end{aligned}$$

The term sets of output parameters are defined respectively as:

$$\begin{aligned}
FDMS1 : T(DSA) &= \{Very\ Bad\ (VB),\ Bad\ (B),\ Normal\ (Nor),\ Good\ (G),\ Very\ Good\ (VG)\};\\
FDMS2 : T(DSA) &= \{Extremely\ Bad\ (EB),\ Very\ Bad\ (VB),\ Bad\ (B),\ Normal\ (Nor),\ Good\ (G),\\
&\quad Very\ Good\ (VG),\ Extremely\ Good\ (EG)\};
\end{aligned}$$

The MFs for the output of FDMS1 are defined as:

$$\begin{aligned}
\mu_{VB}(DSA) &= g(DSA;\, VB_0,\, VB_1,\, VB_{w_l},\, VB_{w_r});\\
\mu_{B}(DSA) &= f(DSA;\, B_0,\, B_{w_l},\, B_{w_r});\\
\mu_{Nor}(DSA) &= f(DSA;\, Nor_0,\, Nor_{w_l},\, Nor_{w_r});\\
\mu_{G}(DSA) &= f(DSA;\, G_0,\, G_{w_l},\, G_{w_r});\\
\mu_{VG}(DSA) &= g(DSA;\, VG_0,\, VG_1,\, VG_{w_l},\, VG_{w_r}).
\end{aligned}$$

The MFs for the output of FDMS2 are defined as:

$$\begin{aligned}
\mu_{EB}(DSA) &= g(DSA;\, EB_0,\, EB_1,\, EB_{w_l},\, EB_{w_r});\\
\mu_{VB}(DSA) &= f(DSA;\, VB_0,\, VB_{w_l},\, VB_{w_r});\\
\mu_{B}(DSA) &= f(DSA;\, B_0,\, B_{w_l},\, B_{w_r});\\
\mu_{Nor}(DSA) &= f(DSA;\, Nor_0,\, Nor_{w_l},\, Nor_{w_r});\\
\mu_{G}(DSA) &= f(DSA;\, G_0,\, G_{w_l},\, G_{w_r});\\
\mu_{VG}(DSA) &= f(DSA;\, VG_0,\, VG_{w_l},\, VG_{w_r});\\
\mu_{EG}(DSA) &= g(DSA;\, EG_0,\, EG_1,\, EG_{w_l},\, EG_{w_r}).
\end{aligned}$$

The MFs used for fuzzification are given in Figure 6.6(a), Figure 6.6(b), Figure 6.6(c), and Figure 6.6(d). In Figure 6.6(e) and Figure 6.6(f) are shown the MFs used for the output parameter. All the linguistic parameters and their term sets are recapped in Table 6.4.

FDMS1 (FDMS2) has three (four) input parameters with three linguistic terms each; therefore, there are 27 (81) rules in the FRB. The FRB of FDMS1 and FDMS2 is shown in Table 6.5 and in Table 6.6, respectively. Since there are more rules in the FRB of FDMS2, more linguistic terms are needed to describe the output parameter in order to maintain input-output continuity. Input-output continuity is an important feature that recommends that small changes of input parameters should result in small changes of output values, and it is achieved when there are not many control rules that fall into the same decision level.

TABLE 6.4: FDMS parameters and their term sets.

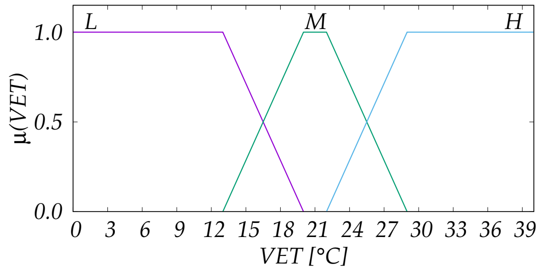
Fuzzy System		**Parameter**	**Term Sets**
FDMS2	FDMS1	VET	Low (L), Medium (M), High (H)
		NL	Quiet (Q), Noisy (N), Very Noisy (VN)
		HR	Slow (S), Normal (No), Fast (F)
		RR	Slow (Sl), Normal (Nm), Fast (Fa)
FDMS1		DSA	Very Bad (VB), Bad (B), Normal (Nor), Good (G), Very Good (VG)
FDMS2		DSA	Extremely Bad (EB), VB, B, Nor, G, VG, Extremely Good (EG)

TABLE 6.5: Fuzzy Rule Base of FDMS1.

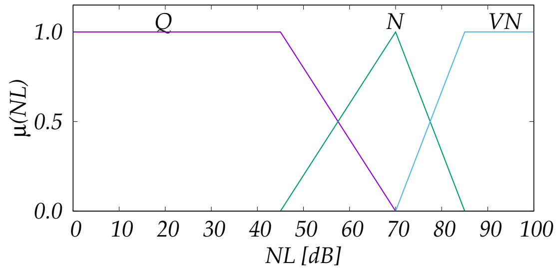
Rule	**VET**	**NL**	**HR**	**DSA**	**Rule**	**VET**	**NL**	**HR**	**DSA**	**Rule**	**VET**	**NL**	**HR**	**DSA**
1	L	Q	S	B	10	M	Q	S	Nor	19	H	Q	S	B
2	L	Q	No	G	11	M	Q	No	VG	20	H	Q	No	G
3	L	Q	F	B	12	M	Q	F	Nor	21	H	Q	F	B
4	L	N	S	VB	13	M	N	S	B	22	H	N	S	VB
5	L	N	No	Nor	14	M	N	No	G	23	H	N	No	Nor
6	L	N	F	VB	15	M	N	F	B	24	H	N	F	VB
7	L	VN	S	VB	16	M	VN	S	VB	25	H	VN	S	VB
8	L	VN	No	B	17	M	VN	No	Nor	26	H	VN	No	B
9	L	VN	F	VB	18	M	VN	F	VB	27	H	VN	F	VB

TABLE 6.6: Fuzzy Rule Base of FDMS2.

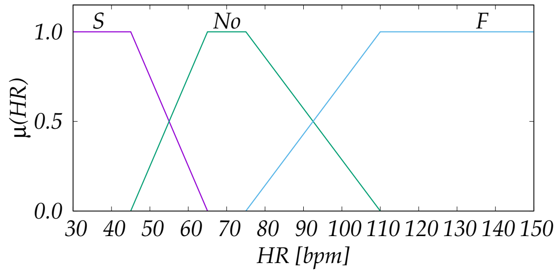
Rule	**VET**	**NL**	**HR**	**RR**	**DSA**	**Rule**	**VET**	**NL**	**HR**	**RR**	**DSA**	**Rule**	**VET**	**NL**	**HR**	**RR**	**DSA**
1	L	Q	S	Sl	VB	28	M	Q	S	Sl	B	55	H	Q	S	Sl	VB
2	L	Q	S	Nm	Nor	29	M	Q	S	Nm	G	56	H	Q	S	Nm	Nor
3	L	Q	S	Fa	VB	30	M	Q	S	Fa	B	57	H	Q	S	Fa	VB
4	L	Q	No	Sl	Nor	31	M	Q	No	Sl	VG	58	H	Q	No	Sl	Nor
5	L	Q	No	Nm	VG	32	M	Q	No	Nm	EG	59	H	Q	No	Nm	VG
6	L	Q	No	Fa	Nor	33	M	Q	No	Fa	VG	60	H	Q	No	Fa	Nor
7	L	Q	F	Sl	EB	34	M	Q	F	Sl	B	61	H	Q	F	Sl	EB
8	L	Q	F	Nm	B	35	M	Q	F	Nm	G	62	H	Q	F	Nm	B
9	L	Q	F	Fa	EB	36	M	Q	F	Fa	B	63	H	Q	F	Fa	EB
10	L	N	S	Sl	EB	37	M	N	S	Sl	VB	64	H	N	S	Sl	EB
11	L	N	S	Nm	B	38	M	N	S	Nm	G	65	H	N	S	Nm	B
12	L	N	S	Fa	EB	39	M	N	S	Fa	VB	66	H	N	S	Fa	EB
13	L	N	No	Sl	B	40	M	N	No	Sl	G	67	H	N	No	Sl	B
14	L	N	No	Nm	G	41	M	N	No	Nm	EG	68	H	N	No	Nm	G
15	L	N	No	Fa	B	42	M	N	No	Fa	G	69	H	N	No	Fa	B
16	L	N	F	Sl	EB	43	M	N	F	Sl	VB	70	H	N	F	Sl	EB
17	L	N	F	Nm	VB	44	M	N	F	Nm	Nor	71	H	N	F	Nm	VB
18	L	N	F	Fa	EB	45	M	N	F	Fa	VB	72	H	N	F	Fa	EB
19	L	VN	S	Sl	EB	46	M	VN	S	Sl	EB	73	H	VN	S	Sl	EB
20	L	VN	S	Nm	VB	47	M	VN	S	Nm	B	74	H	VN	S	Nm	VB
21	L	VN	S	Fa	EB	48	M	VN	S	Fa	EB	75	H	VN	S	Fa	EB
22	L	VN	No	Sl	VB	49	M	VN	No	Sl	Nor	76	H	VN	No	Sl	VB
23	L	VN	No	Nm	Nor	50	M	VN	No	Nm	VG	77	H	VN	No	Nm	Nor
24	L	VN	No	Fa	VB	51	M	VN	No	Fa	Nor	78	H	VN	No	Fa	VB
25	L	VN	F	Sl	EB	52	M	VN	F	Sl	EB	79	H	VN	F	Sl	EB
26	L	VN	F	Nm	VB	53	M	VN	F	Nm	B	80	H	VN	F	Nm	VB
27	L	VN	F	Fa	EB	54	M	VN	F	Fa	EB	81	H	VN	F	Fa	EB



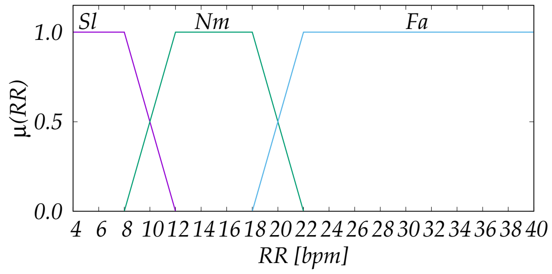
(a) VET



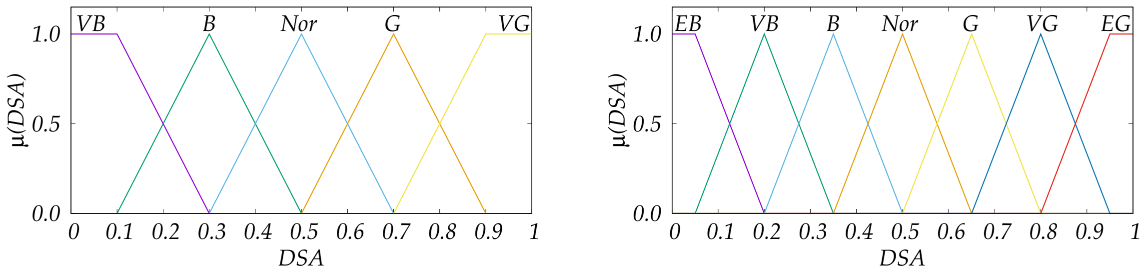
(b) Noise Level



(c) Heart Rate

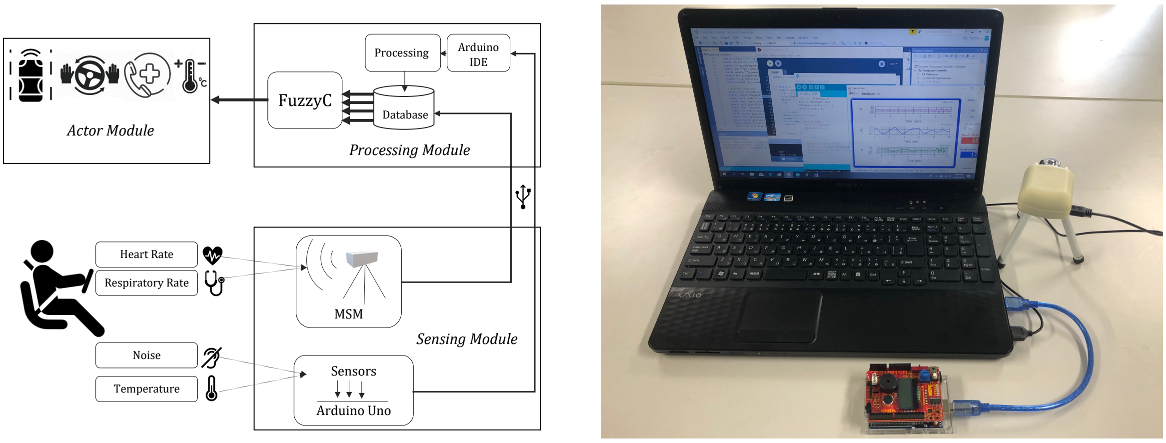


(d) Respiratory Rate



(e) DSA - FDMS1 (f) DSA - FDMS2

FIGURE 6.6: MFs for input and output parameters of FDMS.



(a) The testbed scheme. (b) Snapshot of testbed.

FIGURE 6.7: Scheme and snapshot of FDMS testbed.

6.3.2 FDMS Testbed

In order to evaluate FDMS, we implemented a testbed and carried out experiments in a real scenario [112], [113]. A scheme and a snapshot of the testbed are given in Figure 6.7. As shown in Figure 6.7(a), the testbed is composed of sensing and processing modules, with the actor module showing examples of actions that can be performed based on the provided output. The sensing module is made of non-contact sensors and consists of two parts. The first part is implemented in Arduino Uno, while the second one consists of a Motion Sensor Module (MSM) called DC6M4JN3000. We set up sensors on Arduino Uno to measure the vehicle's environment temperature and noise and used the MSM to measure the driver's heart and respiratory rate. The processing module is composed of three software, i.e., Processing, Arduino IDE, and Visual Studio running on Windows OS, which obtains the sensed data and runs our Fuzzy program called FuzzyC. The sensing components are connected to the processing device via a USB cable. We used the Arduino IDE and Processing to get the sensed data from the first sensing part, whereas the MSM generates its data in the appropriate format we use in our FuzzyC. Depending on the input data, the FDMS1 and FDMS2which are implemented in FuzzyC, determine the DSA. Based on the DSA, the actor module decides whether an action is needed, and, if so, which is the appropriate task to be performed.

6.4 Fuzzy System for Driving Risk Management

Although the above-described system works just fine, it only focuses on the driver and their condition. It is noteworthy to also consider other factors which often are determined to be a leading cause of many accidents such as driving speed, and road and weather conditions among others. In many cases, these parameters are a determinant factor of accidents alone, but a combination with a driver who is experiencing both mental and physical discomfort would lead the driver to a perilous situation. Therefore, the objective of the following work is to develop a non-complex and non-intrusive intelligent driving-support system that can detect a dangerous situation in real-time by taking into consideration different types of parameters that affect the driving process.

The proposed driving-support system is named Fuzzy System for Driving Risk Management (FSDRM), and it makes use of the information acquired from various in-car sensors as well as from communications with other vehicles and infrastructure to evaluate the condition of the considered parameters. We present two system models, one that considers the technical condition of the vehicle, and one that does not. The former is presented under the name of FSDRM2 and the latter as FSDRM1. We redesigned the FSDRM to include the vehicle's technical condition since there are many old vehicles, and by old, we mean vehicles with deteriorating conditions, which are a cause of many crashes in low-income countries.

We evaluate both models by computer simulations. For FSDRM1 we implement also a testbed to attain experimental results in a real scenario. For the implementation of the testbed, we use some IoT devices equipped with various sensors from which we obtain the driver's vital signs and data regarding the inside environment.

6.4.1 FSDRM1 Design

The parameters considered for the implementation of FSDRM1 include factors that affect the driver's ability to drive, such as their current health condition and the inside environment of the vehicle they currently are, the driving speed, and factors related to the outside environment such as the weather and road condition. A model of the proposed system is presented in Figure 6.8.

The model structure is shown in Figure 6.9. It consists of four FLCs and nine input parameters. Although it seems more complex to use four FLCs, it is far better than having nine input parameters in a single FLC because this would result in a very complex FRB composed of thousands of rules, which, in turn, would increase the overall complexity of the system. The considered parameters are described in the following.

Relative Humidity (RH): Humidity is one of the air quality parameters that considerably affects driving comfort and human health [114]. The driver and passengers inside the vehicle continuously generate moisture which increases relative humidity. Contrarily, the air conditioner, which produces hot, dry air, decreases the RH when

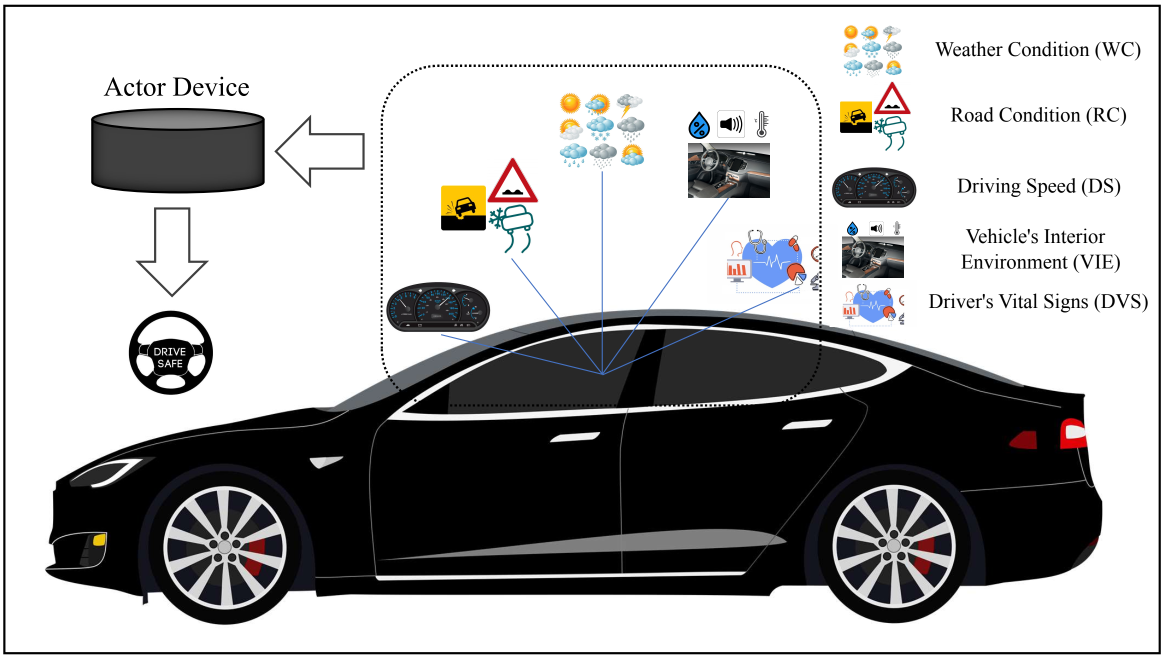


FIGURE 6.8: Visualization of FSDRM1 architecture.

it is kept on. A very high or very low RH both cause great discomfort, which can prevent the driver from focusing only on the driving process.

Noise Level (NL): Ambient noise impacts the driver's mental state by increasing general stress levels and aggravating stress-related conditions. In general, traffic noise and vehicle noise (a noise the vehicle itself generates) are the main sources of noise that disturb the driving experience. A stressed driver is a source of dangerous situations; therefore, we consider this parameter in our system.

Environment Temperature (ET): Temperature is another environmental factor that is considered to be able to affect the driver as well. In [115], authors show that temperature variations can be used to combat drivers' drowsiness. The results indicate that the likelihood of drowsy driving is significantly reduced by maintaining a cooler inside temperature in the vehicle.

Weather Condition (WC): According to Federal Highway Administration, approximately 21% of car crashes that happen every year are weather-related. Weather acts through visibility impairments, precipitation, high winds, and temperature extremes to affect driver capabilities and vehicle performance (i.e., traction, stability, and maneuverability) [116].

Road Condition (RC): Although the weather and road conditions are closely related, we decided to consider this parameter separately because a change of weather conditions is not always reflected in a change of road conditions. For instance, after heavy rain or snow, even if the weather gets better, the roads might still be slippery for a while, or floods may happen, which, in turn, could damage roads. Moreover, roads may have potholes or be bumpy, and such poor road conditions are not related

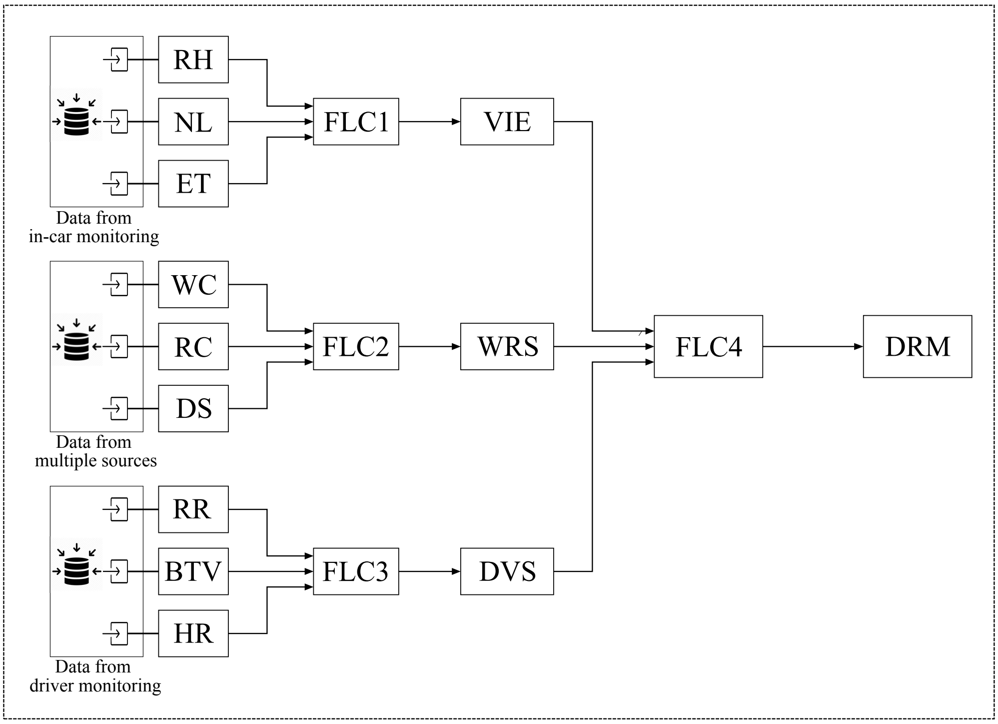


FIGURE 6.9: Diagram of FSDRM1.

to the current weather condition. The authors in [117] present a system that monitors the road condition in real-time.

Driving Speed (DS): The speed at which a vehicle travels has a direct impact on a car crash as well as on the severity of injuries resulting from that crash. Specifically, an increase of 1 km/h in average speed typically results in a 3% higher risk of a crash involving injury, with a 4–5% increase for crashes that result in casualties [1]. In addition, if the speed is combined with a bad condition of the other parameters, the impact certainly escalates.

Respiratory Rate (RR): The respiratory system experience significant changes from wakefulness to drowsiness, thus it makes the breathing rate an interesting variable which can be used to detect driver's drowsiness. Its high degree of effectiveness is reported in various studies [118]. In addition to drowsiness detection, RR can be used to detect mental stress, which is in our interest, too.

Body Temperature Variation (BTV): Effects of the increase of body temperature range from discomfort (feeling hot, sweating, feeling thirsty, slightly hungry, etc.) to fainting, dizziness, weakness, headache, and more, which could lead to fatal driving situations. On the other hand, since the body temperature drops during sleep, it can be used to detect whether the driver is awake or falling asleep.

Heart Rate (HR): Similar to RR, HR is one of the variables that can detect drowsiness as it varies considerably between the different stages of drowsiness, such as alertness and fatigue [75], [76]. Furthermore, if the driver is experiencing anxiety or stress, their heart rate will increase; thus, we can use it to determine different situations which could influence the risk of a crash.

Vehicle's Interior Environment (VIE), Weather-Road-Speed (WRS), and Driver's Vital Signs (DVS) are the output variables of FLC1, FLC2, and FLC3, respectively, and at the same time, serve as input parameters for FLC4. The final output of our system is Driving Risk Management (DRM), which determines the degree of risk that a situation involves at the moment.

The term sets of used linguistic parameters are defined respectively as:

$$
\begin{aligned}
T(RH) &= \{Low\ (L),\ Medium\ (M),\ High\ (H)\};\\
T(NL) &= \{Quiet\ (Q),\ Noisy\ (N),\ Very\ Noisy\ (VN)\};\\
T(ET) &= \{Low\ (Lo),\ Medium\ (Me),\ High\ (Hi)\};\\[4pt]
T(WC) &= \{Very\ Bad\ (VB),\ Bad\ (B),\ Good\ (G)\};\\
T(RC) &= \{Very\ Bad\ (VBa),\ Bad\ (Ba),\ Good\ (Go)\};\\
T(DS) &= \{Slow\ (Sl),\ Moderate\ (Mo),\ Fast\ (Fa)\};\\[4pt]
T(RR) &= \{Slow\ (Sl),\ Normal\ (Nm),\ Fast\ (Fs)\}.\\
T(BTV) &= \{Small\ (Sm),\ High\ (H),\ Very\ High\ (VH)\};\\
T(HR) &= \{Slow\ (S),\ Normal\ (No),\ Fast\ (Fa)\};\\[4pt]
T(VIE) &= \{Extremely\ Uncomfortable\ (EUC),\ Very\ Uncomfortable\ (VUC),\\
&\quad\ Uncomfortable\ (UC),\ Moderate\ (Mod),\ Comfortable\ (C)\};\\
T(WRS) &= \{No/Minor\ Danger\ (N/MD),\ Moderate\ Danger\ (MD),\ Considerable\ Danger\ (CD),\\
&\quad\ High\ Danger\ (HD),\ Very\ High\ Danger\ (VHD)\};\\
T(DVS) &= \{Extremely\ Bad\ (EB),\ Very\ Bad\ (VB),\ Bad\ (B),\ Fair\ (F),\ Good\ (G)\};\\[4pt]
T(DRM) &= \{Safe\ (Sf),\ Very\ Low\ (VL),\ Low\ (Lw),\ Moderate\ (Md),\ Considerable\ (Co),\\
&\quad\ High\ (Hg),\ Very\ High\ (VH),\ Severe\ (Sv),\ Danger\ (D)\}.
\end{aligned}
$$

The MFs for all linguistic parameters are defined as:

$$
\begin{aligned}
\mu_L(RH) &= g(RH;\ L_0,\ L_1,\ L_{w_l},\ L_{w_r});\\
\mu_M(RH) &= g(RH;\ M_0,\ M_1,\ M_{w_l},\ M_{w_r});\\
\mu_H(RH) &= g(RH;\ H_0,\ H_1,\ H_{w_l},\ H_{w_r});\\
\mu_Q(NL) &= g(NL;\ Q_0,\ Q_1,\ Q_{w_l},\ Q_{w_r});\\
\mu_N(NL) &= f(NL;\ N_0,\ N_{w_l},\ N_{w_r});\\
\mu_{VN}(NL) &= g(NL;\ VN_0,\ VN_1,\ VN_{w_l},\ VN_{w_r});\\
\mu_{Lo}(ET) &= g(ET;\ Lo_0,\ Lo_1,\ Lo_{w_l},\ Lo_{w_r});\\
\mu_{Me}(ET) &= g(ET;\ Me_0,\ Me_1,\ Me_{w_l},\ Me_{w_r});\\
\mu_{Hi}(ET) &= g(ET;\ Hi_0,\ Hi_1,\ Hi_{w_l},\ Hi_{w_r});\\[4pt]
\mu_{VB}(WC) &= g(WC;\ VB_0,\ VB_1,\ VB_{w_l},\ VB_{w_r});\\
\mu_B(WC) &= g(WC;\ B_0,\ B_1,\ B_{w_l},\ B_{w_r});\\
\mu_G(WC) &= g(WC;\ G_0,\ G_1,\ G_{w_l},\ G_{w_r});
\end{aligned}
$$

$$\begin{aligned}
\mu_{VBa}(RC) &= g(RC;\, VBa_0,\, VBa_1,\, VBa_{w_l},\, VBa_{w_r}); \\
\mu_{Ba}(RC) &= g(RC;\, Ba_0,\, Ba_1,\, Ba_{w_l},\, Ba_{w_r}); \\
\mu_{Go}(RC) &= g(RC;\, Go_0,\, Go_1,\, Go_{w_l},\, Go_{w_r}); \\
\mu_{Sl}(DS) &= g(DS;\, Sl_0,\, Sl_1,\, Sl_{w_l},\, Sl_{w_r}); \\
\mu_{Mo}(DS) &= g(DS;\, Mo_0,\, Mo_1,\, Mo_{w_l},\, Mo_{w_r}); \\
\mu_{Fa}(DS) &= g(DS;\, Fa_0,\, Fa_1,\, Fa_{w_l},\, Fa_{w_r});
\end{aligned}$$

$$\begin{aligned}
\mu_{Sl}(RR) &= g(RR;\, Sl_0,\, Sl_1,\, Sl_{w_l},\, Sl_{w_r}); \\
\mu_{Nm}(RR) &= g(RR;\, Nm_0,\, Nm_1,\, Nm_{w_l},\, Nm_{w_r}); \\
\mu_{Fs}(RR) &= g(RR;\, Fs_0,\, Fs_1,\, Fs_{w_l},\, Fs_{w_r}); \\
\mu_{Sm}(BTV) &= g(BTV;\, Sm_0,\, Sm_1,\, Sm_{w_l},\, Sm_{w_r}); \\
\mu_{H}(BTV) &= g(BTV;\, H_0,\, H_1,\, H_{w_l},\, H_{w_r}); \\
\mu_{VH}(BTV) &= g(BTV;\, VH_0,\, VH_1,\, VH_{w_l},\, VH_{w_r}); \\
\mu_{S}(HR) &= g(HR;\, S_0,\, S_1,\, S_{w_l},\, S_{w_r}); \\
\mu_{No}(HR) &= g(HR;\, No_0,\, No_1,\, No_{w_l},\, No_{w_r}); \\
\mu_{Fa}(HR) &= g(HR;\, Fa_0,\, Fa_1,\, Fa_{w_l},\, Fa_{w_r});
\end{aligned}$$

$$\begin{aligned}
\mu_{EUC}(VIE) &= g(VIE;\, EUC_0,\, EUC_1,\, EUC_{w_l},\, EUC_{w_r}); \\
\mu_{VUC}(VIE) &= f(VIE;\, VUC_0,\, VUC_{w_l},\, VUC_{w_r}); \\
\mu_{UC}(VIE) &= f(VIE;\, UC_0,\, UC_{w_l},\, UC_{w_r}); \\
\mu_{Mod}(VIE) &= f(VIE;\, Mod_0,\, Mod_{w_l},\, Mod_{w_r}); \\
\mu_{C}(VIE) &= g(VIE;\, C_0,\, C_1,\, C_{w_l},\, C_{w_r}); \\
\mu_{N/MD}(WRS) &= g(WRS;\, N/MD_0,\, N/MD_1,\, N/MD_{w_l},\, N/MD_{w_r}); \\
\mu_{MD}(WRS) &= f(WRS;\, MD_0,\, MD_{w_l},\, MD_{w_r}); \\
\mu_{CD}(WRS) &= f(WRS;\, CD_0,\, CD_{w_l},\, CD_{w_r}); \\
\mu_{HD}(WRS) &= f(WRS;\, HD_0,\, HD_{w_l},\, HD_{w_r}); \\
\mu_{VHD}(WRS) &= g(WRS;\, VHD_0,\, VHD_1,\, VHD_{w_l},\, VHD_{w_r}); \\
\mu_{EB}(DVS) &= g(DVS;\, EB_0,\, EB_1,\, EB_{w_l},\, EB_{w_r}); \\
\mu_{VB}(DVS) &= f(DVS;\, VB_0,\, VB_{w_l},\, VB_{w_r}); \\
\mu_{B}(DVS) &= f(DVS;\, B_0,\, B_{w_l},\, B_{w_r}); \\
\mu_{F}(DVS) &= f(DVS;\, F_0,\, F_{w_l},\, F_{w_r}); \\
\mu_{G}(DVS) &= g(DVS;\, G_0,\, G_1,\, G_{w_l},\, G_{w_r});
\end{aligned}$$

$$\begin{aligned}
\mu_{Sf}(DRM) &= f(DRM;\, Sf_0,\, Sf_{w_l},\, Sf_{w_r}); \\
\mu_{VL}(DRM) &= f(DRM;\, VL_0,\, VL_{w_l},\, VL_{w_r}); \\
\mu_{Lw}(DRM) &= f(DRM;\, Lw_0,\, Lw_{w_l},\, Lw_{w_r}); \\
\mu_{Md}(DRM) &= f(DRM;\, Md_0,\, Md_{w_l},\, Md_{w_r}); \\
\mu_{Co}(DRM) &= f(DRM;\, Co_0,\, Co_{w_l},\, Co_{w_r}); \\
\mu_{Hg}(DRM) &= f(DRM;\, Hg_0,\, Hg_{w_l},\, Hg_{w_r}); \\
\mu_{VH}(DRM) &= f(DRM;\, VH_0,\, VH_{w_l},\, VH_{w_r}); \\
\mu_{Sv}(DRM) &= f(DRM;\, Sv_0,\, Sv_{w_l},\, Sv_{w_r}); \\
\mu_{D}(DRM) &= f(DRM;\, D_0,\, D_{w_l},\, D_{w_r}).
\end{aligned}$$

FLC1, FLC2, and FLC3 all have three input parameters with three linguistic terms each; therefore, there are 27 rules in each FRB. The FRB of FLC 4 has 125 rules because it consists of three input parameters, with every input having five linguistic terms. FRB1, FRB2, FRB3, and FRB4 are shown in Tables 6.7–6.10, respectively.

To maintain input-output continuity[1], we use five MFs for the outputs of FLC1, FLC2, and FLC3 (VIE, WRS, and DVS, respectively) and nine for FLC4 (DRM). This way, we avoid too many control rules to fall into the same decision level; thus, achieving a better continuity. The MFs used for all parameters are given in Figure 6.10.

TABLE 6.7: Fuzzy Rule Base of FLC1 (VIE-FLC).

No	RH	NL	ET	VIE	No	RH	NL	ET	VIE	No	RH	NL	ET	VIE
1	L	Q	Lo	UC	10	M	Q	Lo	Mod	19	H	Q	Lo	UC
2	L	Q	Me	Mod	11	M	Q	Me	C	20	H	Q	Me	Mod
3	L	Q	Hi	UC	12	M	Q	Hi	Mod	21	H	Q	Hi	UC
4	L	N	Lo	VUC	13	M	N	Lo	UC	22	H	N	Lo	VUC
5	L	N	Me	UC	14	M	N	Me	Mod	23	H	N	Me	UC
6	L	N	Hi	VUC	15	M	N	Hi	UC	24	H	N	Hi	VUC
7	L	VN	Lo	EUC	16	M	VN	Lo	VUC	25	H	VN	Lo	EUC
8	L	VN	Me	VUC	17	M	VN	Me	UC	26	H	VN	Me	VUC
9	L	VN	Hi	EUC	18	M	VN	Hi	VUC	27	H	VN	Hi	EUC

TABLE 6.8: Fuzzy Rule Base of FLC2 (WRS-FLC).

No	WC	RC	DS	WRS	No	WC	RC	DS	WRS	No	WC	RC	DS	WRS
1	VB	VBa	Sl	CD	10	B	VBa	Sl	MD	19	G	VBa	Sl	N/MD
2	VB	VBa	Mo	VHD	11	B	VBa	Mo	HD	20	G	VBa	Mo	MD
3	VB	VBa	Fa	VHD	12	B	VBa	Fa	VHD	21	G	VBa	Fa	HD
4	VB	Ba	Sl	CD	13	B	Ba	Sl	MD	22	G	Ba	Sl	N/MD
5	VB	Ba	Mo	CD	14	B	Ba	Mo	CD	23	G	Ba	Mo	MD
6	VB	Ba	Fa	VHD	15	B	Ba	Fa	HD	24	G	Ba	Fa	CD
7	VB	Go	Sl	MD	16	B	Go	Sl	N/MD	25	G	Go	Sl	N/MD
8	VB	Go	Mo	CD	17	B	Go	Mo	MD	26	G	Go	Mo	N/MD
9	VB	Go	Fa	HD	18	B	Go	Fa	CD	27	G	Go	Fa	MD

TABLE 6.9: Fuzzy Rule Base of FLC3 (DVS-FLC).

No	RR	BTV	HR	DVS	No	RR	BTV	HR	DVS	No	RR	BTV	HR	DVS
1	Sl	Sm	S	B	10	Nm	Sm	S	F	19	Fs	Sm	S	B
2	Sl	Sm	No	F	11	Nm	Sm	No	G	20	Fs	Sm	No	F
3	Sl	Sm	Fa	B	12	Nm	Sm	Fa	F	21	Fs	Sm	Fa	B
4	Sl	H	S	VB	13	Nm	H	S	VB	22	Fs	H	S	VB
5	Sl	H	No	B	14	Nm	H	No	F	23	Fs	H	No	B
6	Sl	H	Fa	VB	15	Nm	H	Fa	VB	24	Fs	H	Fa	VB
7	Sl	VH	S	EB	16	Nm	VH	S	EB	25	Fs	VH	S	EB
8	Sl	VH	No	VB	17	Nm	VH	No	VB	26	Fs	VH	No	VB
9	Sl	VH	Fa	EB	18	Nm	VH	Fa	EB	27	Fs	VH	Fa	EB

---

[1] This feature is explained in Section 6.3.1.

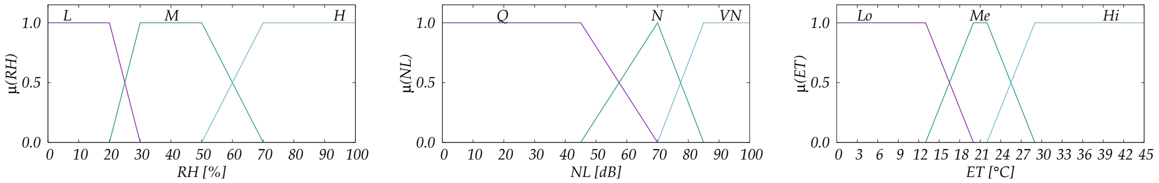
TABLE 6.10: Fuzzy Rule Base of FLC4 (DRM-FLC).

No	VIE	WRS	DVS	DRM	No	VIE	WRS	DVS	DRM	No	VIE	WRS	DVS	DRM
1	EUC	N/MD	EB	Sv	43	VUC	HD	B	Sv	85	Mod	MD	G	VL
2	EUC	N/MD	VB	VH	44	VUC	HD	F	VH	86	Mod	CD	EB	Hg
3	EUC	N/MD	B	Hg	45	VUC	HD	G	Hg	87	Mod	CD	VB	Hg
4	EUC	N/MD	F	Co	46	VUC	VHD	EB	D	88	Mod	CD	B	Co
5	EUC	N/MD	G	Md	47	VUC	VHD	VB	D	89	Mod	CD	F	Md
6	EUC	MD	EB	D	48	VUC	VHD	B	D	90	Mod	CD	G	Lw
7	EUC	MD	VB	Sv	49	VUC	VHD	F	Sv	91	Mod	HD	EB	VH
8	EUC	MD	B	VH	50	VUC	VHD	G	VH	92	Mod	HD	VB	VH
9	EUC	MD	F	Hg	51	UC	N/MD	EB	Hg	93	Mod	HD	B	Hg
10	EUC	MD	G	Co	52	UC	N/MD	VB	Co	94	Mod	HD	F	Co
11	EUC	CD	EB	D	53	UC	N/MD	B	Md	95	Mod	HD	G	Md
12	EUC	CD	VB	D	54	UC	N/MD	F	Lw	96	Mod	VHD	EB	Sv
13	EUC	CD	B	Sv	55	UC	N/MD	G	VL	97	Mod	VHD	VB	Sv
14	EUC	CD	F	VH	56	UC	MD	EB	VH	98	Mod	VHD	B	VH
15	EUC	CD	G	Hg	57	UC	MD	VB	Hg	99	Mod	VHD	F	Hg
16	EUC	HD	EB	D	58	UC	MD	B	Co	100	Mod	VHD	G	Co
17	EUC	HD	VB	D	59	UC	MD	F	Md	101	C	N/MD	EB	Md
18	EUC	HD	B	Sv	60	UC	MD	G	Lw	102	C	N/MD	VB	Lw
19	EUC	HD	F	Sv	61	UC	CD	EB	Sv	103	C	N/MD	B	VL
20	EUC	HD	G	VH	62	UC	CD	VB	VH	104	C	N/MD	F	Sf
21	EUC	VHD	EB	D	63	UC	CD	B	Hg	105	C	N/MD	G	Sf
22	EUC	VHD	VB	D	64	UC	CD	F	Co	106	C	MD	EB	Co
23	EUC	VHD	B	D	65	UC	CD	G	Md	107	C	MD	VB	Md
24	EUC	VHD	F	D	66	UC	HD	EB	D	108	C	MD	B	Lw
25	EUC	VHD	G	Sv	67	UC	HD	VB	Sv	109	C	MD	F	VL
26	VUC	N/MD	EB	VH	68	UC	HD	B	VH	110	C	MD	G	VL
27	VUC	N/MD	VB	Hg	69	UC	HD	F	Hg	111	C	CD	EB	Hg
28	VUC	N/MD	B	Co	70	UC	HD	G	Co	112	C	CD	VB	Co
29	VUC	N/MD	F	Md	71	UC	VHD	EB	D	113	C	CD	B	Md
30	VUC	N/MD	G	Lw	72	UC	VHD	VB	D	114	C	CD	F	Lw
31	VUC	MD	EB	Sv	73	UC	VHD	B	Sv	115	C	CD	G	Lw
32	VUC	MD	VB	VH	74	UC	VHD	F	VH	116	C	HD	EB	VH
33	VUC	MD	B	Hg	75	UC	VHD	G	Hg	117	C	HD	VB	Hg
34	VUC	MD	F	Co	76	Mod	N/MD	EB	Md	118	C	HD	B	Co
35	VUC	MD	G	Md	77	Mod	N/MD	VB	Md	119	C	HD	F	Md
36	VUC	CD	EB	D	78	Mod	N/MD	B	Lw	120	C	HD	G	Md
37	VUC	CD	VB	Sv	79	Mod	N/MD	F	VL	121	C	VHD	EB	Sv
38	VUC	CD	B	VH	80	Mod	N/MD	G	Sf	122	C	VHD	VB	VH
39	VUC	CD	F	Hg	81	Mod	MD	EB	Co	123	C	VHD	B	Hg
40	VUC	CD	G	Co	82	Mod	MD	VB	Co	124	C	VHD	F	Co
41	VUC	HD	EB	D	83	Mod	MD	B	Md	125	C	VHD	G	Co
42	VUC	HD	VB	D	84	Mod	MD	F	Lw					

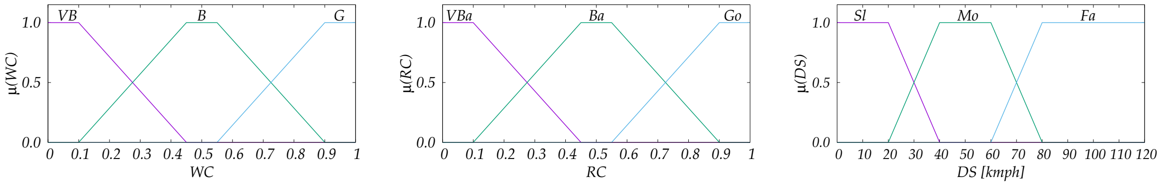
We decided the numeric range of each MF first by following the recommendations and guidelines for humidity, indoor temperature, noise levels, etc., and then we adjusted them during the design process, which included many computer simulations.

6.4.2 FSDRM1 Testbed

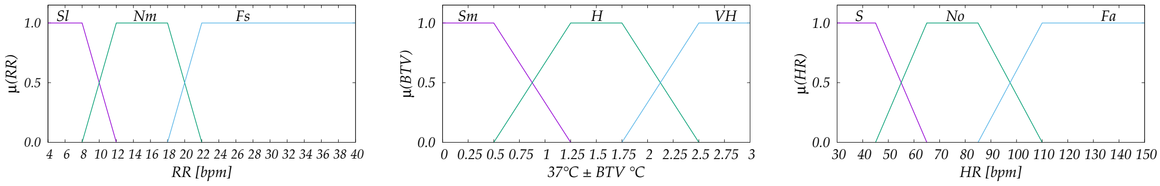
To test the FSDRM1 in a real scenario, we designed and implemented a portable and non-intrusive testbed that allowed us to acquire essential data for our system. The design and a snapshot of the implemented testbed are given in Figure 6.11. The testbed can be considered as an improved model of the previous testbed, and it includes the following: an automated sensing module, a manual data input, a



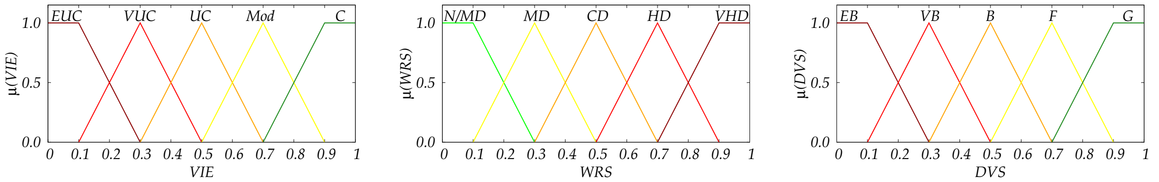
(a) Relative Humidity (b) Noise Level (c) Environment Temperature



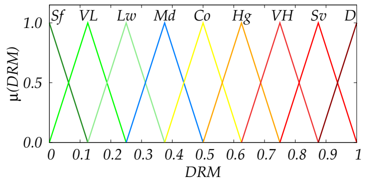
(d) Weather Condition (e) Road Condition (f) Driving Speed



(g) Respiratory Rate (h) Body Temperature Variation (i) Heart Rate



(j) Vehicle's Interior Environment (k) Weather-Road-Speed (l) Driver's Vital Signs

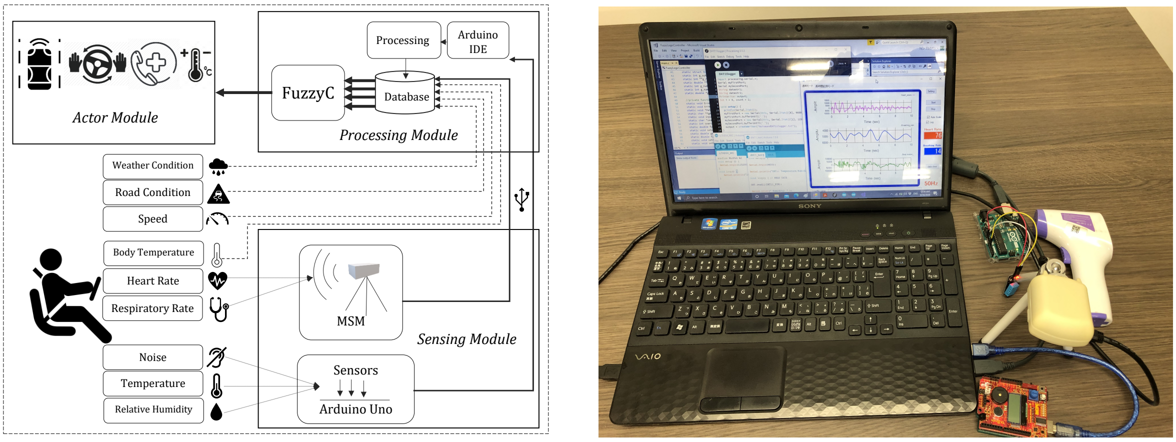


(m) Driving Risk Management

FIGURE 6.10: MFs for input and output parameters of FSDRM1.

processing module, and an actor module instancing different actions that could be carried out when the system's output (DRM) exceeds certain values.

The automated sensing module consists of several sensors set up on an Arduino Uno to measure the relative humidity, temperature, and noise in the vehicle's interior environment and DC6M4JN3000 motion sensor module used to get the driver's heart and breathing rate. Although the data for these parameters are transferred to the



(a) The testbed scheme. (b) Snapshot of testbed.

FIGURE 6.11: Scheme and snapshot of FSDRM1 testbed.

processing module via USB cables, body temperature, speed, and weather/road condition parameters are entered directly into the processing module database through manual data input.

The processing module implemented in Windows OS first makes use of Arduino IDE and Processing software to obtain and convert the parameters data into readable data for our Fuzzy program, i.e., FuzzyC in which we implement our system, and then it runs the FuzzyC through Visual Studio software to determine the DRM value. Afterward, the actor module decides the relevant action according to the degree of risk induced by the DRM.

6.4.3 FSDRM2 Design

For the implementation of FSDRM2, we consider the parameters given in Table 6.11. The parameters are grouped by the type (input or output) and by the FLC they correspond. A diagram of FSDRM2 is shown in Figure 6.12. It consists of five FLCs, four of which are used to lower the overall complexity of the system. While FSDRM2 seems more complex, it is far better this way than having twelve input parameters in a single FLC because this would result in a very complex FRB composed of hundreds of thousands of rules, which in turn would increase the overall complexity of the system. In this section, we describe in detail only the implementation of FLC3 and FLC5 because FLC1, FLC2, and FLC4[2] were presented in Section 6.4.1.
The FLC3 input parameters are explained in the following.

Steering Systems Condition (SSC): When it comes to car operation, the steering, suspension, transmission systems, and engine are all interconnected. The steering and suspension systems faults can trigger unfortunate incidents because the car cannot

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[2] FLC4 of FSDRM2 corresponds to FLC3 of FSDRM1.

TABLE 6.11: FSDRM2 parameters and its FLCs.

Parameter	**Type**	**FLC**
Weather Condition (WC) Road Condition (RC) Driving Speed (DS)	Input	FLC1
Weather-Road-Speed (WRS)	Output	
Relative Humidity (RH) Noise Level (NL) Environment Temperature (ET)	Input	FLC2
Vehicle's Interior Environment (VIE)	Output	
Steering Systems Condition (SSC) Brakes Condition (BC) Tires Condition (TC)	Input	FLC3
Vehicle's Technical Condition (VTC)	Output	
Respiratory Rate (RR) Body Temperature Variation (BTV) Heart Rate (HR)	Input	FLC4
Driver's Vital Signs (DVS)	Output	
WRS, VIE, VTC, DVS	Input	FLC5
Driving Risk Management (DRM)	Output	

respond to the driver's reactions. Transmission and engine faults could prevent the driver from accelerating quickly if the need arises—leaving the car stranded at inopportune moments. Even though steering/suspension/transmission/engine-related problems account for 3% of the occurred crashes assigned to vehicle failures [119], the numbers are considered to be much higher as such malfunctions are harder to detect after a crash occurs.

Brakes Condition (BC): Brake-related problems account for about 22% of all crashes due to technical failures. Bad brakes are a major cause of rear-end collisions, and therefore being aware of their condition helps detect a latent problem that could be deadly if it is not caught early.

Tires Condition (TC): Tire failures are the cause of over one-third of the accidents happening due to vehicular technical failures. Tire blowouts and worn tires drastically reduce the driver's ability to adequately control the vehicle, thus increasing the chances of a crash. A bad condition of the tires combined with bad weather or a high speed would result in a fatal accident.

The Vehicle's Technical Condition is the output parameter of FLC3, which on the other hand, serves as an input for FLC5. The other input parameters of FLC5 are Weather-Road-Speed (WRS), Vehicle's Interior Environment (VIE), and Driver's Vital Signs (DVS), whereas its output is Driving Risk Management (DRM).

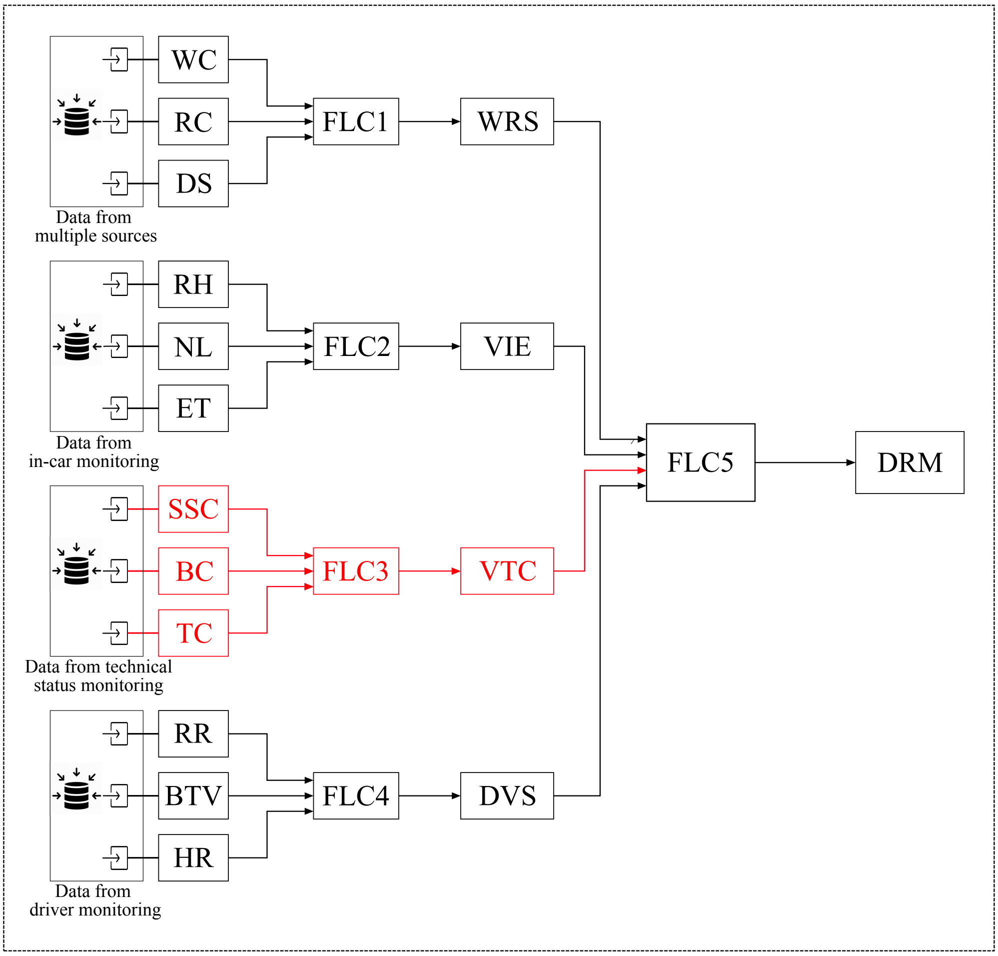


FIGURE 6.12: Diagram of FSDRM2.

The term sets of FLC3 and FLC5 parameters are defined respectively as:

$$\begin{aligned}
T(SSC) &= \{Bad\ (B),\ Fair\ (F),\ Good\ (G)\}; \\
T(BC) &= \{Bad\ (Ba),\ Fair\ (Fa),\ Good\ (Go)\}; \\
T(TC) &= \{Bad\ (Bd),\ Fair\ (Fr),\ Good\ (Gd)\}; \\
T(VTC) &= \{Bad\ (Bad),\ Moderately\ Bad\ (MBad),\ Moderate\ (M),\ Moderately\ Good\ (MGood), \\
&\quad Good\ (Good)\};
\end{aligned}$$

$$\begin{aligned}
T(WRS) &= \{No/Minor\ Danger\ (N/MD),\ Moderate\ Danger\ (MD),\ Danger\ (D)\}; \\
T(VIE) &= \{Uncomfortable\ (UC),\ Moderate\ (Mo),\ Comfortable\ (C)\}; \\
T(VTC) &= \{Bad\ (Ba),\ Fair\ (Fa),\ Good\ (Go)\}; \\
T(DVS) &= \{Bad\ (B),\ Fair\ (F),\ Good\ (G)\}; \\
T(DRM) &= \{Safe\ (Sf),\ Low\ (Lw),\ Moderate\ (Md),\ High\ (Hg),\ Very\ High\ (VH),\ Severe\ (Sv), \\
&\quad Danger\ (Dg)\}.
\end{aligned}$$

The MFs for FLC3 and FLC5 parameters are defined as:

$$\begin{aligned}
\mu_B(SSC) &= g(SSC;\ B_0,\ B_1,\ B_{w_l},\ B_{w_r}); \\
\mu_F(SSC) &= g(SSC;\ F_0,\ F_1,\ F_{w_l},\ F_{w_r});
\end{aligned}$$

$$\begin{aligned}
\mu_G(SSC) &= g(SSC;\, G_0,\, G_1,\, G_{w_l},\, G_{w_r});\\
\mu_{Ba}(BC) &= g(BC;\, Ba_0,\, Ba_1,\, Ba_{w_l},\, Ba_{w_r});\\
\mu_{Fa}(BC) &= g(BC;\, Fa_0,\, Fa_1,\, Fa_{w_l},\, Fa_{w_r});\\
\mu_{Go}(BC) &= g(BC;\, Go_0,\, Go_1,\, Go_{w_l},\, Go_{w_r});\\
\mu_{Bd}(TC) &= g(TC;\, Bd_0,\, Bd_1,\, Bd_{w_l},\, Bd_{w_r});\\
\mu_{Fr}(TC) &= g(TC;\, Fr_0,\, Fr_1,\, Fr_{w_l},\, Fr_{w_r});\\
\mu_{Gd}(TC) &= g(TC;\, Gd_0,\, Gd_1,\, Gd_{w_l},\, Gd_{w_r});\\
\mu_{Bad}(VTC) &= g(VTC;\, Bad_0,\, Bad_1,\, Bad_{w_l},\, Bad_{w_r});\\
\mu_{MBad}(VTC) &= f(VTC;\, MBad_0,\, MBad_{w_l},\, MBad_{w_r});\\
\mu_M(VTC) &= f(VTC;\, M_0,\, M_{w_l},\, M_{w_r});\\
\mu_{MGood}(VTC) &= f(VTC;\, MGood_0,\, MGood_{w_l},\, MGood_{w_r});\\
\mu_{Good}(VTC) &= g(VTC;\, Good_0,\, Good_1,\, Good_{w_l},\, Good_{w_r});
\end{aligned}$$

$$\begin{aligned}
\mu_{N/MD}(WRS) &= g(WRS;\, N/MD_0,\, N/MD_1,\, N/MD_{w_l},\, N/MD_{w_r});\\
\mu_{MD}(WRS) &= g(WRS;\, MD_0,\, MD_1,\, MD_{w_l},\, MD_{w_r});\\
\mu_D(WRS) &= g(WRS;\, D_0,\, D_1,\, D_{w_l},\, D_{w_r});\\
\mu_{UC}(VIE) &= g(VIE;\, UC_0,\, UC_1,\, UC_{w_l},\, UC_{w_r});\\
\mu_{Mo}(VIE) &= g(VIE;\, Mo_0,\, Mo_1,\, Mo_{w_l},\, Mo_{w_r});\\
\mu_C(VIE) &= g(VIE;\, C_0,\, C_1,\, C_{w_l},\, C_{w_r});\\
\mu_{Ba}(VTC) &= g(VTC;\, Ba_0,\, Ba_1,\, Ba_{w_l},\, Ba_{w_r});\\
\mu_{Fa}(VTC) &= g(VTC;\, Fa_0,\, Fa_1,\, Fa_{w_l},\, Fa_{w_r});\\
\mu_{Go}(VTC) &= g(VTC;\, Go_0,\, Go_1,\, Go_{w_l},\, Go_{w_r});\\
\mu_B(DVS) &= f(DVS;\, B_0,\, B_{w_l},\, B_{w_r});\\
\mu_F(DVS) &= f(DVS;\, F_0,\, F_{w_l},\, F_{w_r});\\
\mu_G(DVS) &= f(DVS;\, G_0,\, G_{w_l},\, G_{w_r});\\
\mu_{Sf}(DRM) &= g(DRM;\, Sf_0,\, Sf_1,\, Sf_{w_l},\, Sf_{w_r});\\
\mu_{Lw}(DRM) &= f(DRM;\, Lw_0,\, Lw_{w_l},\, Lw_{w_r});\\
\mu_{Md}(DRM) &= f(DRM;\, Md_0,\, Md_{w_l},\, Md_{w_r});\\
\mu_{Hg}(DRM) &= f(DRM;\, Hg_0,\, Hg_{w_l},\, Hg_{w_r});\\
\mu_{VH}(DRM) &= f(DRM;\, VH_0,\, VH_{w_l},\, VH_{w_r});\\
\mu_{Sv}(DRM) &= f(DRM;\, Sv_0,\, Sv_{w_l},\, Sv_{w_r});\\
\mu_{Dg}(DRM) &= g(DRM;\, Dg_0,\, Dg_1,\, Dg_{w_l},\, Dg_{w_r}).
\end{aligned}$$

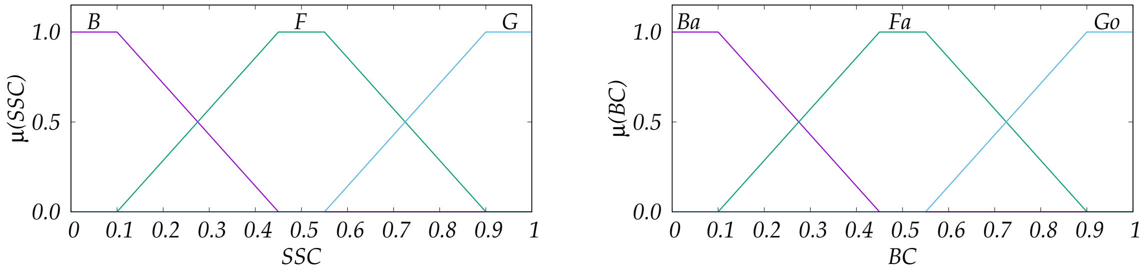
FLC3 (FLC5) has three (four) input parameters with three linguistic terms each; therefore, there are 27 (81) rules in the FRB. The FRB of FLC3 and FLC5 are shown in Table 6.12 and in Table 6.13, respectively. The MFs used for FLC3 and FLC5 parameters are given in Figure 6.13.

TABLE 6.12: Fuzzy Rule Base of FLC3 (VTC-FLC).

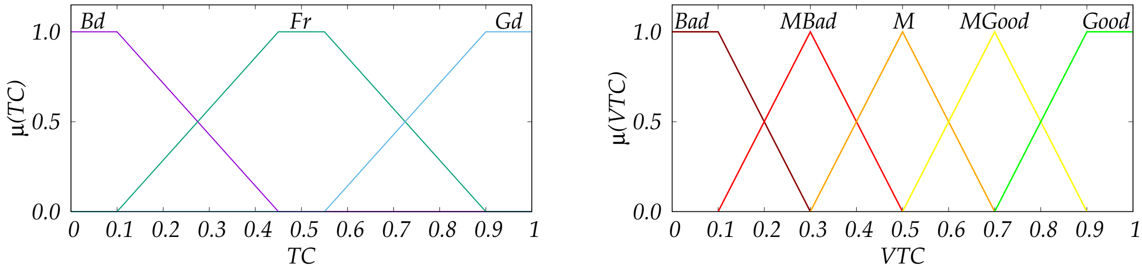
No	SSC	BC	TC	VTC	No	SSC	BC	TC	VTC
1	B	Ba	Bd	Bad	14	F	Fa	Fr	MBad
2	B	Ba	Fr	Bad	15	F	Fa	Gd	M
3	B	Ba	Gd	Bad	16	F	Go	Bd	Bad
4	B	Fa	Bd	Bad	17	F	Go	Fr	M
5	B	Fa	Fr	Bad	18	F	Go	Gd	MGood
6	B	Fa	Gd	MBad	19	G	Ba	Bd	Bad
7	B	Go	Bd	Bad	20	G	Ba	Fr	MBad
8	B	Go	Fr	MBad	21	G	Ba	Gd	M
9	B	Go	Gd	M	22	G	Fa	Bd	MBad
10	F	Ba	Bd	Bad	23	G	Fa	Fr	M
11	F	Ba	Fr	Bad	24	G	Fa	Gd	MGood
12	F	Ba	Gd	MBad	25	G	Go	Bd	M
13	F	Fa	Bd	Bad	26	G	Go	Fr	MGood
					27	G	Go	Gd	Good

TABLE 6.13: Fuzzy Rule Base of FLC5 (DRM-FLC of FSDRM2).

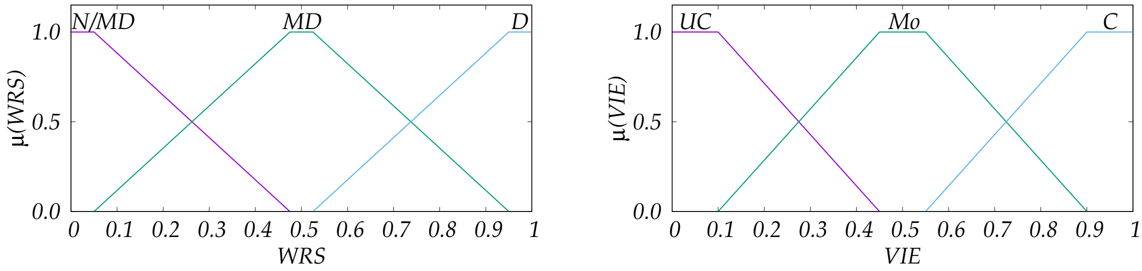
No	WRS	VIE	VTC	DVS	DRM	No	WRS	VIE	VTC	DVS	DRM
1	N/MD	UC	Ba	B	Dg	41	MD	Mo	Fa	F	VH
2	N/MD	UC	Ba	F	Sv	42	MD	Mo	Fa	G	Hg
3	N/MD	UC	Ba	G	Hg	43	MD	Mo	Go	B	VH
4	N/MD	UC	Fa	B	Sv	44	MD	Mo	Go	F	Hg
5	N/MD	UC	Fa	F	VH	45	MD	Mo	Go	G	Md
6	N/MD	UC	Fa	G	Md	46	MD	C	Ba	B	Dg
7	N/MD	UC	Go	B	VH	47	MD	C	Ba	F	VH
8	N/MD	UC	Go	F	Hg	48	MD	C	Ba	G	Hg
9	N/MD	UC	Go	G	Lw	49	MD	C	Fa	B	Sv
10	N/MD	Mo	Ba	B	Sv	50	MD	C	Fa	F	Hg
11	N/MD	Mo	Ba	F	VH	51	MD	C	Fa	G	Md
12	N/MD	Mo	Ba	G	Md	52	MD	C	Go	B	VH
13	N/MD	Mo	Fa	B	VH	53	MD	C	Go	F	Md
14	N/MD	Mo	Fa	F	Hg	54	MD	C	Go	G	Lw
15	N/MD	Mo	Fa	G	Lw	55	D	UC	Ba	B	Dg
16	N/MD	Mo	Go	B	Hg	56	D	UC	Ba	F	Dg
17	N/MD	Mo	Go	F	Md	57	D	UC	Ba	G	Dg
18	N/MD	Mo	Go	G	Sf	58	D	UC	Fa	B	Dg
19	N/MD	C	Ba	B	VH	59	D	UC	Fa	F	Dg
20	N/MD	C	Ba	F	Hg	60	D	UC	Fa	G	Sv
21	N/MD	C	Ba	G	Md	61	D	UC	Go	B	Dg
22	N/MD	C	Fa	B	Hg	62	D	UC	Go	F	Dg
23	N/MD	C	Fa	F	Md	63	D	UC	Go	G	VH
24	N/MD	C	Fa	G	Lw	64	D	Mo	Ba	B	Dg
25	N/MD	C	Go	B	Md	65	D	Mo	Ba	F	Dg
26	N/MD	C	Go	F	Lw	66	D	Mo	Ba	G	Sv
27	N/MD	C	Go	G	Sf	67	D	Mo	Fa	B	Dg
28	MD	UC	Ba	B	Dg	68	D	Mo	Fa	F	Dg
29	MD	UC	Ba	F	Dg	69	D	Mo	Fa	G	VH
30	MD	UC	Ba	G	VH	70	D	Mo	Go	B	Dg
31	MD	UC	Fa	B	Dg	71	D	Mo	Go	F	Sv
32	MD	UC	Fa	F	Sv	72	D	Mo	Go	G	Hg
33	MD	UC	Fa	G	Hg	73	D	C	Ba	B	Dg
34	MD	UC	Go	B	Sv	74	D	C	Ba	F	Dg
35	MD	UC	Go	F	VH	75	D	C	Ba	G	VH
36	MD	UC	Go	G	Md	76	D	C	Fa	B	Dg
37	MD	Mo	Ba	B	Dg	77	D	C	Fa	F	Sv
38	MD	Mo	Ba	F	Sv	78	D	C	Fa	G	Hg
39	MD	Mo	Ba	G	VH	79	D	C	Go	B	Dg
40	MD	Mo	Fa	B	Sv	80	D	C	Go	F	VH
						81	D	C	Go	G	Md



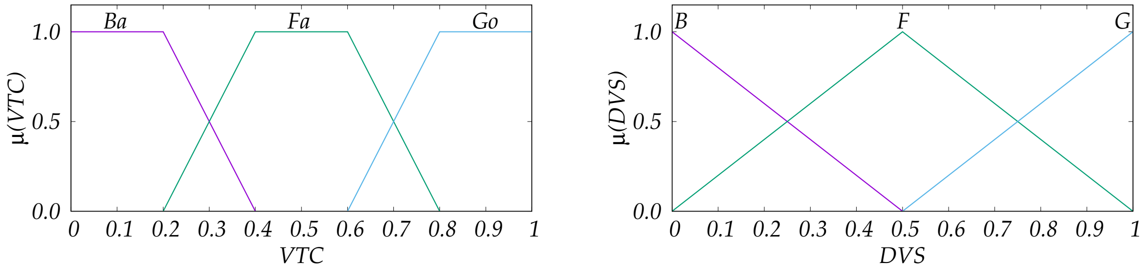
(a) Steering Systems Condition (b) Brakes Condition



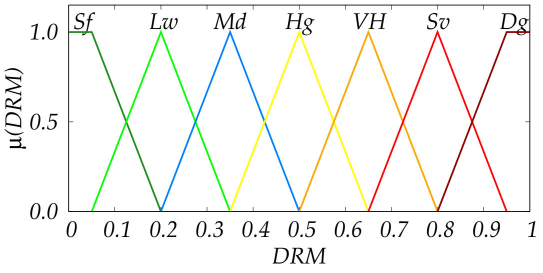
(c) Tires Condition (d) Vehicle's Technical Condition (FLC3 output)



(e) Weather-Road-Speed (f) Vehicle's Interior Environment



(g) Vehicle's Technical Condition (FLC5 input) (h) Driver's Vital Signs



(i) Driving Risk Management

FIGURE 6.13: MFs for parameters of FSDRM2.

Chapter 7

Evaluation of Proposed Systems

This chapter presents the evaluation results of the proposed intelligent systems, and it is organized into four sections. Section 7.1 describes and compares the proposed FCMS models, which are both evaluated by computer simulations. Section 7.2 gives the evaluation results of FDMS. The two FDMS models are evaluated and compared by both simulation and experimental results. An overall comparison between the simulation and the experimental results for both models is also drawn. Section 7.3 discusses the evaluation results of FSDRM1. The simulation results of FSDRM1 are presented and analyzed for each of the FLC FSDRM1 is composed of, whereas the experimental results are given in a general way since the objective of the experiment setup was to see the response of the system in a real scenario. The chapter ends with Section 7.3.3 which shows and analyzes the simulation results of FSDRM2. The computer simulations for all of the proposed systems were conducted using FuzzyC[1] whereas the results were visualized using Gnuplot Version 5.2.

7.1 Simulation Results of FCMS

In this section, we present the simulation results for FCMS1 and FCMS2. The universe of discourse for all input parameters is considered from 0 to 100. From all of the considered parameters, VRSVC needs some extra clarification since the numerical values this parameter takes can be somewhat confusing. As defined in its characteristic functions, a VRSVC equal to 50 simulates the case when the vehicle is traveling at the same speed as other cluster vehicles. A VRSVC less (more) than 50 means that the vehicle is moving slower (faster) than the other cluster vehicles.

The simulation results of FCMS1 are presented in Figure 7.1. We consider the VS as a constant parameter. We show the relation between VRLC and VRSVC for different VDC values. Figure 7.1(a) shows the simulation results considering VS=10. The maximal value of VRLC is when VRSVC is 50. At this value, the vehicle is moving at the same speed as other vehicles in the cluster. Thus, if the vehicle has

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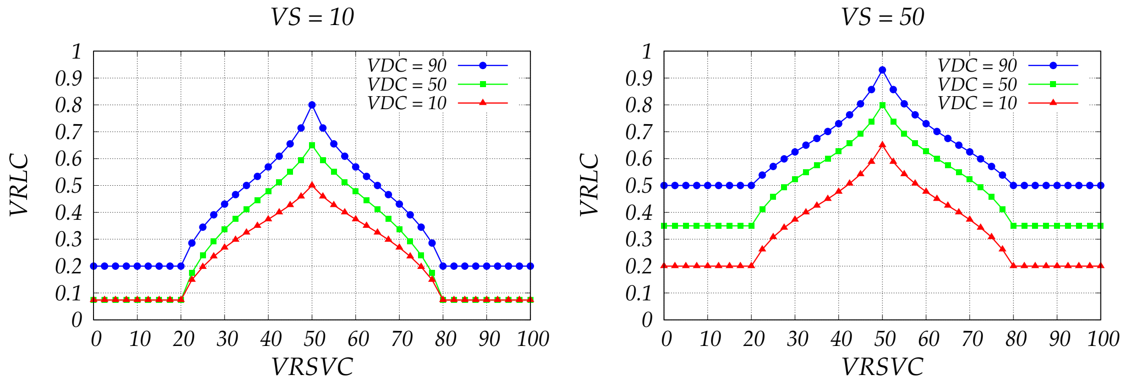
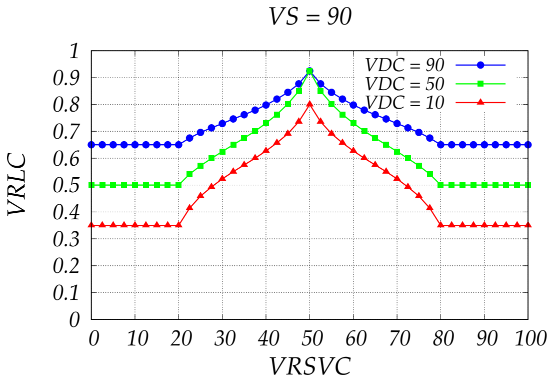
[1] More details for FuzzyC are given in Section 5.4.



(a) VS=10 (b) VS=50



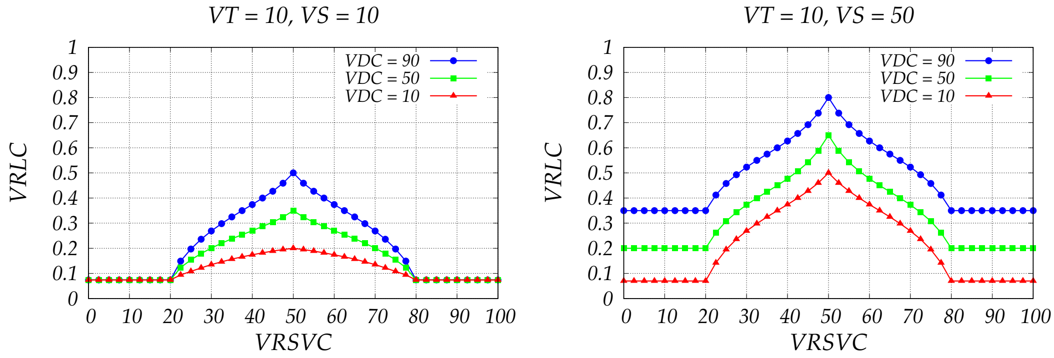
(c) VS=90

FIGURE 7.1: Simulation results for FCMS1.

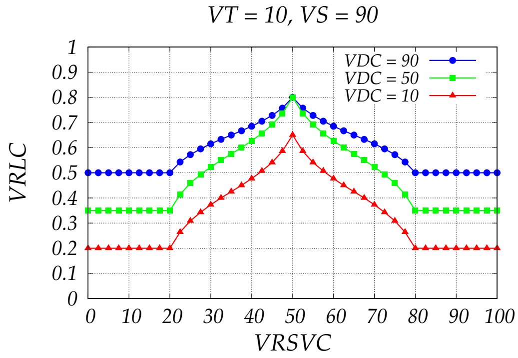
low security and moves slower or faster than other vehicles, it leaves the cluster. The increase of VDC increases the possibility of the vehicle remaining in the cluster. In Figure 7.1(b) and Figure 7.1(c), we consider VS value 50 and 90, respectively. With the increase of VS, VRLC increases, which means that this vehicle has more chances to remain in the cluster because it is more secure.

In Figure 7.2, Figure 7.3, and Figure 7.4 are presented the simulation results of FCMS2. We study the effect of trustworthiness in this system. We consider the VT and VS as constant parameters.

In Figure 7.2, we consider the VT value 10. If VS and VT are both 10, the vehicle will always leave the cluster. It means that vehicles with low trustworthiness and security should leave the cluster even if they move at the same speed as other vehicles. We change the VS value from 10 to 90. As we showed in the simulation results of FCMS1, when VS increases, the VRLC increases, too. Comparing FCMS2 (Figure 7.2) with FCMS1 (Figure 7.1), we see that when VT is low, the VRLC decreases.

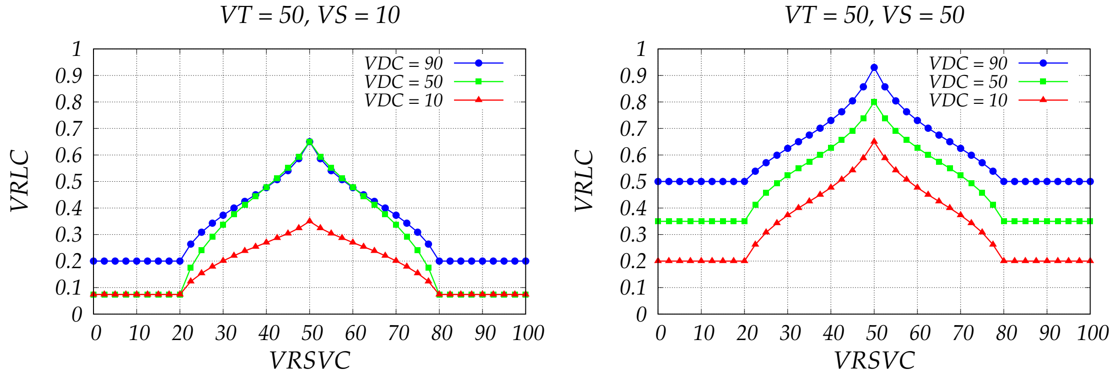


(a) VT=10, VS=10 (b) VT=10, VS=50

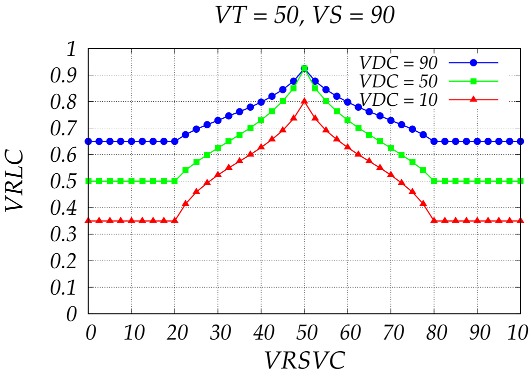


(c) VT=10, VS=90

FIGURE 7.2: Simulation results for FCMS2 [VT = 10].

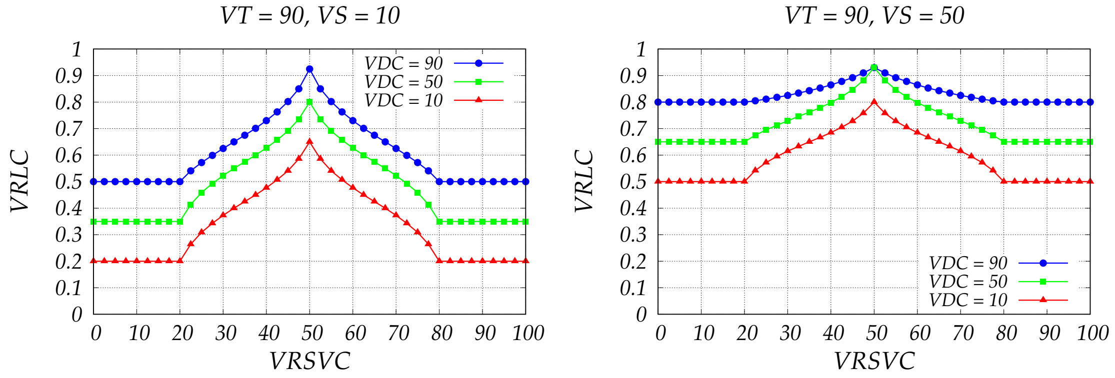


(a) VT=50, VS=10 (b) VT=50, VS=50

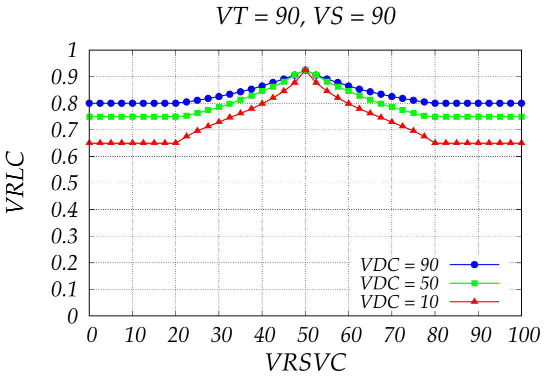


(c) VT=50, VS=90

FIGURE 7.3: Simulation results for FCMS2 [VT = 50].



(a) VT=90, VS=10 (b) VT=90, VS=50



(c) VT=90, VS=90

FIGURE 7.4: Simulation results for FCMS2 [VT = 90].

In Figure 7.3, we increase the VT value to 50. We can see that by increasing the VT value, the VRLC increases. Comparing with FCMS1 (Figure 7.1), we can see that for FCMS1, the values of VRLC are higher when VS is 10, but when VS increases, the VRLC values are higher for FCMS2.

Then in Figure 7.4, we increase the VT value to 90. It can be seen that the VRLC value increases much more.

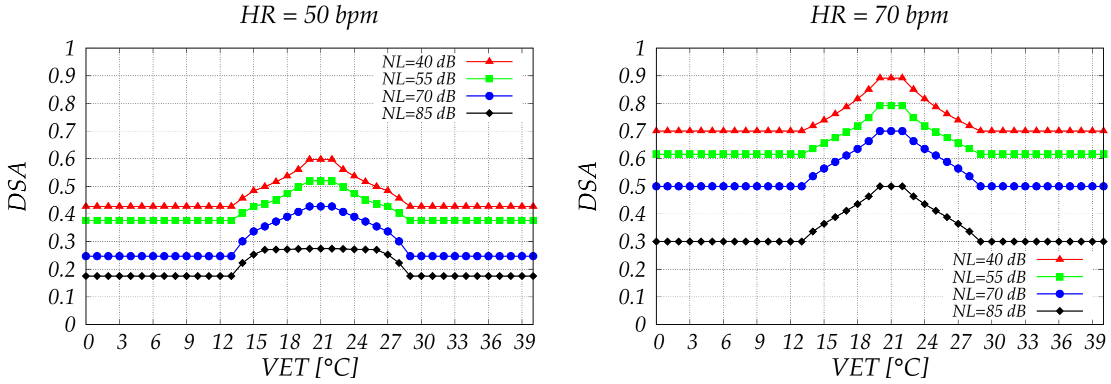
We conclude that vehicles with the same VRSVC and with high VDC, VS, and VT values have a higher possibility to remain in the cluster. This is because these vehicles are moving with the same velocity as the other cluster vehicles, have high connectivity, and also their high security and trustworthiness.

7.2 Evaluation Results of FDMS

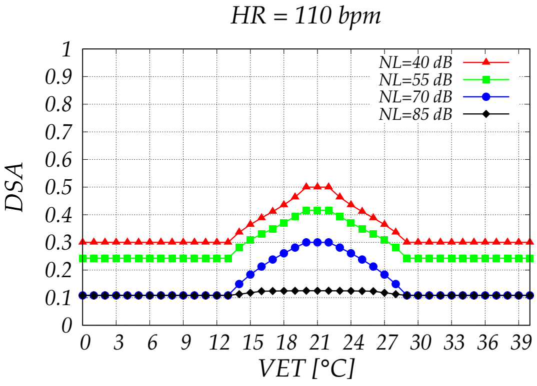
In this section, we present and compare the simulation and experimental results for our proposed FDMS models. We show the effect of the considered parameters on the determination of the driver's situation by both FDMS1 and FDMS2. In addition, we explain how the output values are translated into actions that can support the driver to drive safely.

7.2.1 Simulation Results

The simulation results for FDMS1 are presented in Figure 7.5. We show the relation between DSA and VET for different NL values. The NL values considered for the simulations are 40, 55, 70, and 85 dB, which simulate a quiet, typical, noisy, and very noisy environment, respectively. The HR is considered a constant parameter. We vary the VET parameter from 0 to 40 °C.



(a) HR = 50 bpm (b) HR = 70 bpm



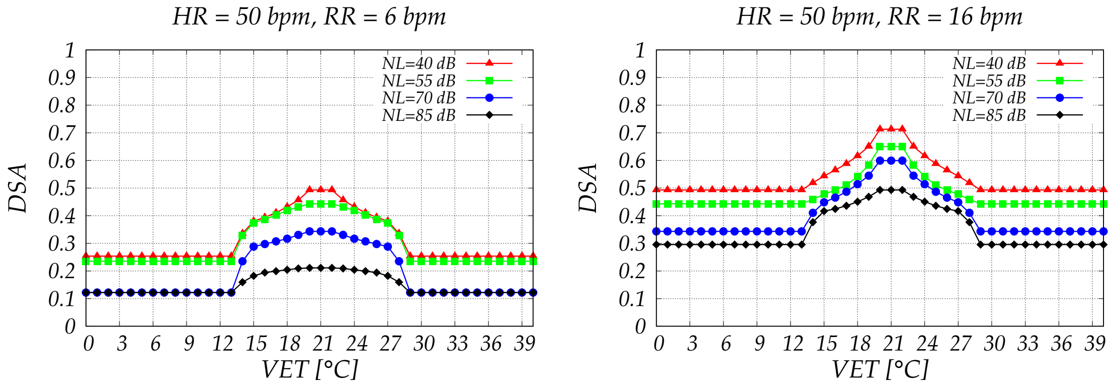
(c) HR = 110 bpm

FIGURE 7.5: Simulation results for FDMS1.

In Figure 7.5(a), we consider the HR value 50 bpm. A "normal" situation for the driver with his heart beating 50 times per minute is when there is not any annoying noise, and also the ambient temperature is between 17 and 25 °C.

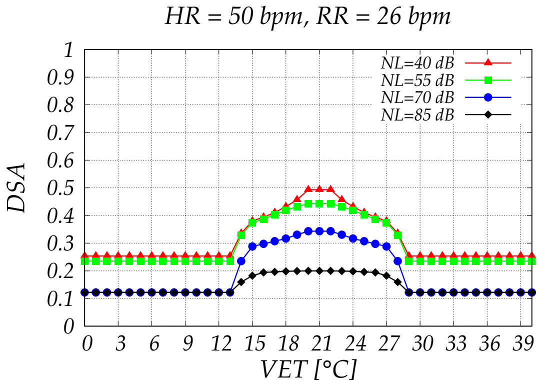
A scenario where the driver's heart is beating at 70 times per minute is shown in Figure 7.5(b). Here, we can see many situations that are decided as "normal" or "good", even in the cases where noise is in the background or the vehicle's environment temperature is not a comfortable one.

In Figure 7.5(c), we increase the value of HR to 110 bpm. We can see that there is not any situation that can be decided to be either "good" or "very good" by FDMS1.



(a) RR = 6 bpm

(b) RR = 16 bpm



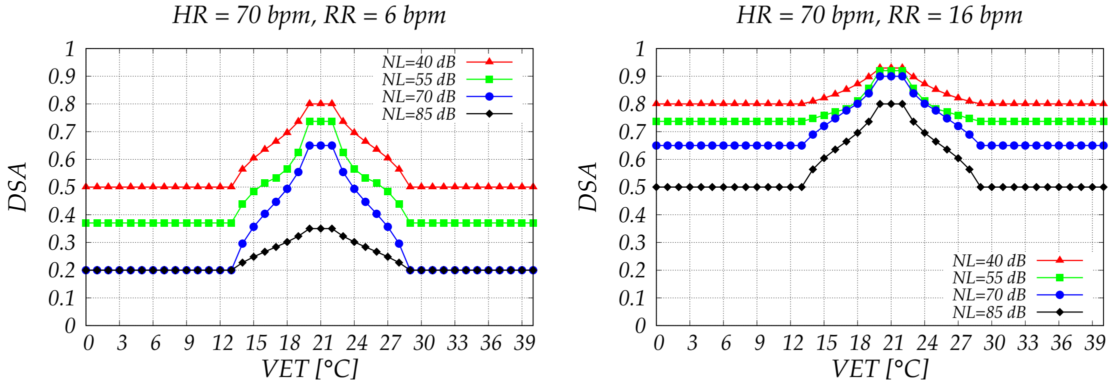
(c) RR = 26 bpm

FIGURE 7.6: Simulation results for FDMS2 [HR = 50 bpm].

The simulation results for FDMS2 are shown in Figure 7.6, Figure 7.7, and Figure 7.8. We see the effect of driver's respiratory rate on the decision of DSA.

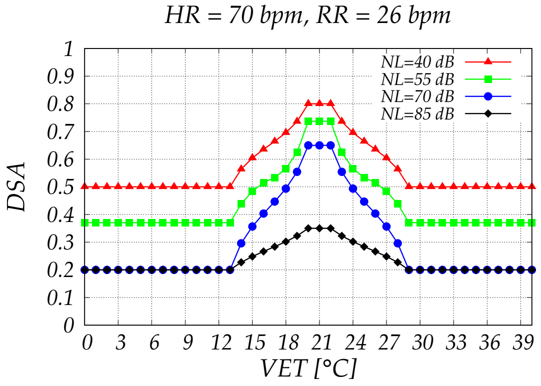
In Figure 7.6, we consider the HR value 50 bpm and change the RR from 6 to 26 bpm. In Figure 7.6(a) and Figure 7.6(c), it can be seen that when the driver breathes abnormally, a "normal" situation by FDMS2 is considered only when NL is 40 dB and VET is around 20 to 22 °C. Comparing with FDMS1, for the same heart rate, the range of temperature and noise for which FDMS2 decides a situation as "normal", is narrowed. On the other hand, when the driver respires normally, these ranges widen (see Figure 7.6(b) and Figure 7.5(a)).

In Figure 7.7, we present the simulation results for HR 70 bpm. When the driver's respiratory rate is "normal" (see Figure 7.7(b)), the DSA values decided by the system are higher than all the other considered scenarios. This is due to the driver's vital signs, which indicate a very good status of the driver's body; therefore, he could manage to drive safely in uncomfortable situations regarding the environment temperature and noise level. In Figure 7.7(a) and Figure 7.7(c), it can be seen that the DSA values decrease as the respiratory rate decreases or increases, and the effect of temperature and noise is more intense.



(a) RR = 6 bpm

(b) RR = 16 bpm



(c) RR = 26 bpm

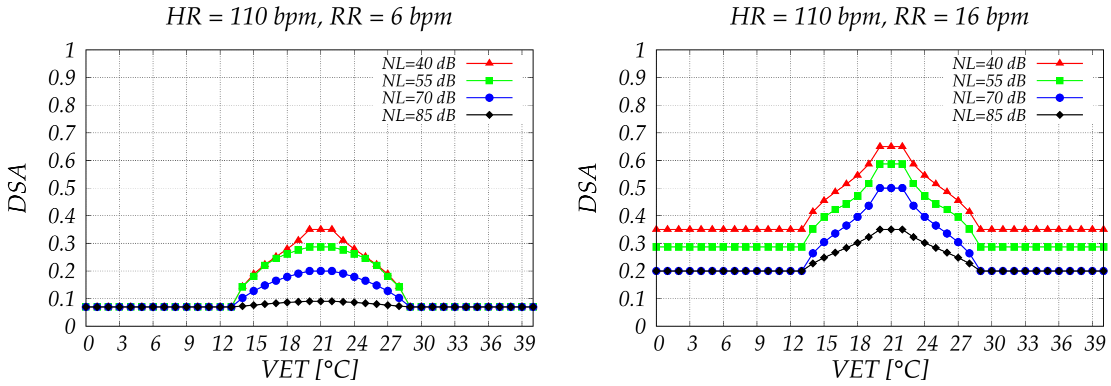
FIGURE 7.7: Simulation results for FDMS2 [HR = 70 bpm].

In Figure 7.8, we increase the value of HR to 110 bpm. If the driver breathes normally, we can see some "good"/"normal" DSA values, especially when the ambient is quiet and/or the temperature is around 17 to 25 °C. However, as his respiratory rate increases/decreases significantly, there is not any situation that can be considered even as a "normal" situation. Comparing with Figure 7.5(c), if the driver is breathing normally, for the same noise levels and temperatures, we get higher DSA values; otherwise, it is the FDMS1 that provides higher DSA values.

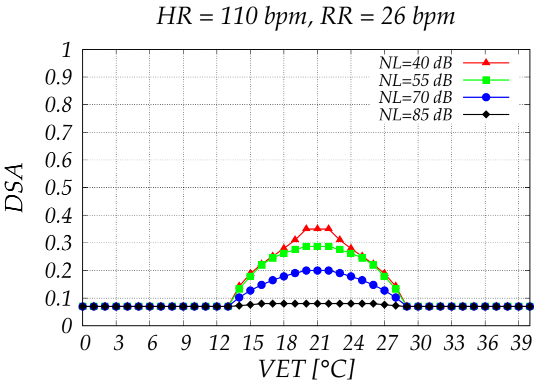
In the cases where the driver's situation is decided as bad or very bad continuously for a relatively long time, the system can perform a certain action. For example, the system may limit the vehicle's maximal speed, suggest him to have a rest, or call the doctor if he breathes abnormally and/or his heart beats at very low/high rates.

7.2.2 Experimental Results

The experimental results for our proposed system models are presented in Figure 7.9, Figure 7.10, and Figure 7.11. In Figure 7.9 are shown the results of DSA for slow heart rate. As we can see, there were just a few DSA values decided as "normal". These



(a) RR = 6 bpm (b) RR = 16 bpm



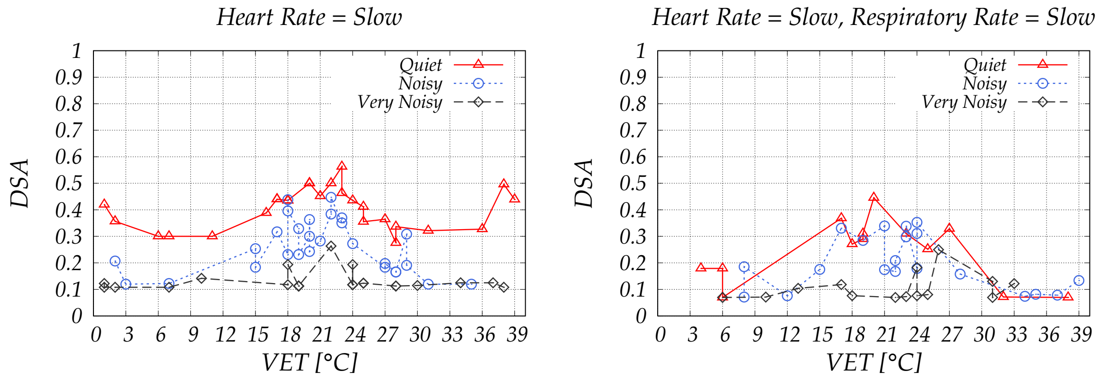
(c) RR = 26 bpm

FIGURE 7.8: Simulation results for FDMS2 [HR = 110 bpm].

values were achieved when the ambient was quiet and when the temperature was around 18 to 24 °C. If the driver's respiratory rate is taken into consideration, the number of "normal" DSA values slightly increased when he breathed normally and decreased when he experienced difficulty breathing.

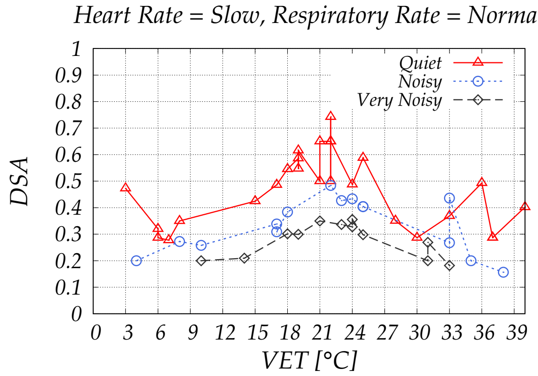
The results of DSA when HR was "normal" are presented in Figure 7.10. Here, when the driver breathed normally, many values were decided as "good" or "very good". Several values were decided as "extremely good" as well. As we explained in the simulation results (Figure 7.7), we got higher DSA values due to the driver's vital signs, which indicated a very good status of the driver's body.

In Figure 7.11 are shown the results of DSA for fast heart rate. The results are almost the same as that of Figure 7.8, where the "good" and "normal" values happen to be only when the driver breathes normally, and the ambient is quiet, or the temperature is between 17 and 25 °C. When he breathed rapidly any situation was decided as "bad", "very bad" or "extremely bad". In these situations, the driver might have been experiencing forms of anxiety which increase the risk of a potential accident.


Heart Rate = Slow

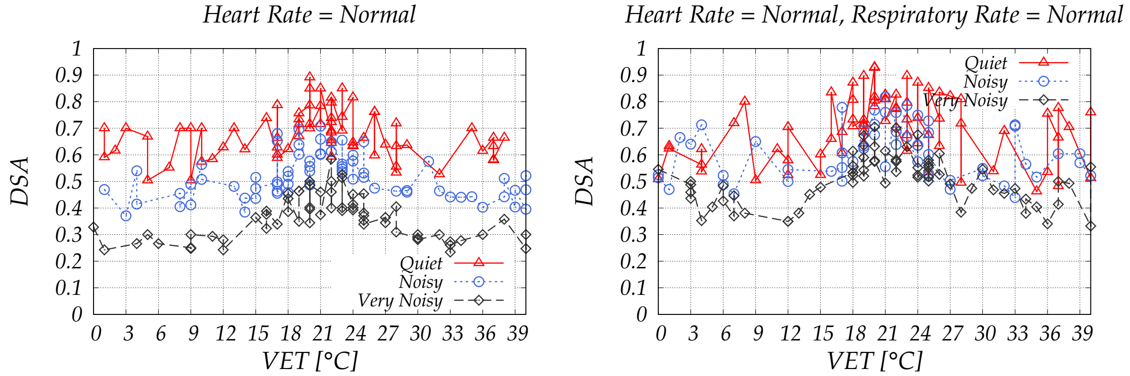
Heart Rate = Slow, Respiratory Rate = Slow

(a) FDMS1 (b) FDMS2 (RR = Slow)


Heart Rate = Slow, Respiratory Rate = Normal

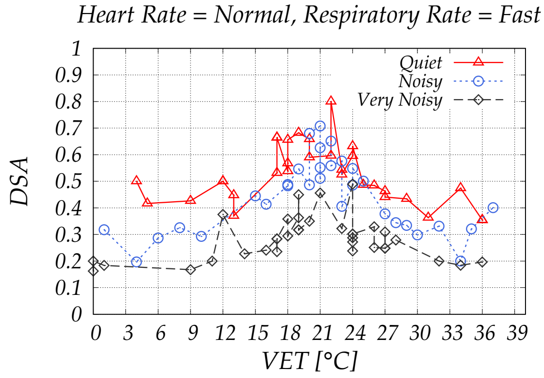
(c) FDMS2 (RR = Normal)

FIGURE 7.9: Experimental results for slow heart rate.


Heart Rate = Normal

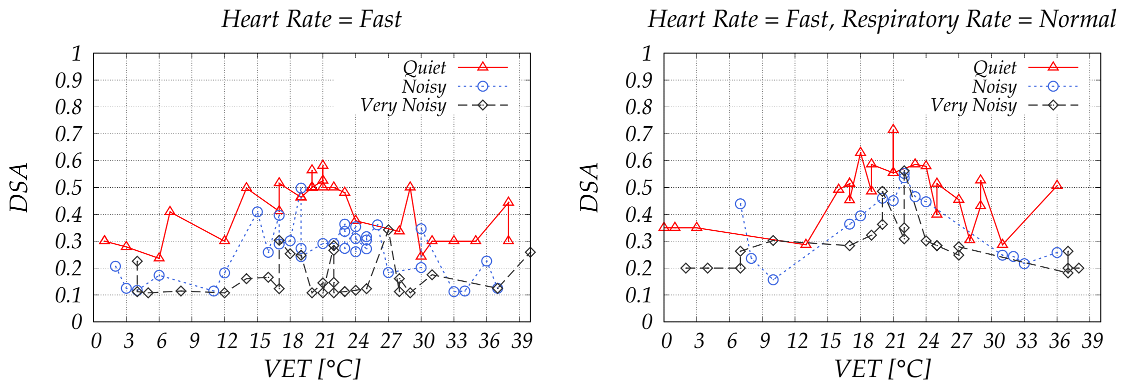
Heart Rate = Normal, Respiratory Rate = Normal

(a) FDMS1 (b) FDMS2 (RR = Normal)

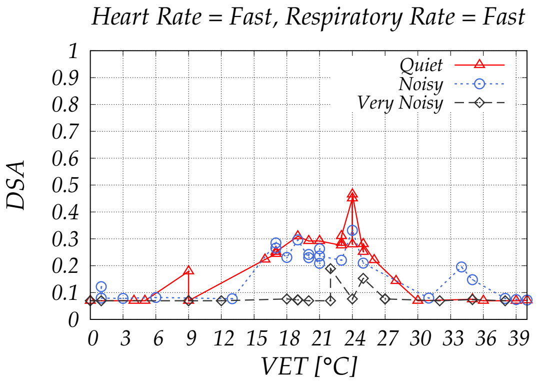

Heart Rate = Normal, Respiratory Rate = Fast

(c) FDMS2 (RR = Fast)

FIGURE 7.10: Experimental results for normal heart rate.



(a) FDMS1 (b) FDMS2 (RR = Normal)



(c) FDMS2 (RR = Fast)

FIGURE 7.11: Experimental results for fast heart rate.

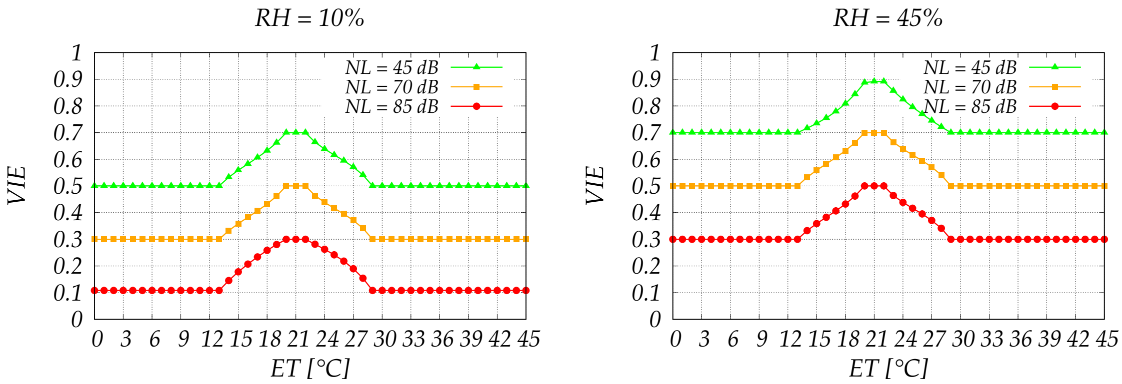
7.3 Evaluation Results of FSDRM

This section presents the simulation results of the two FSDRM models, together with the experimental results from the implementation of FSDRM1 in a real scenario. We describe in detail the relation between the driving risk levels and the input variables and explain how these risk levels are translated into actions that can help the driver to manage certain risky situations, with the goal of improving driving safety.

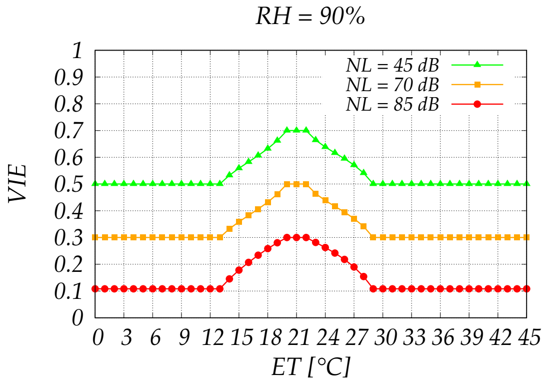
7.3.1 Simulation Results of FSDRM1

Grouping together the variables not only decreased the overall complexity of the system but also helped us to better understand the results and single out implementation flaws. The simulation results of FSDRM1 are shown in Figures 7.12–7.15.

In Figure 7.12 is shown the relation between VIE and ET for different RH and NL values. Regarding RH, we consider the scenarios with a dry, normal, and humid inside environment represented by a 10%, 45%, and 90% relative humidity, whereas for the NL parameter, we consider the values 45, 70, and 85 dB, which simulate a quiet, noisy, and very noisy environment, respectively.



(a) RH = 10% (b) RH = 45%



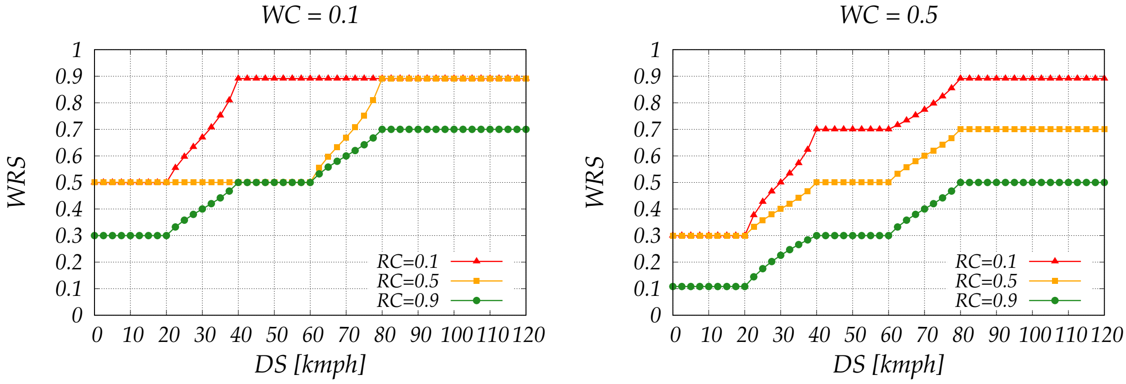
(c) RH = 90%

FIGURE 7.12: Simulation results of FLC1 for low, medium and high humidity.

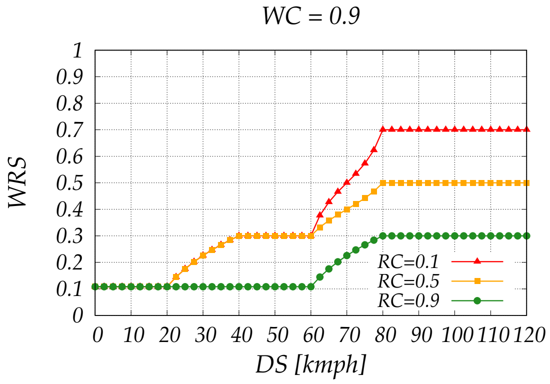
Relative humidity plays an important role in the comfort levels, and we can see this fact also in our results. When the inside ambient is dry or humid (see Figure 7.12(a) and Figure 7.12(c)), we can see that there is not any situation that the vehicle's inside environment is decided as comfortable. As we can see from Figure 7.12(b), the only scenario when the environment is comfortable (VIE = 0.9) is when the humidity is at normal levels. However, regardless of the normal levels of RH, if the driver is driving in low/high temperatures or a noisy environment, VIE is never decided as comfortable. Anyway, a moderate level of comfort is still acceptable, but any other levels may have an impact on the driver, which in turn may affect the driving performance.

In Figure 7.13 is shown the relation between WRS and DS for different WC and RC values. The values 0.1, 0.5, and 0.9 of both WC and RC simulate a very bad, bad, and good weather/road condition, respectively.

Figure 7.13(a) shows the considered case with the worst weather condition (WC = 0.1). As expected, most WRS values show a very high danger. When it is combined with a very bad road condition (RC = 0.1), the scenario with the lowest degree of



(a) WC = 0.1 (b) WC = 0.5



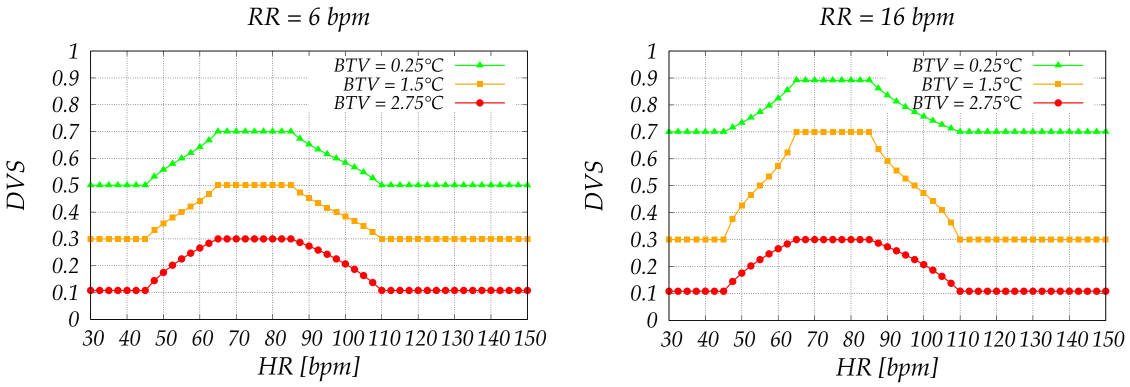
(c) WC = 0.9

FIGURE 7.13: Simulation results of FLC2 for very bad, bad, and good weather condition.

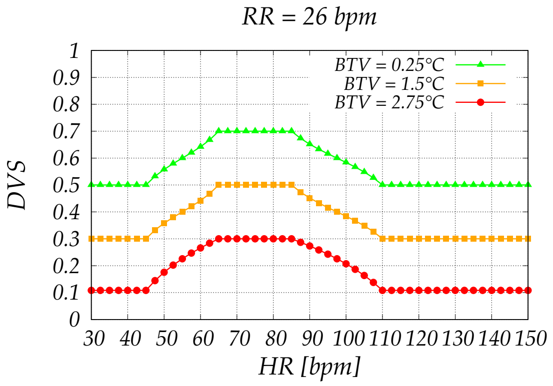
danger is when the vehicle is moving slowly and yet is decided as a situation with a Considerable Danger (WRS = 0.5). The increase of RC—better road conditions—results in a decrease in WRS values. The WRS values decrease even more when the weather gets better (see Figure 7.13(b)–7.13(c)), and when both the weather and road condition are good (WC = 0.9 and RC = 0.9), many situations are decided with No or Minor Danger—WRS = 0.1. Driving at high speeds poses a threat itself, regardless of the road or weather condition; therefore, these scenarios are not decided with a "No/Minor Danger" on any occasion.

The effect of HR, RR, and BTV in the determination of DVS values is shown in Figure 7.14. For the simulations, we consider a RR of 6, 16, and 26 bpm, and a BTV of 0.25, 1.5, and 2.75 °C. The considered HR values range from 30 to 150 bpm.

A good condition is determined only when all three variables are within the normal range (Figure 7.14(b), for BTV = 0.25 °C and HR between 60 and 95 bpm). If one of the vital signs deteriorates, DVS values immediately drop to the fair level (DVS = 0.7), and when it happens to two of them, DVS values decrease even more. Thus, the system can detect if the driver is experiencing anxiety and stress since the



(a) RR = 6 bpm (b) RR = 16 bpm



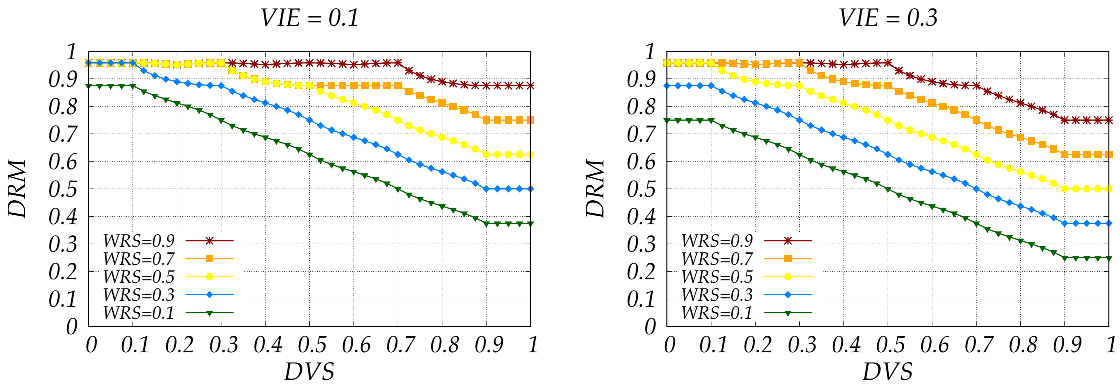
(c) RR = 26 bpm

FIGURE 7.14: Simulation results of FLC3 for slow, normal, and fast respiratory rate.

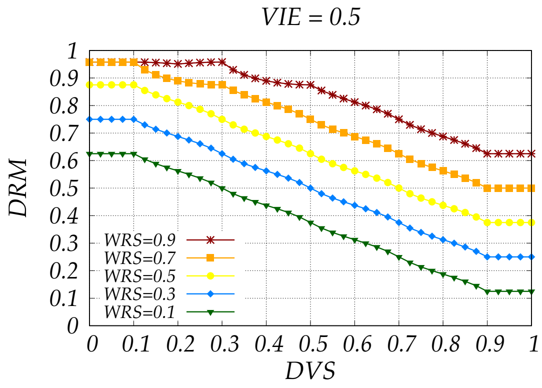
heart and breathing rate speed up in these situations. The opposite happens when the driver is drowsy, their heart and respiratory rate decreases, yet again the system can detect it. Moreover, in these situations, the body temperature also drops, thus helping to determine such cases with a better accuracy.

In Figure 7.15, we give the relation between DRM and DVS while considering all the possible levels of VIE and WRS. In other words, we consider the values 0.1, 0.3, 0.5, 0.7, and 0.9, which imply scenarios with an extremely uncomfortable, very uncomfortable, uncomfortable, moderate, and comfortable environment, respectively. However, for WRS, we consider No/Minor, Moderate, Considerable, High, and Very High Danger simulated through the values of 0.1, 0.3, 0.5, 0.7, and 0.9.

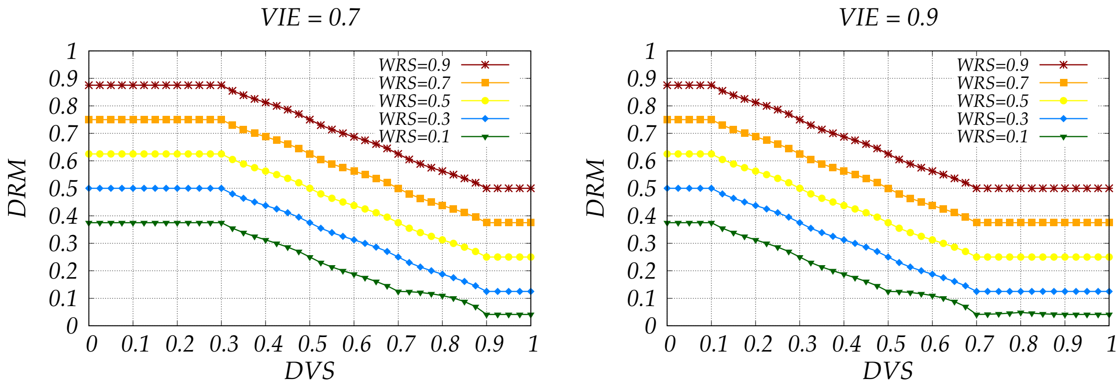
In Figure 7.15(a), we consider the VIE value 0.1 and change the WRS from 0.1 to 0.9. We can see that all DRM values are greater than 0.3125 (the border between low and moderate risk), implying the existence of risky situations. This is due to extremely uncomfortable VIE, i.e., dry/humid, cold/hot, and very noisy environment, as it could affect the driver's ability to focus on the driving process. In addition, if the road and weather conditions are not good, or the driver is driving at high speed,



(a) VIE = 0.1 (b) VIE = 0.3



(c) VIE = 0.5



(d) VIE = 0.7 (e) VIE = 0.9

FIGURE 7.15: Simulation results of FLC4 for extremely uncomfortable, very uncomfortable, uncomfortable, moderate, and comfortable vehicle inside environment.

the risk levels are decided even up to the "Danger" level—DRM ≥ 0.9375. If the driver's vital signs indicate a very good condition of their physical and mental health, we can see a slight improvement on the risk levels, yet not enough for the situation to be decided with a low risk.

By comparing the DRM values for all the considered cases, we can see the great impact of the input parameters on the determination of the driving risk. As we can see from Figure 7.15(c)–7.15(e), when VIE is equal or greater than 0.5, situations with very low risk are now present and happen when the driver is in good health condition while WRS remains low. Regarding WRS, a driver with a good mental and physical condition can manage to drive a comfortable vehicle with a low risk only if WRS remains below 0.5.

If several consecutive DRM values are above the low risk level, the system can invoke a certain action. For instance, when the DRM values fall within the moderate level, the system could take action to change the driver's mood or improve the vehicle's interior environment. If the risk is caused by a very low DVS, which means that the driver is in a very bad condition, the system should act immediately. For example, the system suggests or urges the driver to pull over and take a rest based on the degree of DVS, and at the same time, reports their health status to the doctor. When the DRM values are very high, the system could even decide to lower the speed limit to a speed that the risk is reduced significantly.

7.3.2 Experiment Setup and Results

At this time, we have implemented and run FSDRM1 only in one case scenario. The experiment was made to test and see the response of the system in a real scenario, rather than to determine its accuracy.

The results shown in Figure 7.16, present the DRM values determined by the system using the data collected during approximately 8 hours of driving, in an opportunistic process that took place between 6 AM and 11 PM, mostly in an urban driving environment. Considering the nature of the input parameters—different parameters change differently over time and with different frequencies, i.e., speed and noise change instantaneously but humidity and temperature change gradually—we set the system to decide an output every 15 seconds. This was done to also permit the manual data input (the automated sensing module runs in real-time) and to minimize the error of the automated part by calculating the average value of the samples collected during the 15-seconds time frame.

The results indicate that most driving situations are determined with no risk present, with several situations showing risks to certain degrees. The low DRM values are an outcome of the driving scenario, which took place mostly in an urban environment and during a day with good weather, and with the driver in a good mental and physical condition. The small fluctuations, on the other hand, are due to the frequent changes in noise and speed, which come from traffic lights, crossroads, and pedestrians. To obtain a variation in the condition of some parameters, we adjusted the heating and cooling functions (in some cases, it was turned off) so the temperature and humidity could change, varied the sound volume produced by the vehicle audio, and also drove to some countryside areas. As it appears, the DRM

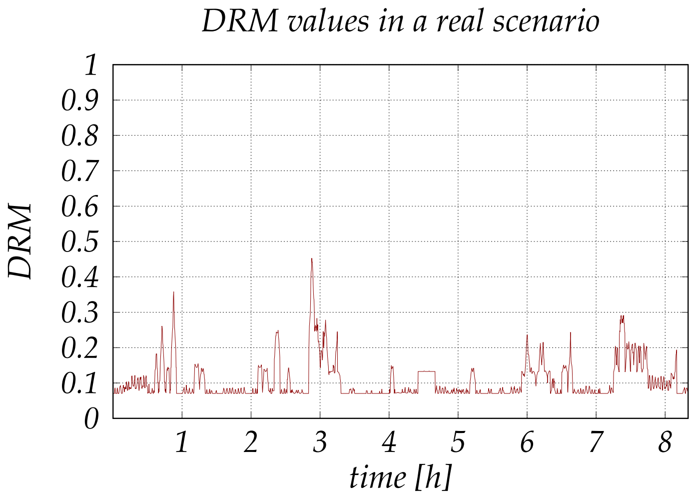


FIGURE 7.16: Experimental results.

values fluctuate between different risk levels, and the cases with higher DRM values are the scenarios that include the combination of several parameters with bad/fair conditions.

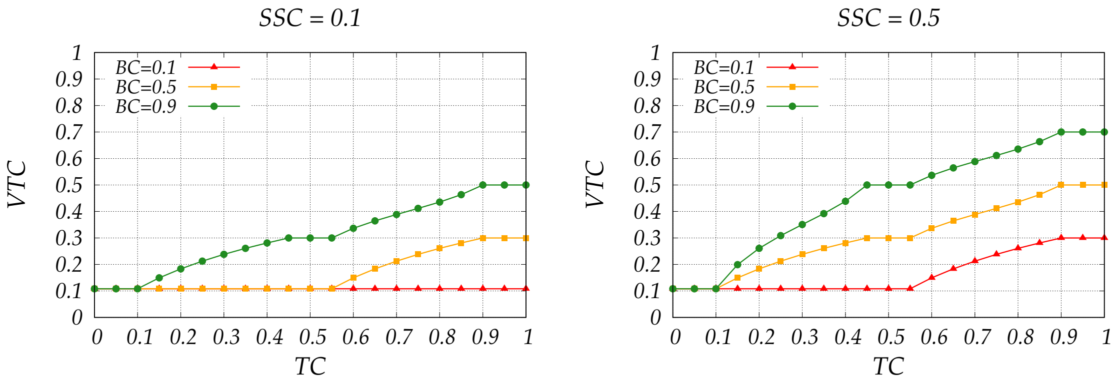
7.3.3 Simulation Results of FDRMS2

This section presents and analyzes the simulation results for FSDRM2. While some of the FSDRM2 FLCs remain untouched from FSDRM1, there is an additional FLC introduced for this system, and that is described in detail.

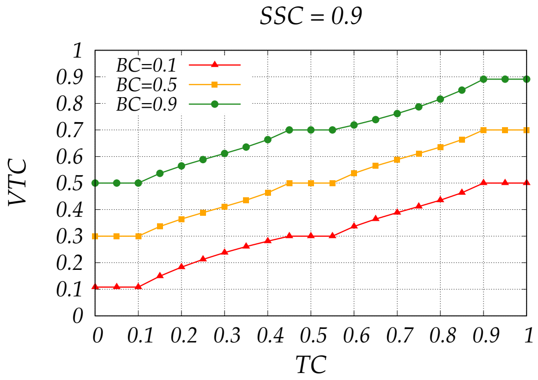
The simulation results are presented in Figure 7.17–7.20. In Figure 7.17 are shown the results for FLC3. We show the relation between VTC and TC for different SSC and BC values.

A vehicle in bad condition is a step backward for road safety. Although a vehicle can operate even when it is not in the optimal technical condition, it is strongly recommended to be aware of the degree of its problems and avoid driving in these situations. From the simulations, the only situation when VTC is decided as good is when all three parameters are in good conditions (see Figure 7.17(c)). The VTC decreases when one of the parameters is in fair condition, and it decreases even more if its condition is bad. In Figure 7.17(a) and Figure 7.17(b), we can see that in the cases when two or more parameters deteriorate, VTC values are decided even less than 0.5. If a vehicle operates in these conditions, it risks its driver and passengers, other cars, and pedestrians.

The simulation results presented in Figure 7.18–7.20 show the relation between DRM and DVS for different VTC values. The VTC values considered for simulations are 0.1, 0.5, and 0.9, which simulate a vehicle with a bad, fair, and good technical condition, respectively.



(a) SSC = 0.1 (b) SSC = 0.5

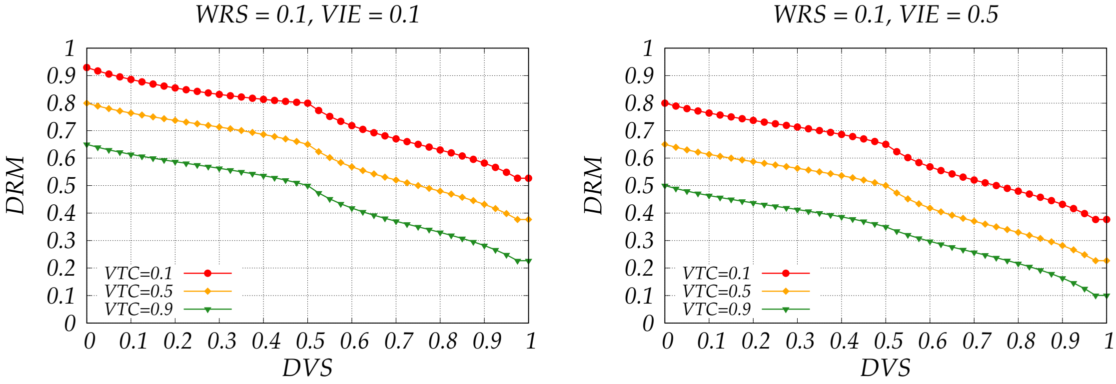


(c) SSC = 0.9

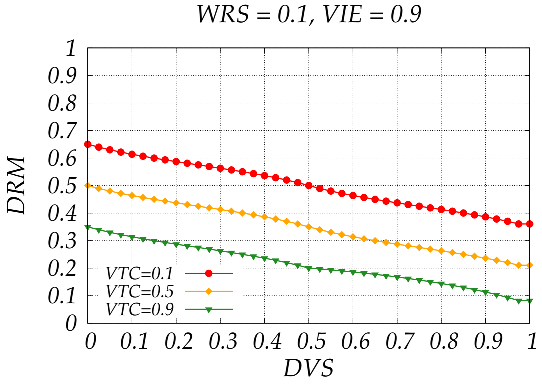
FIGURE 7.17: Simulation results for FLC3

In Figure 7.18 we consider the WRS value 0.1 and change VIE from 0.1 to 0.9. From Figure 7.18(a), we can see that there is not any situation considered as safe. The lowest DRM value is decided when a driver with good vital signs drives a vehicle in good technical condition, and it is decided as a situation with low risk. This is due to the bad condition of the vehicle's interior environment, which can make the driver uncomfortable; thus, preventing them from focusing totally on the driving operation. When the inside environment is comfortable (see Figure 7.18(c)), we can see that the risk is reduced and safe situations are now present. However, this happens only when the vehicle is in optimal technical condition, and when the conditions deteriorate, the DRM decreases.

Figure 7.19 shows the simulation results for WRS=0.5. When the inside environment is uncomfortable, all the scenarios include situations with risk present to certain degrees based on the DVS and VTC. For example, when the VTC is not good, many DRM values are decided as very high, severe, and danger. From Figure 7.19(c), it can be seen that the risk is present (DRM>0.2) in all situations, even when the VIE is comfortable. This is due to WRS because a WRS value of 0.5 is decided when the road or weather conditions are not good and the driver is driving at high speed.

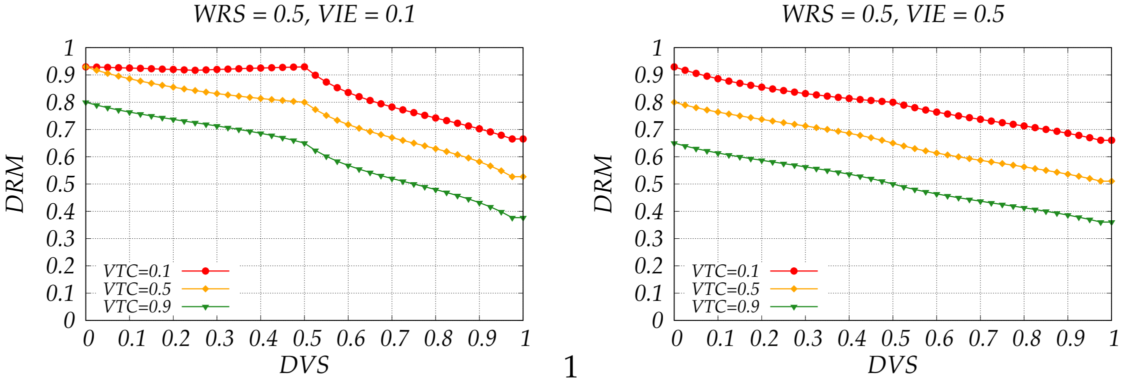


(a) VIE = 0.1 (b) VIE = 0.5



(c) VIE = 0.9

FIGURE 7.18: Simulation results for FLC5 [WRS = 0.1].



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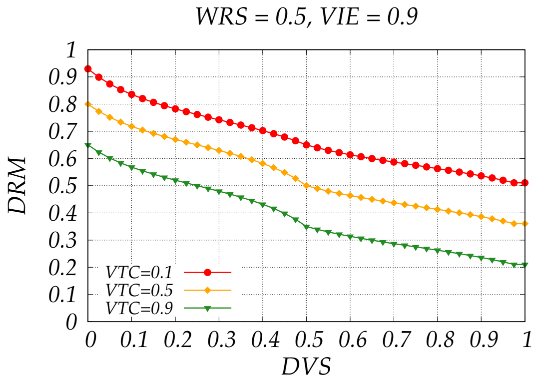
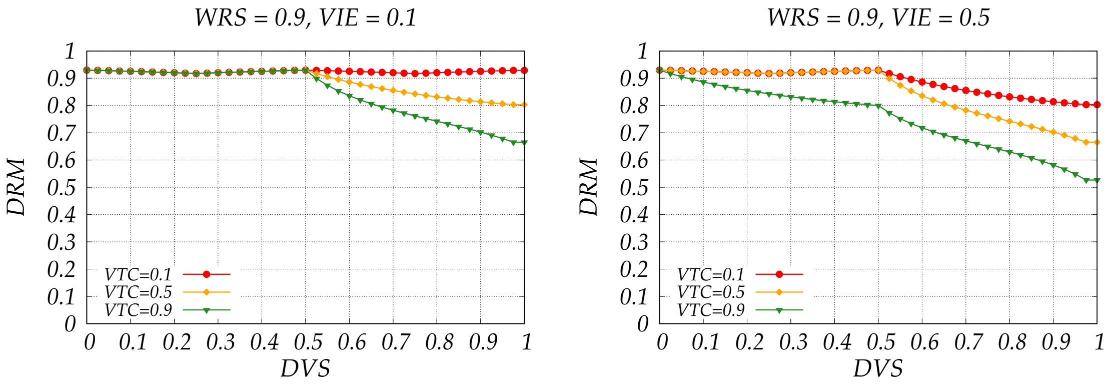
(a) VIE = 0.1 (b) VIE = 0.5



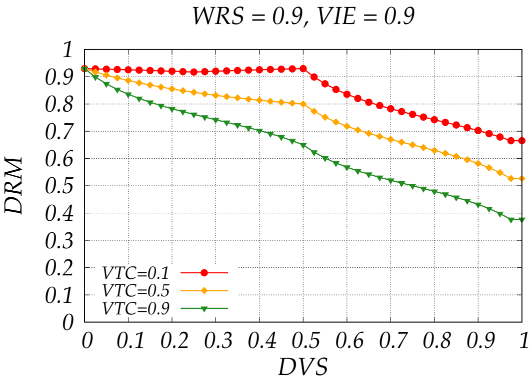
(c) VIE = 0.9

FIGURE 7.19: Simulation results for FLC5 [WRS = 0.5].



(a) VIE = 0.1

(b) VIE = 0.5



(c) VIE = 0.9

FIGURE 7.20: Simulation results for FLC5 [WRS = 0.9].

When WRS is increased even more (Figure 7.20), we see that the DRM values increase drastically. These scenarios include driving at high speeds in bad weather/road conditions, which is dangerous even when it is not combined with other factors. Therefore, all situations must be taken seriously, and appropriate action should be taken immediately.

When a number of consecutive decided DRM values are slightly above 0.2, the system can perform a certain action. For instance, if VIE is the cause of the risk, the system could take action to lift the driver's mood or improve the vehicle's interior environment. On the other hand, if the high DRM values are caused by DVS or WRS, the system suggests or urges the driver to pull over while limiting the vehicle's operating speed to a speed that the risk level is decreased significantly. And, more importantly, if the DRM is above 0.2 due to the bad VTC, the system can prevent the driver from starting the vehicle at all.

Chapter 8

Conclusions

Vehicular networks are the key to the safety and well-being of road users. Had them been fully deployed, massive crashes involving dozens of vehicles and causing many fatalities would have never happened. Although there has been good progress with the initial deployments, much remains to be done since the ultimate goal of this technology is to have the number of road fatalities from traffic crashes reduced to zero.

8.1 Summary of Thesis and Conclusions

After presenting the background, objectives, and main contributions of this thesis, in Chapter 2, we presented Wireless Networks. We gave an overview of next generation wireless networks and discussed recent advances that are expected to support the trend of upcoming applications. The concepts were also described in regard to how these technologies are expected to assist in the widespread deployment of vehicular networks.

Then, in Chapter 3, we investigated in detail different applications and use cases of vehicular networks, introduced their network architectures and radio access technologies, and discussed aspects of security, privacy, and trust mechanisms. We highlighted the limitations of the current architectures and explored some of the emerging solutions.

Chapter 4, was dedicated to Intelligent Algorithms and their applications. Neural networks, genetic algorithms, and the most common techniques and methods of swarm intelligence and local search are among the intelligent approaches that were reviewed throughout the chapter.

In Chapter 5, we gave a thorough description of theoretical concepts underlying fuzzy logic, fuzzy sets, and fuzzy systems. The provided concepts are discussed in regards to the application of fuzzy logic presented in this thesis in order to enable a complete understanding of the proposed systems, which are detailed in Chapter 6.

The proposed intelligent fuzzy logic systems take into consideration the challenges that vehicular networks are currently facing. First, we proposed a fuzzy clustering approach that deals with network management, network partitioning, and communication issues that are caused by the rapid and constant change of the network topology. For the evaluation of this approach, we implemented two system models. Both models take into account the speed and mobility of vehicles as leading factors to the frequent density changes. Moreover, they consider the implemented security mechanisms resulting in different security levels, with the second model considering the trustworthiness of the involved vehicles as an additional parameter. Based on these parameters, these system models decide whether vehicles should remain in or leave the cluster to which they currently belong. The simulation results given in Chapter 7 show that the proposed approach can effectively manage the cluster through the periodic decisions made for each cluster vehicle.

The proposed systems chapter continued with the details of the two fuzzy driver monitoring system models to end with the explanation of two models of the fuzzy driving risk management system. All the implemented models and their parameters were described by delineating the reason behind their selection. The set of linguistic values for each parameter, the chosen membership functions, and the fuzzy rule base of every fuzzy logic controller comprising the proposed systems, were also presented as information that is needed if one wants to obtain the same simulation results. After explaining each model, we introduced the testbed that we implemented to carry out experiments and to evaluate the systems experimentally. The testbed was first used for the driver monitoring system and then upgraded to be used for the driving risk management system.

Both simulation and experimental results of the driving-support systems follow the results of the fuzzy cluster management system in Chapter 7. The first model of driver monitoring system considers the vehicle's environment temperature, noise level, and driver's heart rate. While for the second model, we added the driver's respiratory rate to determine the driver's situation awareness. We saw that the changes in respiratory rate, in most cases, cause a variation of 0.2 to 0.3 (20%–30%) in the output value. On the other hand, this variation is around 15%–20% in contrast with the output values decided by the first model in which this parameter was not included. Such changes show the great importance of respiratory rate because this difference is translated into 1–2 levels on the determination of the driver's condition. Although adding another parameter increases the complexity of the system, it does not cause any problems as the system still runs in real-time. While the simulation results accentuate the importance of the considered parameters, the comparison between the simulations and experiments shows that there is a high similarity between simulation and experimental results.

For the implementation of the driving risk management system, we considered the following input parameters: the vehicle's interior environment temperature and relative humidity, noise level, the driver's vital signs, i.e., heart rate, respiratory rate, and body temperature variation, the road condition, weather condition, and the vehicle speed. We showed through simulations and experiments the effect of these parameters on the determination of the driving risk. When the output exceeds certain limits, the system can take the appropriate action that reduces the risk and supports the driver. The vehicle's technical condition parameter evaluated by the steering systems, brakes, and tires condition, was included in the extended model to detect more potential risks, making it a much more complete driving-support system.

8.2 Future Directions

For the driving-support systems, we demonstrated a few actions that can be performed based on the decided output of the system. However, the systems may provide an output that decides that an action should be taken, when, in fact, the real situation does not include any risk or bad situation of the driver.

Therefore, it is noteworthy to determine the accuracy of the system as it can show which parameters lead mostly to a false positive output and what should be improved to reduce the false-negative outputs. Therefore, we intend to evaluate the performance by looking into correct detection in many realistic case scenarios which would involve several drivers and various driving environments.

In the future, we would like to enhance our intelligent driving-support systems, by switching the parameters that lead to false positives with others that cause many accidents, as well as with parameters that determine accurately the driver's ability to drive, e.g., EEG and PERCLOS; to achieve what is ultimately the goal of the driving-support technologies, reducing the risk of car accidents.

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