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Development and Implementation of Active Pedestrian Safety and Driver Comfort Systems for Connected Vehicles

Tesi di Laurea Magistrale in
Mechanical Engineering - Ingegneria Meccanica

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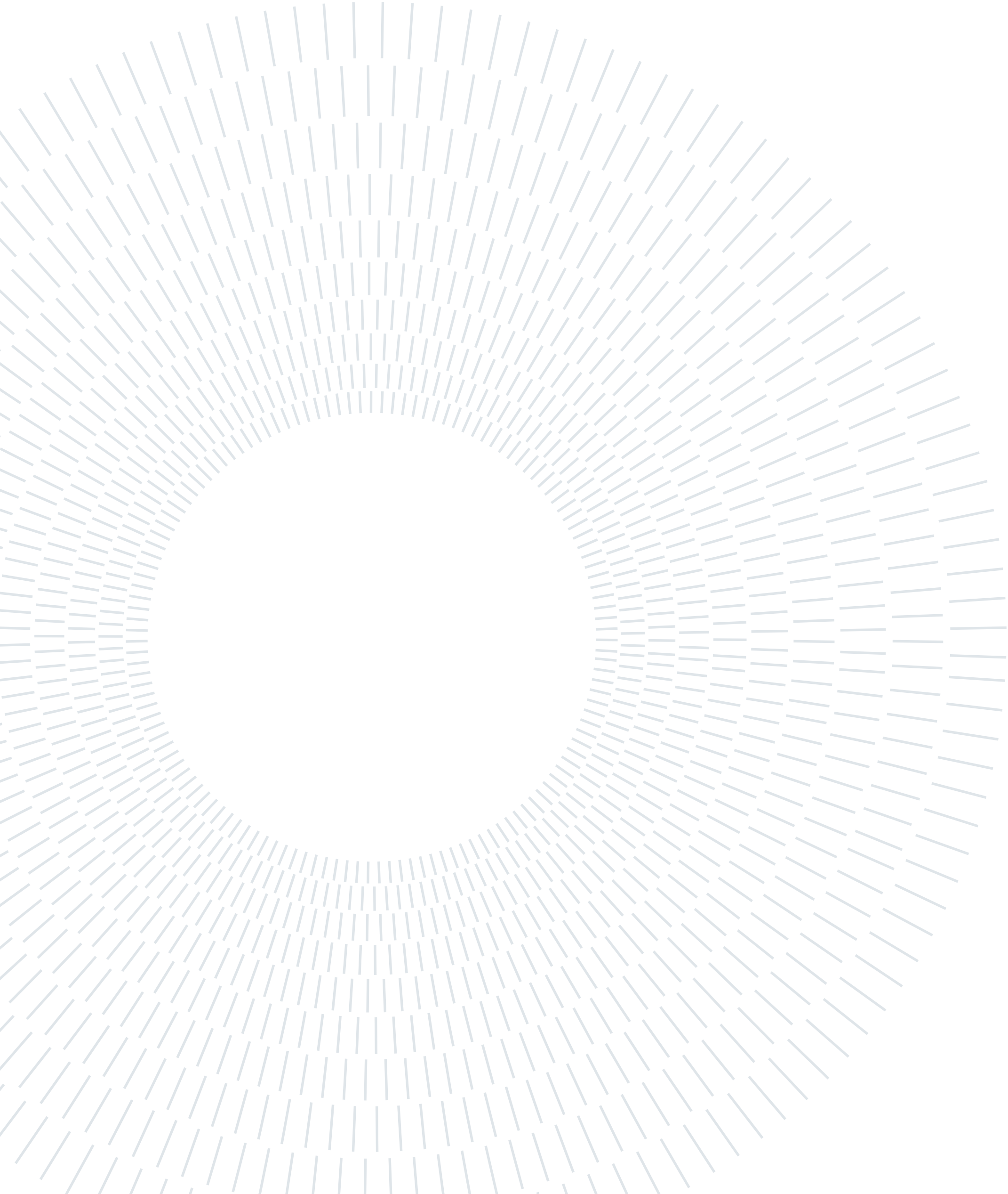
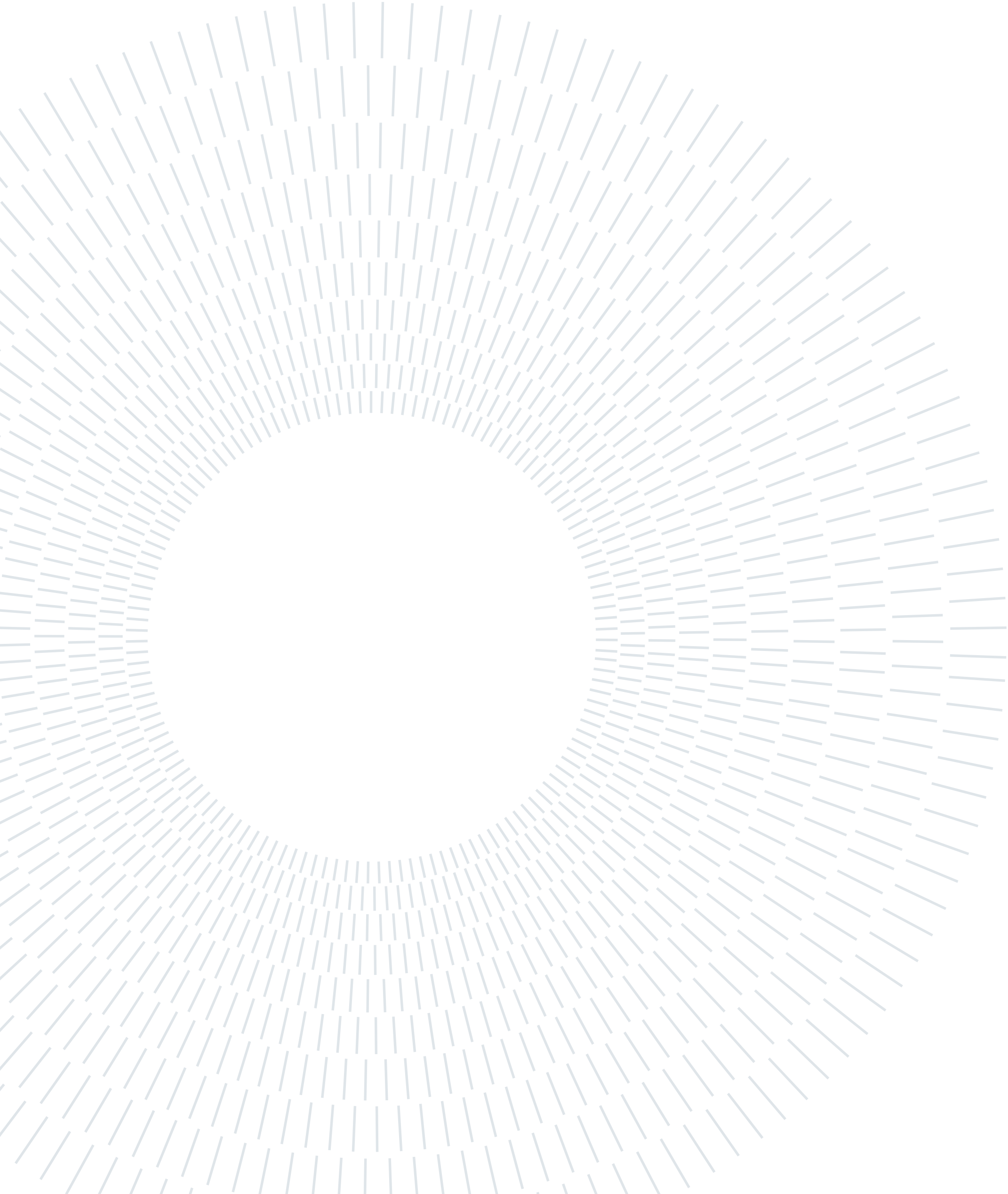


Abstract

Automotive industry today is witnessing four major disruptive trends - Connectivity, Autonomous Driving, Shared Mobility and Electrification (CASE). These trends are shaping the future of cars, and thereby mobility itself. They are being enabled by the rapid development and technological advancements in fields of communication, sensing and computation power. 5G's promise of ultra low latency, high peak data rate, ultra high reliability and high throughput under high mobility and connection density has further accelerated the impact of this disruption. In line with the industry's quest to support the drivers of today and develop connected autonomous vehicles for tomorrow, in this thesis, two Connected Advance Driver Assistance Systems (C-ADAS) have been developed and implemented. The first system, *Pedestrian Intersection Collision Warning and Avoidance System (P-ICWAS)*, aims to improve safety of pedestrians at intersections, where detection with on-board sensors is difficult, using infrastructure based detection and 5G-V2X communication. This system warns driver about the possible collision with pedestrian and if the driver fails to act within reasonable time frame, Autonomous Emergency Braking (AEB) is triggered. The threshold for actuation of AEB is decided on the basis of desired deceleration and braking distance. The second system, *Driver Profile Load System (DPLS)*, aims to improve comfort and convenience of Shared Car users as well as private users. The driver is identified by the cloud using a camera mounted on board and the user's driving configuration is automatically loaded. Additionally, This system can load the configuration in upto 66% less time when starting from reset position in comparison to the user doing it manually. Functioning of both the systems were also experimentally validated and their proof-of-work was demonstrated at the Project Base5G seminar held at Politecnico di Milano, Durando Campus. The experimental results demonstrated that 5G based P-ICWAS could effectively help drivers make appropriate operation decisions. It can potentially reduce the number of vehicle-to-pedestrian collisions and near-collisions and mitigate damages at any 5G equipped intersections.

Keywords: *Connected Advance Driver Assistance Systems (C-ADAS), 5G-V2X, Pedestrian Intersection Collision Warning and Avoidance System (P-ICWAS), Driver Profile Load System (DPLS), Autonomous Emergency Braking (AEB)*



Abstract in lingua italiana

L'industria automobilistica oggi sta assistendo a quattro principali tendenze dirompenti: connettività, guida autonoma, mobilità condivisa ed elettrificazione (CASE). Queste tendenze stanno plasmando il futuro delle automobili, e quindi la mobilità stessa. Sono abilitati dal rapido sviluppo e dai progressi tecnologici nei campi della comunicazione, del rilevamento e della potenza di calcolo. La promessa del 5G di latenza ultra bassa, velocità dati di picco elevate, affidabilità ultra elevata e throughput elevato in condizioni di elevata mobilità e densità di connessione ha ulteriormente accelerato l'impatto di questa interruzione. In linea con la ricerca del settore per supportare i conducenti di oggi e sviluppare veicoli autonomi connessi per domani, in questa tesi sono stati sviluppati e implementati due Connected Advance Driver Assistance Systems (C-ADAS). Il primo sistema, *Pedestrian Intersection Collision Warning and Avoidance System (P-ICWAS)*, mira a migliorare la sicurezza dei pedoni agli incroci, dove il rilevamento con i sensori di bordo è difficile, utilizzando il rilevamento basato sull'infrastruttura e la comunicazione 5G-V2X. Questo sistema avverte il guidatore di una possibile collisione con un pedone e, se il guidatore non interviene entro un ragionevole lasso di tempo, si attiva la frenata autonoma di emergenza (AEB). La soglia di attivazione dell'AEB viene decisa in base allo spazio di decelerazione e frenata desiderato. Il secondo sistema, *Driver Profile Load System (DPLS)*, mira a migliorare il comfort e la praticità degli utenti di auto condivise e degli utenti privati. Il conducente viene identificato dal cloud tramite una telecamera di bordo e la configurazione di guida dell'utente viene caricata automaticamente. Inoltre, questo sistema può caricare la configurazione fino al 66% in meno di tempo quando si avvia dalla posizione di ripristino rispetto all'utente che lo fa manualmente. Il funzionamento di entrambi i sistemi è stato validato e la loro proof-of-work è stata dimostrata al seminario Project Base5G tenutosi presso il Politecnico di Milano, Campus Durando. I risultati sperimentali hanno dimostrato che P-ICWAS basato su 5G potrebbe effettivamente aiutare i conducenti a prendere decisioni operative appropriate. Può potenzialmente ridurre il numero di collisioni tra veicoli e pedoni e di quasi incidenti e mitigare i danni in qualsiasi incrocio dotato di 5G.

Parole chiave: *Sistemi avanzati di assistenza alla guida connessi (C-ADAS), 5G-V2X,*

sistema di avviso di collisione ed evitamento degli incroci pedonali (P-ICWAS), sistema di carico del profilo del conducente (DPLS), frenata di emergenza autonoma (AEB)

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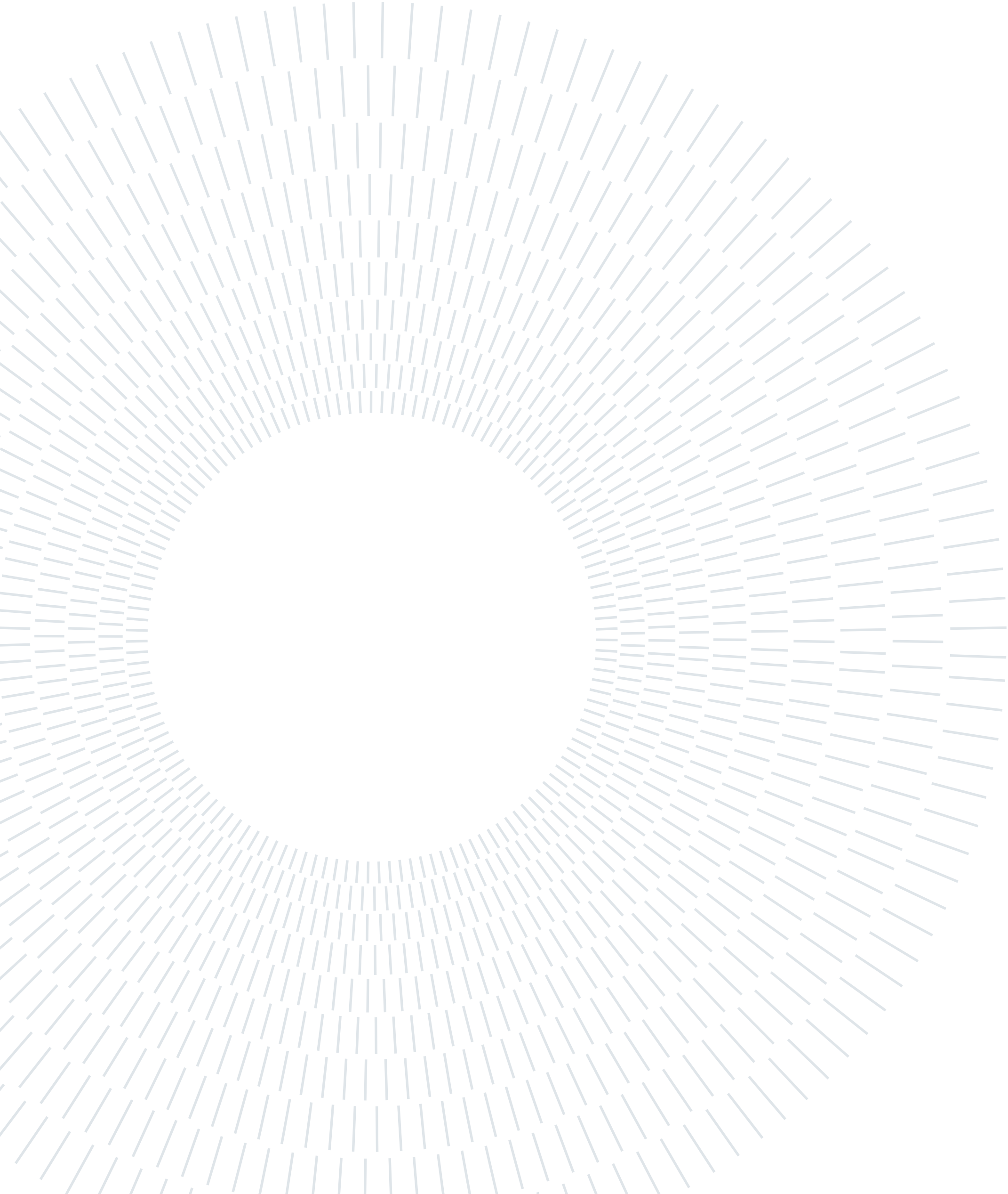


Introduction

Mobility has been a rudimentary requirement of our society throughout history. Starting from the time when we were hunter-gatherers and continuing until today in the year 2023 CE, we have been in constant need to move people and goods from one place to another for various motivations. As a fundamental cornerstone of our way of life today, this movement must be *efficient, safe, secure, inclusive, environmental-friendly, and smart*; "Smart" in the sense that mobility must leverage the potential of digital technologies and the extremely powerful tool of Information Exchange among different elements of the system, to achieve the other five objectives.

Driven by the same inspirations, the global automotive industry is presently undergoing significant technological transformations. Through integration of smart sensors, vehicles are quickly becoming more automated and aware of their surroundings. Vehicles on road are soon destined to share information in real time with other vehicles, road infrastructure, pedestrians, and communication networks (V2V, V2I, V2P and V2N). Vehicles would be able to collaborate with one another and expand their perception range beyond the capabilities of their own sensors, thanks to Vehicle-to-Everything (V2X) communication, enabling new vehicular services that holds the potential to eventually increase traffic efficiency and improve road safety. To this end, the way people will be moving is witnessing the emergence of new disruptive trends: Autonomous, Connected, Electric and Shared Mobility. Collectively termed as ACES or CASE, they are changing the ways in which OEMs are developing and innovating the modern day vehicle and its components. Development of these trends also align with the automotive industry's ultimate goal of Vision Zero [55].

Numerous cost-benefit analyses and socioeconomic studies have shown that the adoption and increasing market penetration of these trends will have positive effects in the future. In particular, Maria et al. have compiled a summary of the economic benefits and impact of Connected Autonomous Vehicles (CAVs) on the industry in different regions [10]. It is anticipated that CAVs could generate economic benefits ranging from 500 to 800 billion dollars between 2030 and 2050 in various regions. Although the potential industrial

Figure 1: Industry Trends: CASE/ACES

benefits may be impacted by the adoption of Shared Mobility, its adoption could lead to increased socioeconomic benefits and effective resource utilization.

In this thesis work, with inclination towards aforementioned trends, our main goal was the proof of concept of two different driving assistance systems enabled by connectivity and in particular made possible by 5G network's features: *ultra low latency, high peak data rate, ultra high reliability and high throughput* under high mobility and connection density. In detail, the work consisted of designing of these systems to experimental test phase of an active safety system and a comfortable one.

Our first system, which we have named as the *Pedestrian-Intersection Collision Warning Assistance System (P-ICWAS)* has been designed to enhance road safety at intersections and pedestrian crossings for all road users, focussing on Vulnerable Road Users (VRUs). Its primary objective is to alert drivers of potential collisions with pedestrians who may not be visible to them while crossing the road. To achieve this, the system uses a camera installed at the intersection to transfer data through the 5G cellular network to the driver. If the warning is ignored due to the driver's negligence or inability to respond, the designed system will autonomously engage the brakes to mitigate any damage.

Our second system, named as the *Driver Profile Load System (DPLS)* is aimed at improving the comfort and convenience of the driver. By detecting the driver's identity using 5G enabled camera and automatically loading the driver's preferred seat and side-mirror configuration upon boarding the vehicle, based on stored data, it negates the redundant activities to be performed by the driver every-time he boards a car, reducing driver fatigue. The benefits are more profound in case of shared mobility.

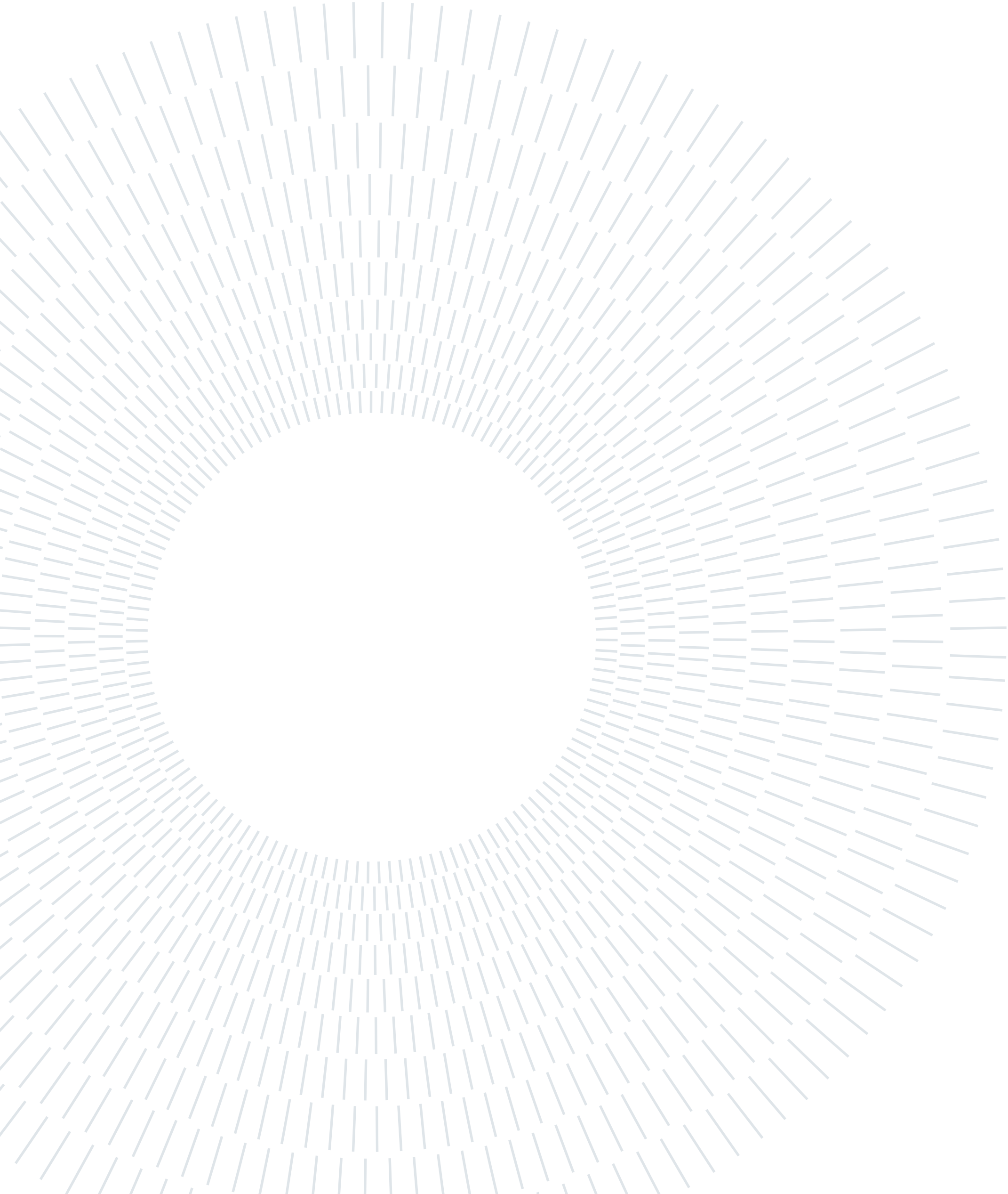
Our Proof-of-Concept demonstration at the Base 5G seminar held at Politecnico di Milano validated that our 5G based collision warning system (CWS) could effectively help drivers make appropriate operation decisions and and can reduce the number of right angle collisions and near-collisions at any 5G equipped intersections.

It could also be understood that improving safety at the intersections and pedestrian crossings, along with enhancing driver's comfort not only would be a significant step towards Vision Zero, realizing a zero-accident-society, but also reflects well on the economy.

Chapter Outline

The thesis is structured as follows:

- The First chapter discusses Connected Mobility and how recent developments in Vehicular Communication, such as 5G technology, have disrupted the industry by enabling the development of Intelligent Transportation Systems (ITS). The chapter further explores the technology enablers and some of the use cases.
- The Second chapter provides insight into Advanced Driver Assistance Systems (ADAS) and the various levels of automation involved, as well as previous developments in collision avoidance systems for vehicles. The chapter also broaches the Curvilinear coordinate system, which is used in our algorithm, and explains how pedestrian collision calculations are performed.
- The Third chapter describes in detail the system structure, the components and the algorithm of Pedestrian-ICWAS (P-ICWAS).
- The Fourth chapter delves deeper into one out the four disruptive trends of modern mobility: Shared Mobility. It also discusses about the potential benefits of Shared Economy and the reasons for increasing market penetration.
- Chapter Five introduces the second part of our work, Driver Profile Load System (DPLS), dedicated towards reducing annoyance and improving convenience for the Shared Mobility User. Limitations of present seat and/or side-mirror memory systems are discussed. To overcome the same, different components and working of the DPLS is described in detail.
- Chapter Six entails the details of the Validation tests, their results and the successful demonstration of the two systems developed, P-ICWAS and DPLS, during the event organised by Polimi - Project Base 5G.
- The Final Chapter concludes the thesis with remarks on the outcome of our work and tries to provide a glimpse about the future scope of work.



1 | Connected Mobility

1.1. Introduction

Connected mobility refers to the use of advanced technologies and connectivity solutions to improve transportation services and increase mobility options for individuals and communities. It relies on the integration of various elements such as connected vehicles, communication networks, data analytics, and other digital technologies to create a seamless and efficient transportation system. This system aims to enhance user experience, increase safety, and reduce congestion and pollution.

1.1.1. Evolution of Connected Vehicles

The evolution of connected vehicles has been driven by advances in communication and sensor technologies, as well as the growing demand for more efficient, safe, and convenient transportation. Here are some of the key milestones in the evolution of connected vehicles:

- **Early telemetry**: The first connected vehicles used simple telemetry systems to transmit data about vehicle performance, such as speed, fuel consumption, and engine temperature, to a remote monitoring system.

- **Onboard diagnostics**: In the 1980s, onboard diagnostics systems were introduced, allowing vehicles to self-diagnose problems and report them to the driver or service technician.

- **GPS navigation**: In the 1990s, GPS navigation systems were introduced, allowing drivers to navigate more efficiently and accurately.

- **Telematics**: In the early 2000s, telematics was established, combining GPS navigation with other features such as vehicle tracking, remote diagnostics, and emergency assistance.

- **Advanced driver assistance systems (ADAS)**: During the 2010s, Advanced Driver Assistance Systems (ADAS) were introduced, which utilized sensors and cameras to aid drivers with various tasks, including lane departure warning, adaptive cruise control, and automatic emergency braking.

- **V2X communication**: In the late 2010s, vehicle-to-everything (V2X) communication systems as a concept started to take shape. It envisions vehicles to communicate with other vehicles, pedestrians and infrastructure such as traffic lights and road signs.
- **Autonomous vehicles**: Simultaneously in the 2010s, autonomous vehicles also began to be developed, using advanced sensors, cameras, and artificial intelligence with an aim to navigate the roads without human intervention.

1.1.2. Current State of Connected Mobility

Currently, there is a growing interest in research on connected vehicles, with features such as GPS navigation, telematics, and ADAS systems now becoming standard in many new vehicles. As communication and sensor technologies continue to evolve, we can expect to see even more advanced features and capabilities in the years to come, including fully autonomous connected vehicles and perhaps new forms of mobility such as flying cars and autonomous drones.

There are numerous examples of connected mobility solutions being researched in both academia and industry today, some of which include:

1. Electric and autonomous vehicles that are designed to be connected and communicate with other vehicles and infrastructure to improve safety and efficiency.
2. Vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies that enable vehicles to communicate with each other and with infrastructure such as traffic lights and road signs.
3. The Vehicle to everything (V2X) pedestrian collision prevention system, a promising technology that can greatly enhance the safety of both drivers and pedestrians on the road. The system can provide real-time information to the driver about the surrounding environment, such as the presence of pedestrians, their location, and movement patterns. This information can help the driver make informed decisions and take appropriate actions to avoid collisions.
4. Intelligent transportation systems (ITS) that use sensors, cameras, and data analytics to improve traffic flow and optimize routes.
5. Shared mobility services such as ride-hailing, car-sharing, and bike-sharing that pro-

vide on-demand access to transportation options and reduce the need for individual car ownership.

Connected mobility has the potential to transform transportation and make it more sustainable, efficient, and accessible to all.

1.1.3. Moving towards Connected Autonomous Vehicles

Autonomous vehicles (AVs), alternatively called driverless or self-driving cars, are designed to function without requiring constant input from a driver and without the need for the driver to continuously monitor the road. There are different levels of autonomy in vehicles, ranging from Level 0 (no automation) to Level 5 (full automation). The levels of autonomy is described in detail in next chapter (*Refer 2.2.2*). These AVs use a combination of advanced sensors, cameras, GPS, and artificial intelligence (AI) to perceive their surroundings and make decisions about how to navigate the roads.

The connectivity among the AVs is realized using the technology called vehicular networks or vehicular ad-hoc networks. Connected Vehicles (CVs) are designed to support better connectivity by utilizing various levels of communication which includes Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I). Furthermore, Connected-Autonomous Vehicles (CAVs) have connectivity with all the levels of communication channels and retrieves information from Vehicle-to-Everything (V2X) communication level to provide a complete field view and hence optimize the autonomous driving of other road users.

CAVs, as a part of ITS have the potential to revolutionize the connected mobility industry by reducing accidents, improving traffic flow, and increasing the scope of mobility for individuals who cannot drive due to age, disability, or other reasons. While previous studies on the energy impact of CAVs are limited, a review of eco-driving literature suggests considerable benefits. CAVs have unprecedented access to information, owing to advanced sensors and V2X communication, and can plan and execute maneuvers more efficiently than human drivers. As CAVs improve the throughput of traffic and economy of fuel by optimizing the route and cooperative driving, they could also have a significant impact on the environment by reducing emissions and energy consumption. Authors in this research [72] discuss the potential for CAVs to improve energy efficiency. Static road information previewed by CAVs can save up to 3% energy in highway driving, and V2I communication can save up to 10% energy in arterial driving. Reservation-based intersections can save up to 20% energy with full penetration of CAVs. Other potential gains include platooning for trucks (7-10%), cooperative car following and lane selection, and harmonizing traffic (up to 20% savings in stop-and-go driving).

Despite the potential benefits of autonomous vehicles, there are also concerns around safety, cybersecurity, and the impact on employment in the transportation industry. As a result, there is ongoing research and development to address these challenges and ensure that CAVs are safe and beneficial for society.

1.2. 5G - The disruption

Today, development of CAVs have the possibility to harness support from the latest cellular network, which is referred to as 5G or fifth generation. With the utilization of 5G technology, which can provide speeds of up to 10 Gbps and a remarkably low latency of 1 ms for regular mobile users, the concept of Connected Mobility can take a step forward towards realising ITS in the future. The 5G new radio (5GNR) was introduced in 2015 by the International Telecommunication Union (ITU) as a novel cellular communication standard that has the capability of supporting large-scale, delay-sensitive Vehicular Network applications by employing 5G. 5G offers Massive Machine Type Communication (mMTC), improved mobile internet, and Ultra-Reliable Low Latency Communication (URLLC). Low latency means that data can be transmitted and processed much faster than with previous generations of wireless technology. This ultra-reliable low latency will enable vehicles to communicate with other vehicles, pedestrians, and infrastructure in real-time, allowing for faster response times and better decision-making. Putting all of it together, the benefits of 5G can be used to meet the needs of Autonomous Vehicles in the realms of Connected Mobility .

Specific to the topic of our thesis, 5G network has the potential to significantly improve vehicle-pedestrian collision avoidance. Following are some scenarios reported from literature, where 5G has been researched to play a role to increase pedestrian safety[57] [15] [33]. There are several ways in which if 5G network is explored, it could be deployed for vehicle-pedestrian collision avoidance system.

1. Pedestrian detection: If 5G is deployed as a mode of communication between the road side infrastructure and the vehicles, it could be used to relay the information of detected pedestrians and other objects in the road using sensors and cameras. This information might then be shared with other vehicles in the area to help them avoid collisions.
2. V2P (Vehicle-to-Pedestrian) communication: Vehicles could use 5G technology, if chosen as a preferred network, to communicate with pedestrians directly, using their smartphones or other connected devices. This can be particularly useful in

situations where pedestrians may not be visible to the driver, such as at night or in poor weather conditions.

3. V2X (Vehicle-to-Everything) pedestrian collision prevention could serve as an advanced driver assistance system (ADAS) that chooses to utilise 5G communication to establish communication between vehicles and pedestrians in the vicinity. One of its main objectives would be to decrease the number of collisions that occur between vehicles and pedestrians. The 5G based V2X pedestrian collision prevention system could employ sensors, cameras, and radar systems in conjunction with wireless communication technology to identify situations where a potential collision between the vehicle and pedestrians may occur. Once a potential collision is detected, the 5G network could be used to send warnings to both the driver and pedestrians through audio, visual, or haptic feedback, alerting them to the potential danger.
4. Intersection safety: 5G could also be used to improve safety at intersections, if chosen as a preferred mode of communication by allowing vehicles and infrastructure to communicate with each other in real-time. For example, traffic lights could be connected to the network and communicate with vehicles to ensure that they are aware of upcoming red lights or stop signs.
5. Emergency braking: In the event of an emergency, if 5G network is used to communicate, it would ensure faster transmission of information to the vehicle, allowing the vehicle to automatically apply its brakes and avoid a collision with another vehicle or VRU. This could be particularly useful in situations where a pedestrian suddenly steps out into the road.

Overall, 5G network shows the potential to significantly improve vehicle-pedestrian collision avoidance by enabling faster and more accurate communication between vehicles, pedestrians, and infrastructure. This could help to reduce the number of accidents and make our roads safer for everyone. To the best of our knowledge, the above mentioned systems are still in concept stage and have not been implemented or demonstrated as a proof of concept yet. Our aim in this thesis is to implement a 5G network based V2I collision warning system to enhance VRU safety. The rest of this chapter deals with understanding Connected Mobility better in order to provide a bedrock to implement our designed systems better.

1.3. Architecture of Connected Mobility

Connected Mobility encompasses a range of technologies that enable inter-vehicle connectivity for various services such as traffic safety, roadside assistance, improved driving efficiency, remote monitoring, traffic congestion avoidance, maintenance, and system failure management. ACVs, as a part of connected mobility, utilize a variety of sensors installed onboard that communicate with each other through the Controller Area Network (CAN) bus, as well as communication infrastructures and other vehicles. Connected Mobility as a concept is being extensively researched by both academics and industry professionals, with the goal of enhancing safety for VRUs, improving traffic flow, reducing fuel consumption, and lowering travel costs. *Fig. 1.1* illustrates the basic infrastructure required for implementing and deploying Connected Mobility to provide Intelligent Transportation Systems (ITS).

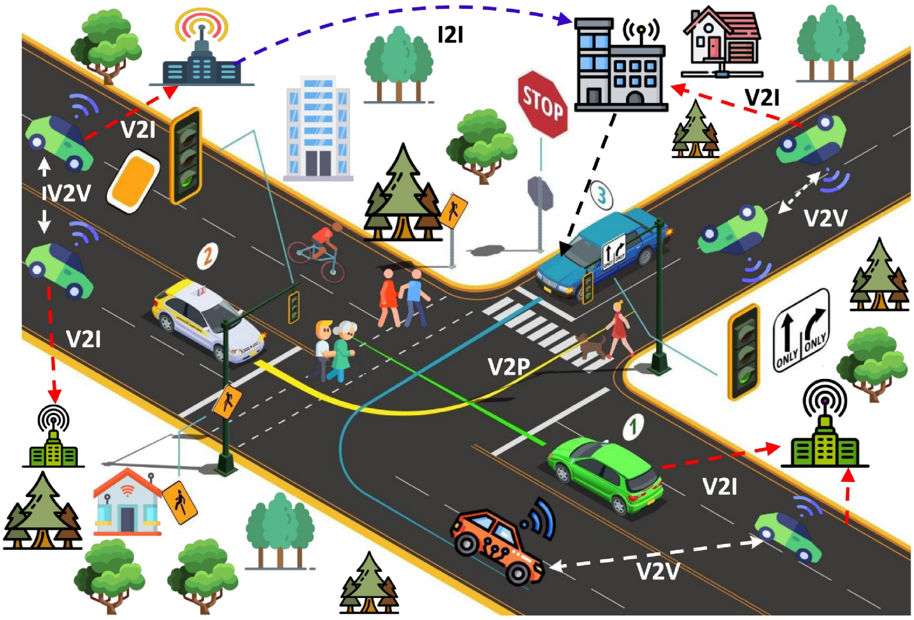


Figure 1.1: Illustration of Autonomous Connected Vehicles, Infrastructure, Environment and Communication as a part of ITS.

As illustrated in *Fig. 1.1*, the entire network can be divided into two main categories of nodes:

- Vehicles equipped with on-board sensor units, and
- Communication-based infrastructures located alongside the roads.

Communication channels within the network include V2V, Infrastructure-to-Infrastructure (I2I), V2I, V2P, and V2X. On-board sensor units within vehicles consist of sensors that can detect objects and obstacles within their dedicated range. Table 1.1 provides information on frequently used sensors, their sensing range, and potential applications.

Sensor Type	Range	Example	Usage
Proximity sensors	5 m	Ultrasonic sensor	Detects nearby obstacles, parking assistance
Short range sensors	30 m	Forward camera Backward camera Short range radars	Recognition of traffic signs Detection of blind spots Alerting cross traffic Lane detection
Medium range sensors	80-160 m	LiDAR Medium range radars	Detection of pedestrians Collision avoidance
Long range sensors	250 m	Long range radars	Support adaptive cruise control Information collection at high speed

Table 1.1: On Board sensor Types, Range and Usages

The general architecture of 5G enabled Vehicle-to-Everything communication is schematised in *Fig. 1.2*. This architecture is comprised of three layers, each responsible for different functionalities.

- The first layer is the *perception layer*, which uses sensors mounted on the vehicle to gather raw information from the environment. Using sensor fusion techniques, the perception layer calculates local and global location parameters and generates a map of the environment.
- The *planning/processing layer* is the next layer, which determines the best global route based on the current position and requested destination using remote data on road and traffic. Using the environment map generated by the perception layer, the planning/processing layer computes trajectory planning and tracking.
- The final layer is the *control layer*, which provides appropriate commands to control the various actuators of the ACV, such as the steering wheel, gas pedal, and brake pedal.

In addition to these main functionalities, the perception layer shares perceived information of the environment with other road users, enabling cooperative driving with the help of inter-connectivity among vehicles and infrastructure. The planning/processing layer is responsible for decision-making related to control of the motor and actuator.

The complexity of deploying ACVs increases due to the need for connectivity among vehicles, infrastructure, and road users to make high-level and important decisions. To this end, V2I communication and the presence of heterogeneous sensors in the vehicles and infrastructure supported by 5G network holds the potential to keep the communication fast and safe, the two major requirements to realise Connected Mobility in reality.

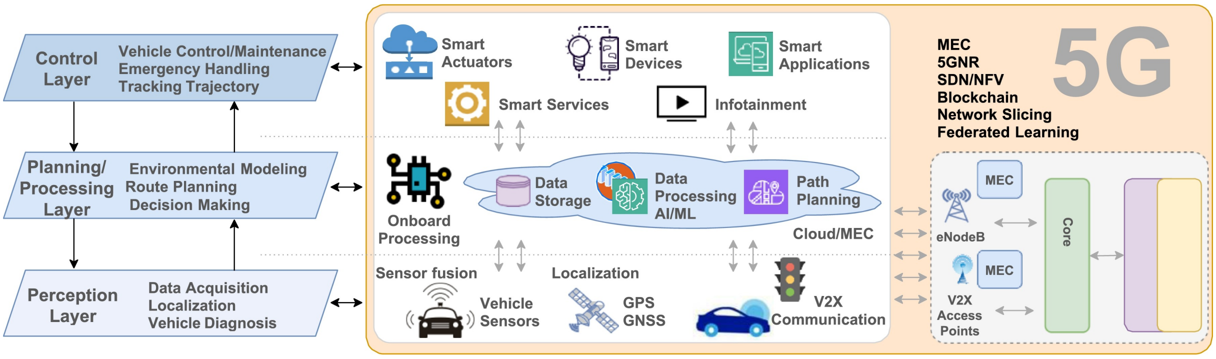


Figure 1.2: General architecture of 5G enabled V2X communication

1.4. Technology Enablers for Connected Mobility

Traditional methodologies may not be suitable for implementing and deploying Connected Mobility's salient features. However, recent innovative technologies in sensors, cloud computing, and artificial intelligence can help in developing and designing intelligent ACVs with numerous benefits.

This section explores the enablers that can support ACVs' deployment in the real world.

1.4.1. Sensing Environment

Traditional Vehicular Networks typically focus on sensor networks that employ single type or homogeneous sensors. In contrast, Connected Mobility relies on heterogeneous sensors and commonly use three types of sensors, as depicted in *Fig. 1.3*.

- *Detection sensors* are mounted on vehicles to identify environmental features and monitor vehicle performance.
- *Ambient sensors* monitor the environment and gather sensitive legacy data, which is transmitted to the appropriate authorities.
- *Back-scatter* sensors are designed for use with various objects and enhance awareness of the external world, including cyclists, trespassers, and other potential hazards.

These heterogeneous sensors put together forms the sensing environment required to enable Connected Mobility in general, and V2I communication in particular to our thesis.

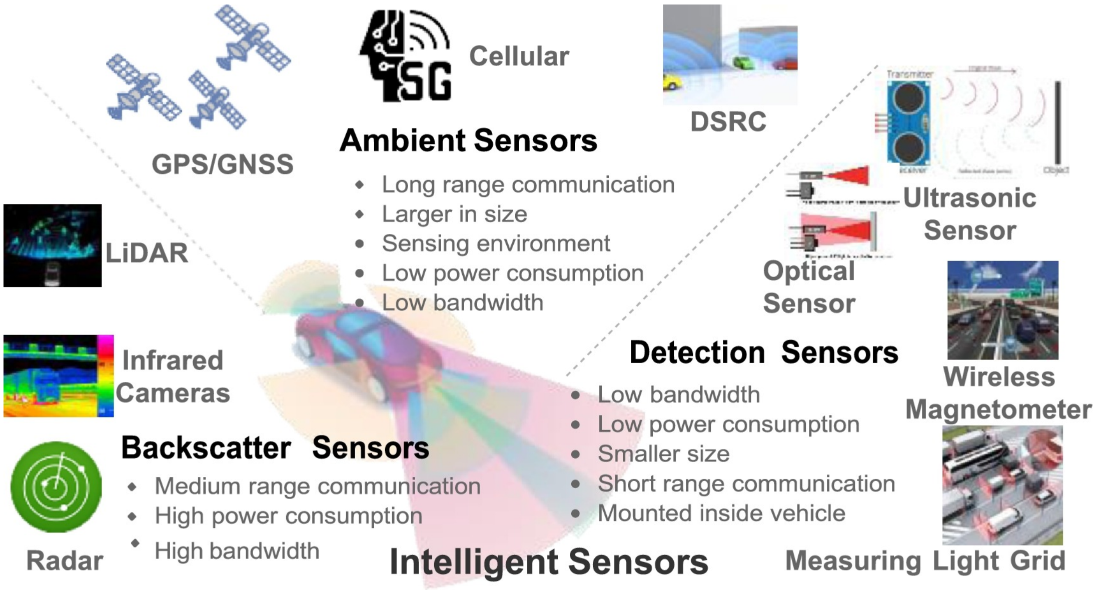


Figure 1.3: Heterogeneous Sensors deployed in Connected Mobility environment

1.4.2. Data Acquisition

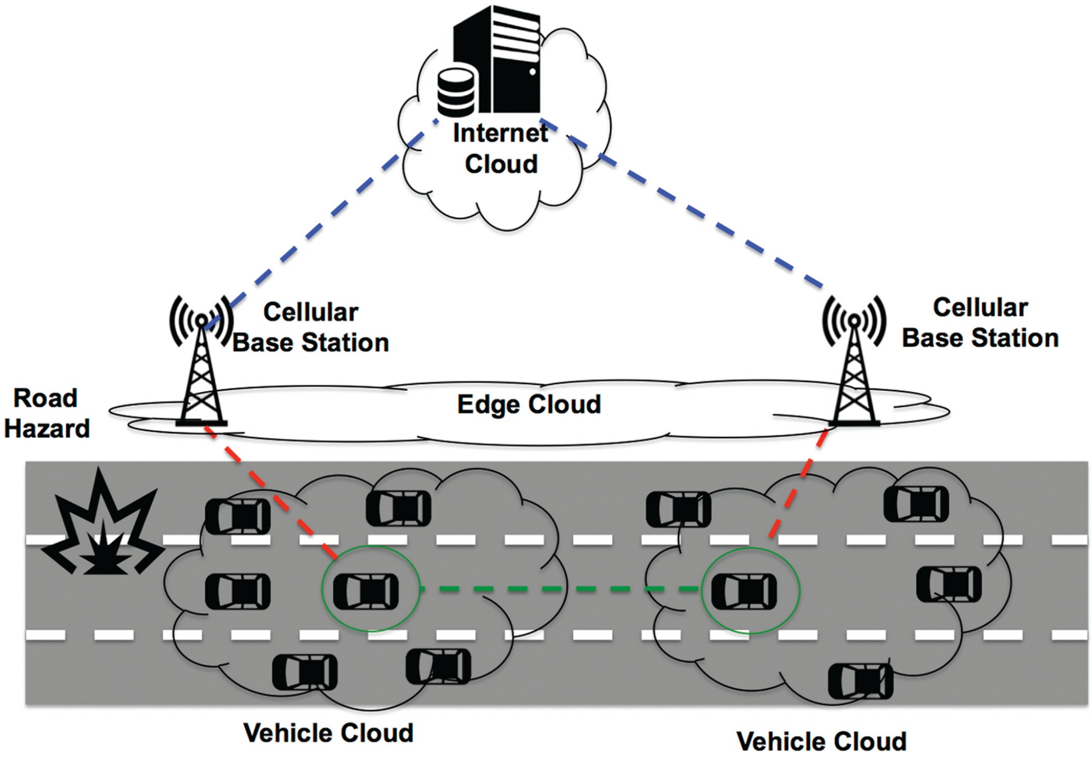


Figure 1.4: Data acquisition through Cloud Computing

ACVs generate significant amounts of data in the form of signals emitted by sensors mounted on, in, and around the vehicles. The data must be accessible to permitted authorities, other vehicles in the network, and other infrastructures in the vehicular environment to make timely decisions. Storing and accessing such vast amounts of data requires high-end resources and servers for temporary storage or archiving. Cloud computing provides virtual resources on demand [38], enabling ACVs to communicate more efficiently with everything in their environment. In reference to *Fig.1.4*, the vehicle cloud computes and communicates safe routes. Security and privacy protection is required as V2V communication occurs without reliance on the Internet cloud. In addition to cloud-based technology, fog, edge, and roof computing are other key technologies that support accessing huge amounts of vehicular data. Recently, vehicular fog nodes have been developed using fog computing technology [26], providing better information on the environment and facilitating intra-vehicular and inter-vehicular communications. The data collected by fog nodes can be analyzed using algorithms to optimize their performance further.

1.4.3. Vehicular Communication

Vehicular communication is an important domain of ITS dealing with the exchange of safety messages between vehicles and roadside infrastructure to improve road safety, with functionalities of ACVs heavily relying on the data obtained by the heterogeneous sensors and their reception. To this end, different technologies have been proposed for V2X communication. With the prospect of safer commutes and reducing congestion, there is emphasis on choosing technology that meets safety concerns; Technologies such as Direct Short-Range Communication (DSRC) or 5G-cellular as options for communicating between vehicles.

Dedicated Short Range Communication

Dedicated Short Range Communication (DSRC) is an existing technology based on IEEE 802.11p that was created specifically for V2X communication and is currently available for the automotive industry. Since DSRC uses 802.11, wireless access points are required to establish a connection. DSRC was designed to meet each of the V2X requirements, having dedicated bandwidth of 75 MHz set aside without competition. DSRC is ready for deployment, has already been tested in use cases with success.

5G cellular

5G, also known as C-V2X, is an emerging generation of Cellular V2X that evolved from 4G. It is newer to the automotive industry and uses existing cellular network infrastructure. 5G has vast improvements in connectivity versus its previous 4G version bringing it up to par with DSRC. Since 5G is an emerging technology, it'll use existing cellular infrastructure for communication, therefore, no costly RSU required for DSRC needs to be purchased or maintained.

To improve performance and communication, high-bandwidth connections capable of transmitting gigabits per second are necessary. One way to achieve this is by utilizing millimeter-wave (mmWave) for ACVs as depicted in *Fig. 1.5*, which can be used for intra-vehicular communication, V2V communication, and V2I communication.

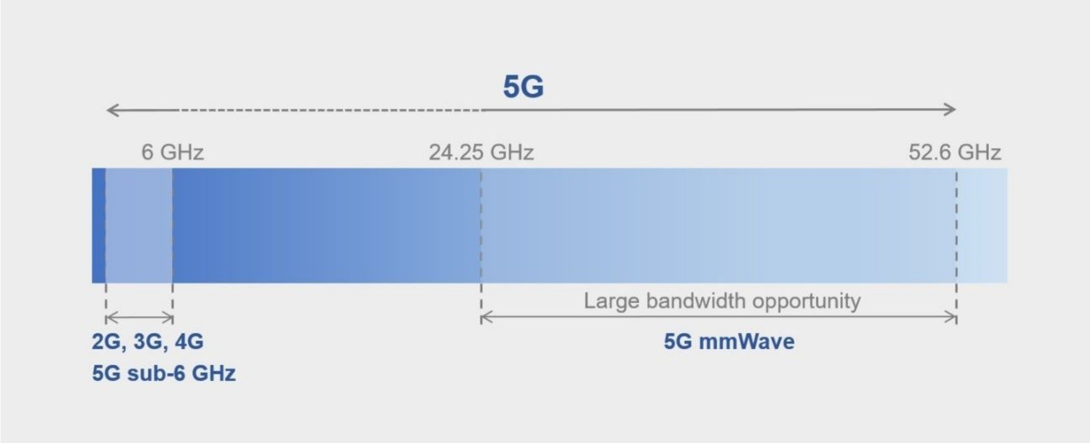
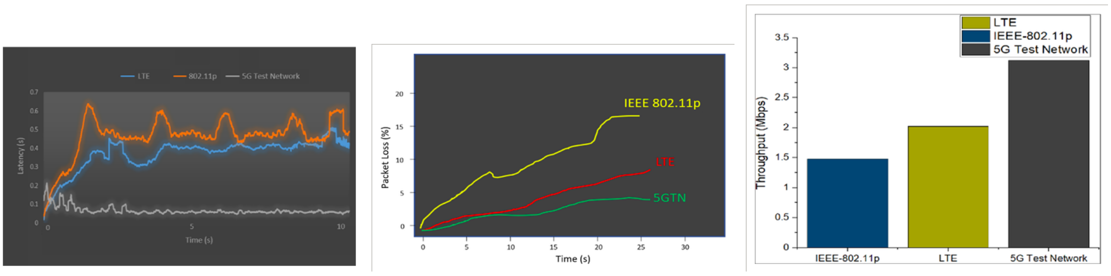


Figure 1.5: 5G mmWave provides a large bandwidth opportunity for Vehicular communication

The 5th Generation (5G) network is based on this mmWave technology to provide ultra-low latency communication via efficient use of resources.[11] In previous cellular standards (4G LTE), there were issues and limitation factors for vehicular communication. One important issue was the selection of beams that strongly relied on correct localization information and a convoluted transceiver chain, causing unnecessary overhead and network delay.[11] With mmWave V2V links, vehicles can exchange raw information with neighboring vehicles in their environment. For road safety-based applications, mmWave V2I links can be used to collect data from vehicles and send it to the cloud for storage and decision-making. High-data rate mmWave links can also be used for downloading real-time maps and dynamic environment streams. [9]

According to the performance evaluation of the three vehicular networks, comparing IEEE-802.11p (DSRC), 4G LTE and 5Gth in V2V and V2I scenarios, based on field measurements conducted and analysed by authors in [71] , the results referred to in the figures *Fig. 1.6a*, *Fig. 1.6b* and *Fig. 1.6c.* and *Table 1.2* illustrate that 5G test network has performed better than the other two technologies in terms of latency (ms), packet loss (%) and throughput(Mbps).



(a) Latency (ms) (b) Packet Loss % (c) Throughput (Mbps)

Figure 1.6: Comparison between DSRC (IEEE 802.11p), 4G LTE and 5G cellular based on field test conducted by [71]

Technology	Latency (s)	Packet loss (%)	Throughput (Mbps)
IEEE-802-11p	0.05	17.02	1.48
LTE	0.04	7.5	2.02
5G	0.01	4.07	3.12

Table 1.2: Performance analysis of DSRC (IEEÉ 802.11p), LTE and 5GTN. [71]

Because of the above mentioned advantages, interest in 5G development will continue to progress for V2X applications, and hence has been used for our P-ICWAS V2I communication. The building blocks for features that enables 5G to be integrated with Connected Mobility has been introduced in the next section.

1.5. 5G enabled Connected Mobility

The 5G platform supports existing and novel applications with low latency, improving connectivity and coverage for vehicular communication. Building blocks for using 5G in Connected mobility is discussed in this section.

1.5.1. Proximity Service

5G communication's key feature Proximity Services (ProSe) *Fig.1.7*, first introduced in Release 12 of the 3GPP specifications, is a D2D (Device-to-Device) technology that allows user equipment (UE), in our case the moving vehicles, to detect each other and to communicate directly. Current 4G LTE network requires Evolved Node B (eNB), which is the radio base station in 4G LTE networks. In vehicular communication, ProSe offers awareness to vehicles about devices, infrastructure, and other objects in their vicinity. ProSe

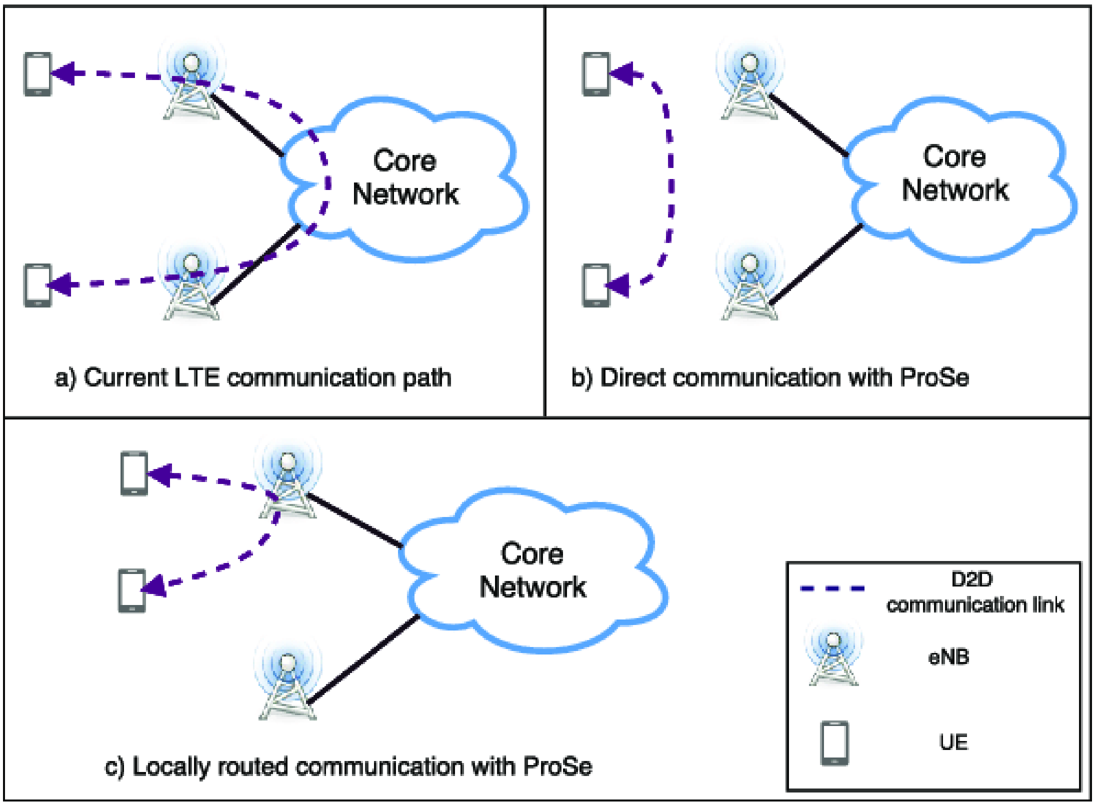


Figure 1.7: 5G ProSe provides instant vehicular communication

provides instant communication and interactions within a certain location, making it ideal for identifying moving vehicles and VRUs on the road, and serving as a communication service for public safety scenarios. [27]

1.5.2. Multi-access Edge Computing

The main feature of Connected Mobility enabled by 5G is the ability to achieve low latency, which can be as low as 100 ms for safety purposes and 1 ms for autonomous connected vehicles (ACVs).To achieve such low latency, one method is to move the basic and core functionalities closer to the end users, which is known as the edge. Multi-access Edge Computing (MEC) enables cloud computing capabilities to be brought closer to the network edge, reducing congestion and latency, enabling faster application processing, and providing real-time analytics for applications such as traffic analysis, big data analytics in ITS and smart cities, etc. [45, 65]

Apart from providing low latency, MEC offers high-bandwidth, and real-time access to radio network resources, enabling Internet-of-Things (IoT) integration. [47] MEC-enabled 5G services play a vital role in fast communication and processing of complex data in real-

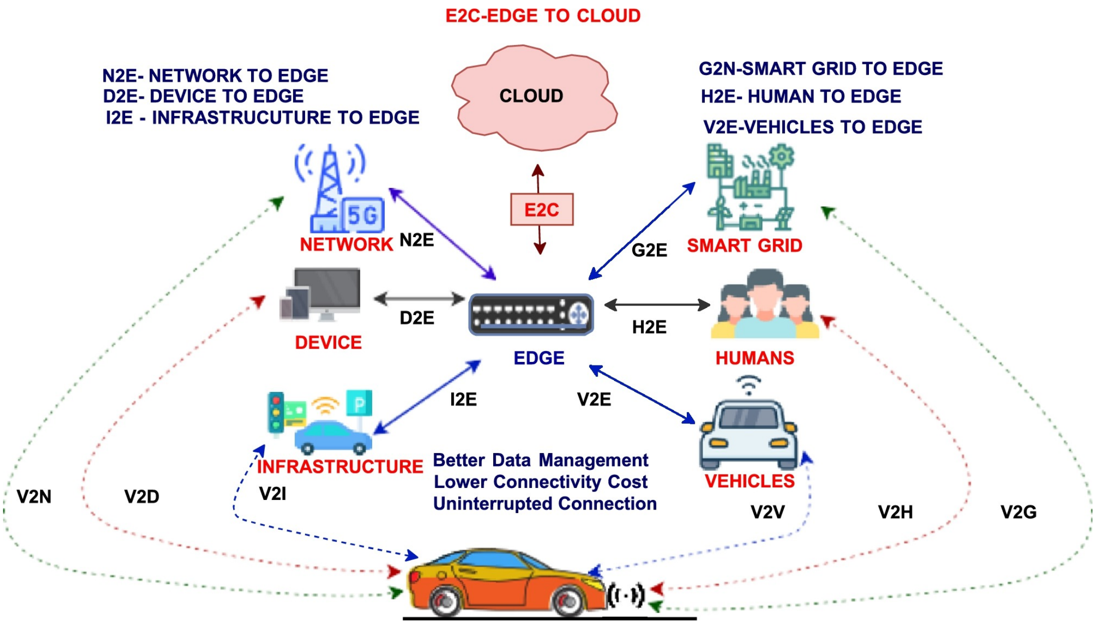


Figure 1.8: MEC enabled 5G for Connected Mobility

time analytics, allowing for offloading latency-sensitive and computing-intensive tasks to edge devices as depicted in *Fig. 1.8.* Enormous data generated from AVs can be used for recognition of external and road features, and MEC can help with tasks such as collision avoidance and lane merging by processing multiple computer vision operations in real-time.

1.5.3. Network Slicing

As explained earlier, the scope of 5G is to support all existing access technologies by providing a wider range, which is a complex task considering the numerous networks utilizing different access technologies. Network slicing is an effective solution to this challenge by logically separating the networks. This separation is done by slicing the networks based on their applications and requirements, such as safety applications, infotainment applications, and mission-critical system applications. Each application can be logically separated as a network slice, with customized network functions that satisfy their specific communication requirements.

Thus, Network Slicing (NS) becomes a crucial enabler of 5G communication networks, enabling multiple logical networks on the same physical and virtual resources. The NS architecture comprises a service instance layer, network slice instance layer, and resource layer, with the network slice orchestrator coordinating their functionality. In the context of ACVs, network slicing allows for the allocation of network slices with specific character-

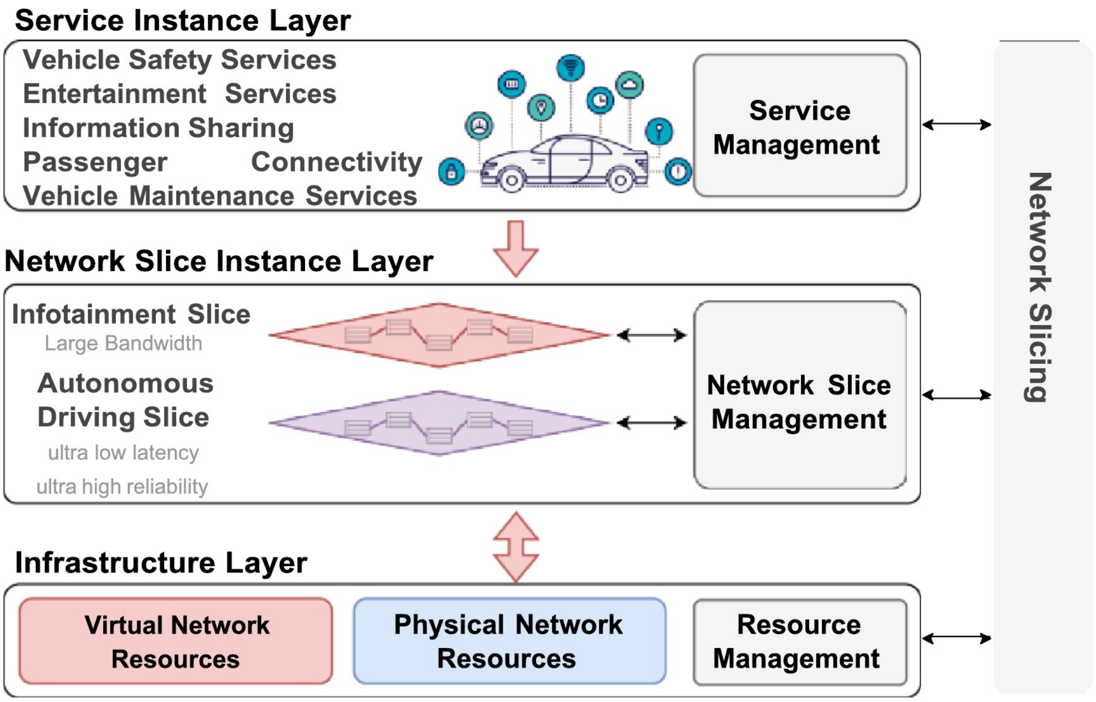


Figure 1.9: Network Slicing

istics, such as a high bandwidth network slice for vehicle infotainment and a low latency and high reliability network slice for ACVs. This is illustrated in *Figures 1.9* and *1.10*.

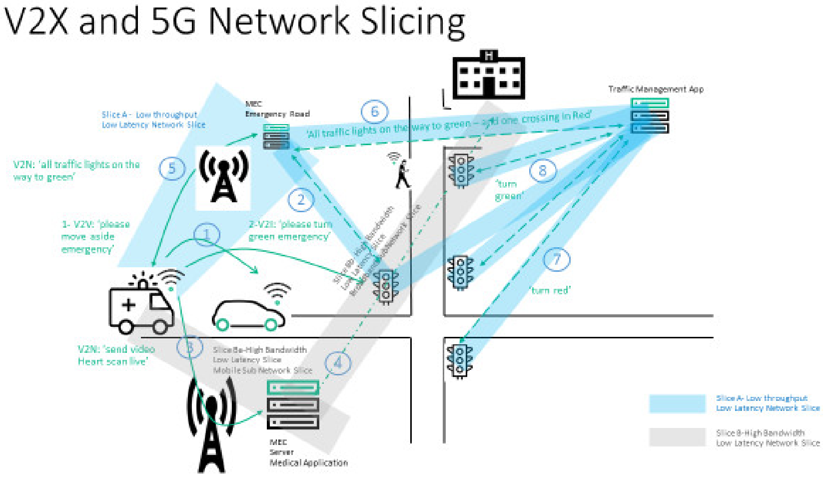


Figure 1.10: 5G Network Slicing in V2X

1.5.4. mMTC, URLCC and eMBB

Machine type communications (MTC) is another crucial technology enabler in 5G Vehicular Communication systems and can be divided into two types: massive Machine Type Communication (mMTC) and ultra-reliable Machine Type Communication (uMTC). mMTC is designed to provide connectivity to a vast number of low-power and low-complexity devices with minimum data traffic, low latency, and high throughput. One of the major concerns for mMTC is to optimize the power usage of these devices. Key characteristic of mMTC is that it transmits small packets with low user data rates, achieving optimal power usage and long battery life. In contrast, uMTC is used to connect adequate wireless links for network services, which are typically employed in V2X. This will be used to connect large numbers of IoT devices that are part of the Connected Mobility, and is expected to transform the mobility industry.

Ultra-reliable Low-Latency Communication (URLLC) is an essential technology in 5G that provides a secure and low-latency connection. It is particularly suitable for applications that demand a high degree of network reliability, exceeding 99.999%, and very low latency of around 1 millisecond for data transmission. This translates to a maximum of only 0.001% of 20-byte packets failing to reach their destination within 1 ms. Due to its reliability and low latency, URLLC is a critical enabler for 5G-based Vehicular Communications.

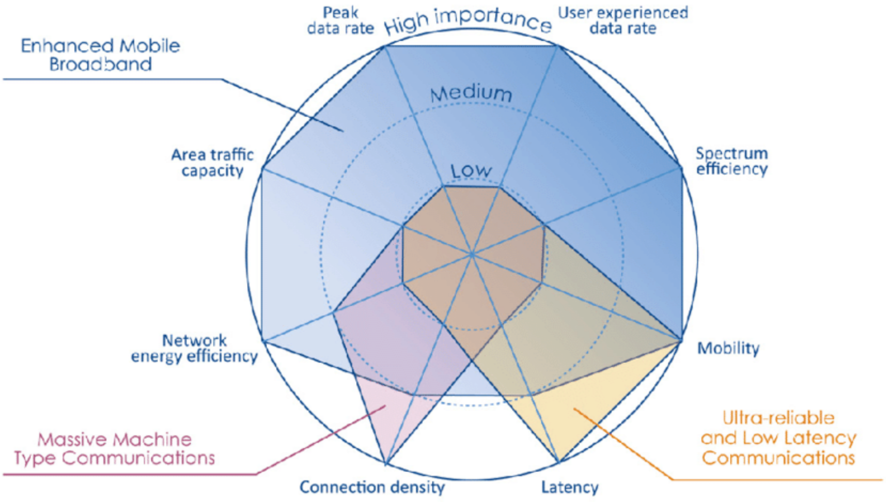


Figure 1.11: 5G Usage Scenarios (eMBB, MMTC, uRLLC)

Enhanced Mobile Broadband (eMBB) focuses on meeting the needs of human-centric applications that require access to multimedia content, services, and data. It provides high-speed and stable connections, especially for cell-edge users, such as high-speed vehicles in Connected Mobility environments. eMBB is characterized by large data payloads and a stable device activation pattern over a long period. This enables the network to schedule wireless resources for eMBB devices, ensuring that no two devices access the same resource at the same time. The primary goal of eMBB is to maximize the data rate while maintaining moderate reliability, with a packet error rate (PER) of about 10^-3.

The usage scenarios of mMTC, URLCC and eMBB in Connected Mobility is depicted in *Fig. 1.11*.

1.6. 5G enabled Connected Mobility Use Cases

Vehicle to everything (V2X) technology is when a vehicle is able to recognize and communicate with all of the facets of transportation in an ITS, i.e. Vehicles (V2V), Infrastructure (V2I), Pedestrians or VRUs (V2P), and Network (V2N). 5G networks potentiall can be the key in providing connectivity for V2X communications. So, 5G-V2X is a potential set of use cases supporting vehicle to all communication that relies in the use of 5G networks, amongst others to focus on safety, traffic efficiency, and infotainment services. Key functional and performance requirements for *safety* have already been described by the European Telecommunications Standards Institute's (ETSI) technical committee on ITS. [23]

As we are aware, the Intelligent Transport System (ITS) involves a mix of manual and self-driving vehicles along with VRUs, impacting traffic, but also CAVs' and VRUs' safety. While AVs can adapt based on information from signals, manual drivers rely on situational awareness. To address this, a deep learning model has been proposed by authors in [78] for a 5G-enabled ITS that uses natural-driving and driving trajectory datasets in long short term memory networks. Their function computes the probability matrix of each lane change intention, achieving an 85% accuracy rate in the decision layer.

V2X use cases have also been identified by 3GPP [6], taking into account services and parameters defined in the first release of ETSI ITS [23]. In this group of use cases the maximum tolerable latency is 100 ms, while the target radio layer message reception reliability is 95%. These use cases assume a single enabling technology, namely cellular based V2X communication. Enhanced V2X (eV2X) use cases [7] have been defined by 3GPP as part of Release 15, including more advanced use cases such as cooperative intersection control *(Fig. 1.13)*, lane merging*(Fig. 1.12b)*, and platooning*(Fig. 1.12a)*, which have more stringent requirements.

The rest of this section introduces some of these potential 5G-V2X use cases discussed in literature which put together may form ITS in the future, bringing Connected Mobility to be a lived reality.

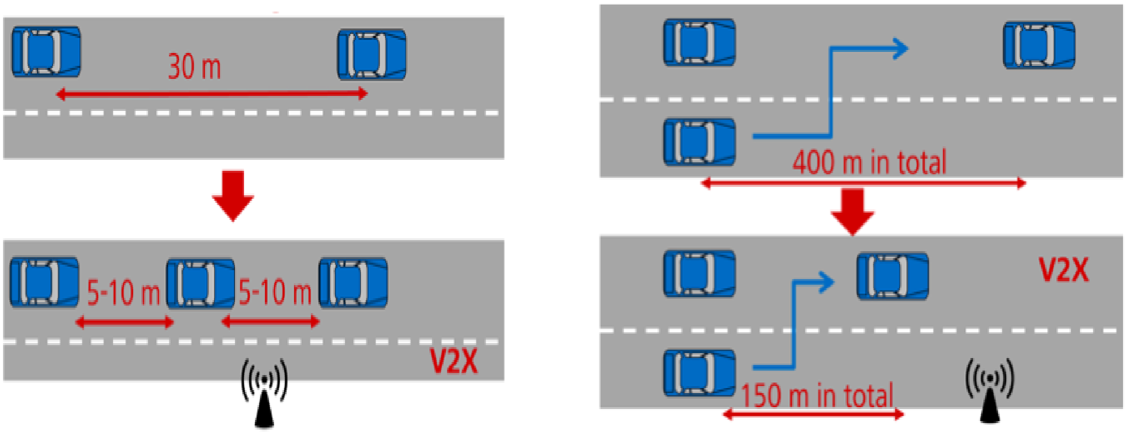
1.6.1. Navigation and Path Planning

The first potential use case of 5G based V2X is in Navigation and Path Planning. In order to revolutionize road transportation, ACVs need to utilise 5G for local perception and controlling short-range vehicles. Navigation is a critical function, requiring access to road network data to plan routes from source to destination. Autonomous navigation would involve path planning, obstacle detection, avoidance, and finding the safest and most efficient travel route. [36]. To this end, autonomous navigation would depend on localization, planning and control, as basic requirements to ensure Connected Mobility.

Current Challenges with Navigation and Path Planning include, but is not limited to non-connected AVs relying on sensors such as radar, lidar, and camera to receive signals, but each device faces unique challenges. Camera devices struggle with poor climatic conditions, while radar struggles to differentiate object types due to its longer wavelength. Lidar is costly and can be inaccurate in bad weather conditions like fog and snow. Constructing maps from lidar and camera inputs is a difficult and time-intensive process. Additionally, predicting agent behavior is a safety challenge, as AVs struggle to sense the behavior of other objects and infrastructure, including human error.

In Connected Mobility, CAVs are like powerful mobile devices equipped with sensors alongwith computational resources. Current efforts for automated driving usually involve a non-cooperative approach that aims to replace human drivers with robot drivers consisting of sensors and software in the vehicle. However, this approach has minimal impact on road throughput and safety. Connected vehicles, whether automated, tele-operated, or human-driven, have the potential to cooperate and improve traffic flow on highways, intersections, and parking lots, thereby enhancing safety, and reducing energy consumption.

Proactive communication of locations, speeds, and trajectories is beneficial in platooning, Cooperative Adaptive Cruise Control (CACC), and lane merging, as it shortens the time and space required to perform a maneuver. Connected automated parking use case utilizes communication for centralized control and planning, which combined with on-board



(a) Platooning/Cooperative Adaptive Cruise Control (b) Lane merging

Figure 1.12: 5G-V2X use cases

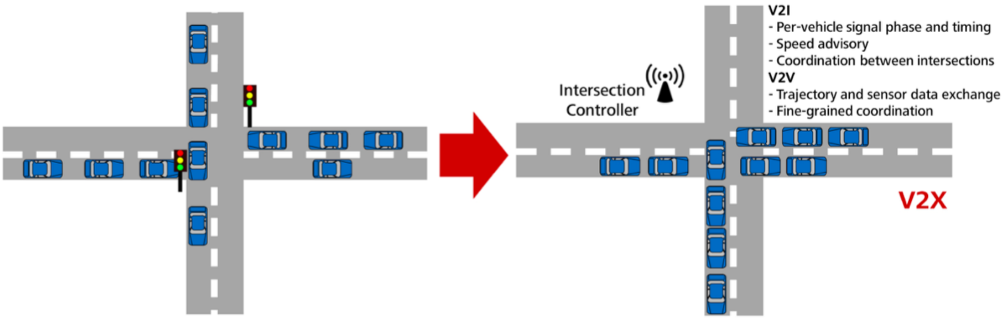


Figure 1.13: 5G assisted-Cooperative Intersection Control

sensors (OBS), reduces the required lateral and longitudinal spacing between vehicles, halving the space needed to park a vehicle. Cooperative intersection control enables more efficient intersection operation by informing vehicles about signal phase and timing, dynamically adjusting speed, and coordinating flow through multiple intersections based on traffic conditions. In the table 1.3, the primary 5G-V2X use cases requiring navigation and path planning and their vital performance requirements are presented in terms of communication latency, reliability, and expected data rate per vehicle. Each type of use case specifies a particular set of functions that a CAV must perform:

- **Cooperative awareness**: Warning and increase of environmental awareness (e.g., Emergency Vehicle Warning, emergency electronic brake light etc.) as illustrated in *Fig. 1.14*.
- **Cooperative sensing**: Exchange of sensor data (e.g., raw sensor data) and object information that increase vehicles' environmental perception. *Illustration 1.15*

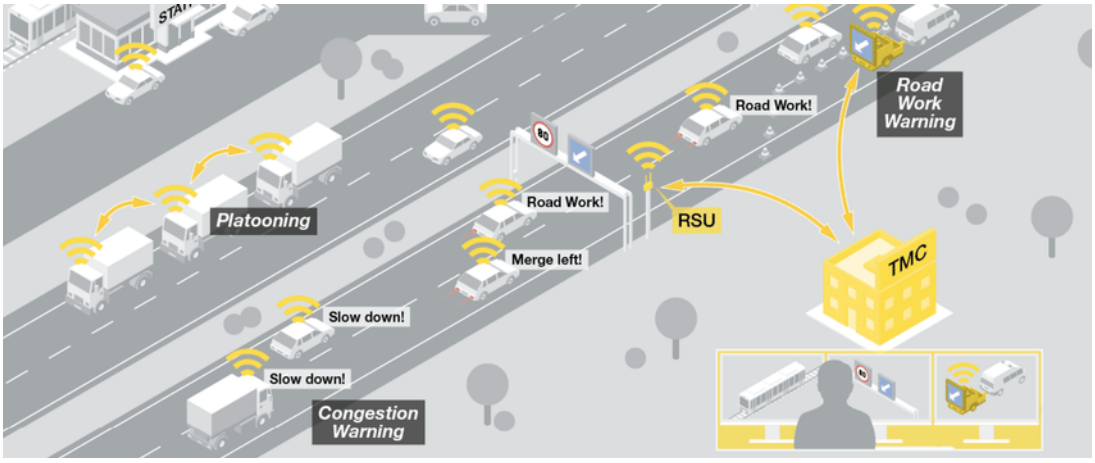


Figure 1.14: The CAM (Cooperative Awareness Message), depicted as yellow beacons, broadcasts a vehicle's position, direction, speed, and other data. It is analyzed by ITS stations to detect events, which are then communicated through the DENM (Decentralized Environmental Notification Message), depicted as messages in grey box, specifying the event, time, and location. Both CAM and DENM have a range of several hundred meters and are instantly received by all ITS Stations in range.

serves as an example

- **Cooperative maneuver**: includes use cases for the coordination of the trajectories among vehicles (e.g., lane change, platooning, CACC, and cooperative intersection control, which are shown in *(Fig. 1.13), (Fig. 1.12b), and (Fig. 1.12a).*
- **Vulnerable Road User (VRU)** in V2P scenario: notification of pedestrians, cyclists etc. as depicted in *Fig. 2.3.*
- **Traffic efficiency**: update of routes and dynamic digital map update.
- **Teleoperated driving**: enables operation of a vehicle by a remote driver.

Use Case Type	**V2X Mode**	**End-to-End Latency**	**Reliability**	**Data Rate per veh. (kbps)**
Cooperative Awareness	V2V/V2I	100ms-1sec	90-95%	5-96
Cooperative Sensing	V2V/V2I	3ms-1sec	>95%	5-25000
Cooperative Maneuver	V2V/V2I	<3ms-100ms	>99%	10-5000
Vulnerable Road User	V2P	100ms-1sec	95%	5-10
Traffic Efficiency	V2N/V2I	>1sec	<90%	10-2000
Teleoperated Driving	V2N	5-20ms	>99%	>25000

Table 1.3: Performance Requirements of 5G use cases derived from [7]

CAVs equipped with 5G-V2X share fast and reliable information, allowing them to make

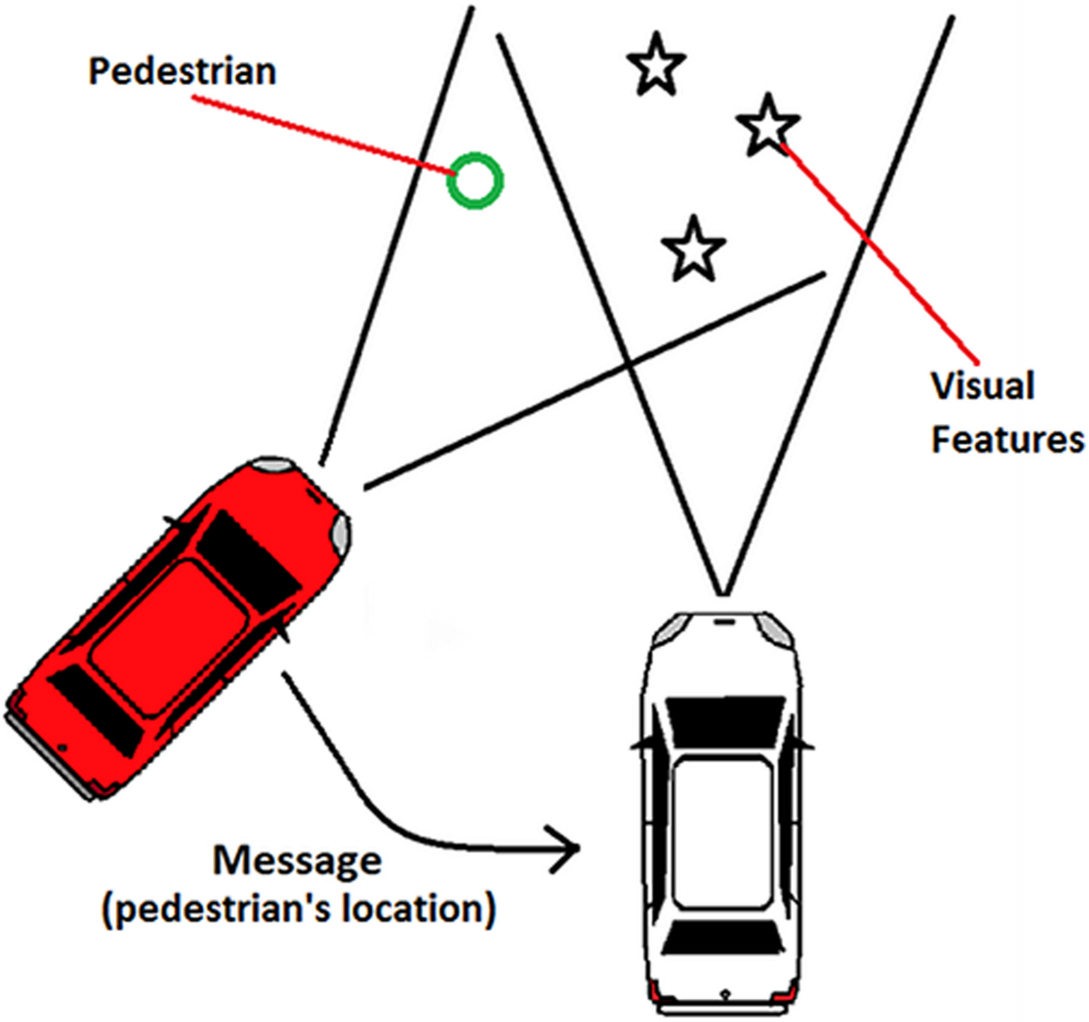


Figure 1.15: Cooperative Sensing/Perception: The vehicle in red shares raw sensor data with the vehicle in white to prevent pedestrian collision

highly predictive decisions. In addition, V2X wireless sensors provide a 360-degree view and can detect non-line-of-sight objects, enabling CAVs to sense a wide range of areas. 5G-enabled CAVs can achieve more precise location positioning, and with the integration of artificial intelligence (AI), they can make dynamic decisions more quickly and accurately. *Fig. 1.16* illustrates the use cases' stringent requirements, according to *table 1.3*. Higher value represent more stringent requirement (e.g. larger range or lower latency). While neither of the use case categories results in high requirements in all dimensions, combined they ask for a communications system that is able to support long range, low latency, high reliability, and high data rate, in favor of 5G-V2X communications.

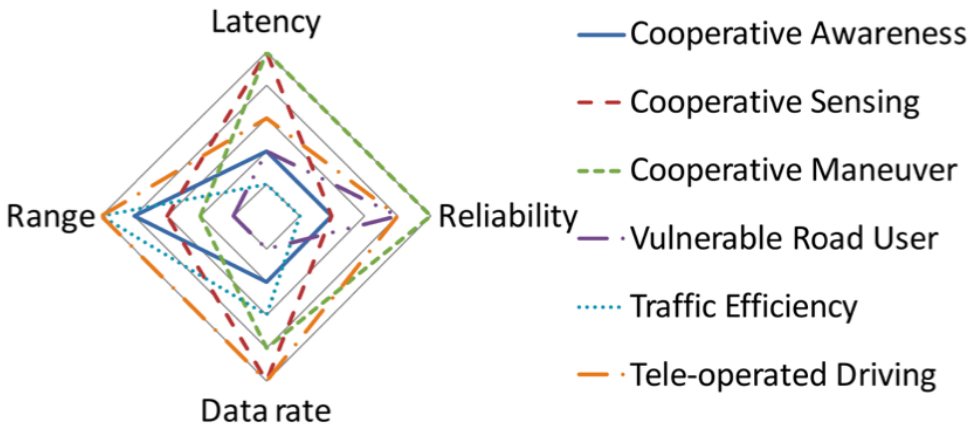


Figure 1.16: Performance requirements 5G-V2X

1.6.2. Teleoperated Driving

The next potential use case for 5G in Vehicular communication is Teleoperated Driving (ToD). Vehicles are expected to be connected to ITS application servers through V2N for traffic management services. There is a specific use case, especially for cellular technologies, i.e. vehicle teleoperation on public roads. This does not require strict latency, can operate with moderate reliability but has very high range and reliability requirements, as referred to in *Fig. 1.16*.

ToD on public roads involves remote control of vehicles over the network by a remote operator, who can control one or multiple vehicles simultaneously with the help of sensors mounted on the vehicle. Vehicle teleoperation could be used alongside automated driving as a transition technology or to complement it in complex driving situations. With the potential for high reliability, availability, and sub-10 ms end-to-end delays (*refer table 1.3 and Fig.1.17*), 5G network could enable connected autonomous teleoperated vehicles.

1.6.3. Identifying Malicious Vehicle

The next potential use case of 5G V2X communication comes in with identifying Malicious Vehicle in the realm of Connected Mobility. AVs primarily rely on radar sensors and light detection and ranging sensors to detect nearby circumstances. However, the reliability of these high-end sensors is limited when a vehicle enters an area with reduced visibility or over longer distances. To enhance data exchange between vehicles, one alternative solution is to use roadside equipment. However, there are risks associated with data sharing, such as when a malicious vehicle intentionally sends fake data to manipulate

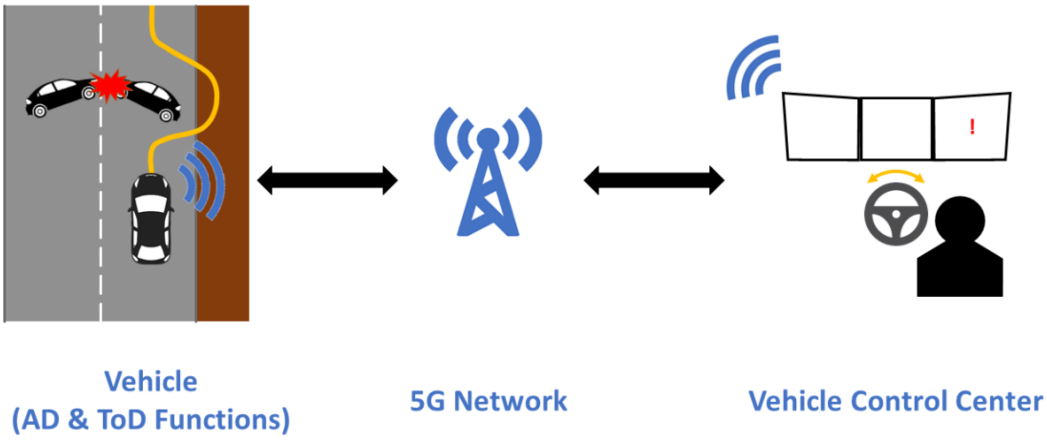


Figure 1.17: ToD function as a part of Autonomous Driving

receivers or when faulty sensors communicate incorrect data. If AVs rely on incorrect information provided by the source vehicle, they may switch lanes or accelerate faster, posing significant risks to human life. Therefore, it is essential that the vehicle detects and filters out incorrect information as the decision-making process of AVs heavily relies on shared data and sensors. To address these challenges, a novel approach was proposed in [58] to support a host vehicle in verifying the motion behavior of a target vehicle and the truthfulness of sharing data with other vehicles in the network. The detection system at the host vehicle recreates the motion behavior of the target vehicle by extracting positioning information from received V2V messages. The next states of the vehicle are predicted based on the unscented Kalman filter, and the predicted trajectory checkpoints are periodically corrected with a reliable measurement source, namely 5G V2V multi-array beamforming localization. If there is any inconsistency between the estimated position and the reported position from V2V, the target vehicle is classified as abnormal.

1.6.4. Object Detection/Collision Avoidance

Another potential use case for 5G-V2X communication is in detecting objects to avoid collision. These objects can be another vehicle, pedestrians or other VRUs.

As we are aware AVs generate vast amounts of data, including video streaming, sensor data, object detection, and lane condition. Providing cloud services to AVs is a significant challenge due to concerns about latency and security. In their study, the authors of [51] have suggested an architecture at the network edge for 5G-enabled vehicular networks to address the latency issue,featuring a computer vision application for object detection. According to their experimental results, the proposed 5G-enabled vehicular network achieved a round trip time of 49.2 ms to transfer a message from the vehicle to the server. *Fig. 3.2* illustrates object detection in AVs. Their object detection algorithm can detect the object, wherein Gaussian filter techniques have been utilized to minimize granularity for greater accuracy.

To prevent collisions and ensure safe navigation, precise localization is essential for CAVs. Although GPS provides an accurate position, its accuracy is limited to 10 meters higher or lower, whereas the precise position of AVs should be no more than 5 meters. To achieve accurate vehicle positioning, the use of 5G communication technology for cooperative localization (CL) is proposed in [52], which introduces a CL approach for multi-modal fusion between AVs. The proposed model employs a Laplacian Graph Processing framework, where all vehicles serve as vertices in a graph and communication paths function as edges. The experimental results show that the proposed 5G model has a faster response time and a higher GPS accuracy rate.

This is the particular 5G-I2V use case that we are concerned with in designing and implementing our P-ICWAS, which is discussed in details in the next two chapters.

2 | Intersection - Collision Warning and Avoidance Systems

2.1. Introduction

Intersections and pedestrian crossings are critical components of the road network where vehicle-VRUs collisions occur frequently. European Commission describes Vulnerable Road Users (VRUs) as "non-motorised road users, such as pedestrians and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation". Intersections are the places where numerous traffic flows merge and interact, making them accident-prone areas. In the United States, traffic intersections and neighbouring areas account for 47% of all traffic incidents (National Highway Traffic Safety Administration, 2015). According to India's 2015 annual traffic collision statistics, intersections and pedestrian crossings account for almost 49% of all traffic collisions (MORTH, 2016).In Europe, 20% of road crashes occur at intersections.

Available literature strongly suggests that the leading causes of violent fatalities around the world is road traffic collisions, and pedestrians are amongst the most vulnerable with respect to such incidents. Moreover, speed has been found as a significant risk factor in these collisions, affecting both the likelihood of a collision and its severity. [30]

Hence, our motivation was to design a 5G based Vehicle-to-Infrastructure (V2I) collision warning system (CWS) and conduct experimental tests to improve driver performance/comfort and enhance safety at pedestrian crossings, irrespective of it being a signalised or unsignalised crossing.

2.2. Literature Review and State of Art

2.2.1. Distractions

Distractions on the road occur when the driver attends to a secondary task unrelated to driving. Three causes of distraction were found by Strayer et al.

1. Cognitive (when attention is diverted from the driving task)
2. Manual (when the driver's hands are not on the steering wheel)
3. Visual (when the driver's eyes are not on the road)

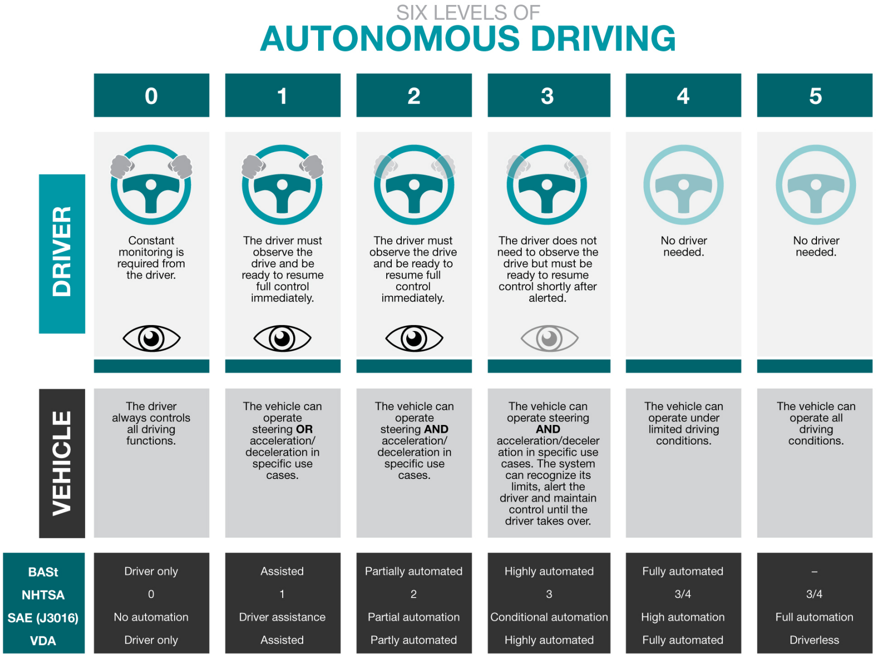
To assist a driver in case he is distracted by any measure, we have Advanced Driver Assistance Systems (ADAS) to prevent misfortune on the road. We are going to discuss ADAS in the next subsection.

2.2.2. Advanced Driver Assistance Systems

Advanced Driver Assistance Systems (ADAS) are designed to assist drivers in critical situations while they are operating the vehicle. Based on the capabilities of ADAS, the Society for Automotive Engineers (SAE) taxonomy [32] has defined six levels of vehicle automation driving, from 0 to 5, as reported in *Fig. 2.1.* These levels represent how much has the control shifted from the driver to the autonomous system to ensure safer driving. For higher levels the driver will have less control on the vehicle, so the system will greatly help the driving, and vice versa. The maturity and affordability of new technologies have turned the possibility of having self-driving cars into reality. Self-driving functions being implemented in commercial cars is already a lived reality. Consequently, many nations are getting ready to adopt new laws allowing autonomous vehicles on public roads.
The levels of driving automation are defined as follows, according to SAE taxonomy:

- Level 0 (No automation): The human driver has total control of the vehicle. Most of the commercial cars present on the road still have this level of automation. System like emergency braking still represents a Level 0 automation, as they do not assist during driving, but only in emergency situations.
- Level 1 (Driver assistance): Vehicles with control systems that partially help the driver in driving, are included in this level, such as lateral and longitudinal control of motion.
- Level 2 (Partial driving automation): A vehicle with more than one ADAS installed

is usually in this class. These systems are in control of many aspects of the driving action, even though the driver can always take control of the car. A level 2 means a system controlling lateral and longitudinal tasks at the same time. Examples include autopilot, adaptive cruise control, lane maintaining assistance.



SIX LEVELS OF
AUTONOMOUS DRIVING

	0	1	2	3	4	5
DRIVER	Constant monitoring is required from the driver.	The driver must observe the drive and be ready to resume full control immediately.	The driver must observe the drive and be ready to resume full control immediately.	The driver does not need to observe the drive but must be ready to resume control shortly after alerted.	No driver needed.	No driver needed.
VEHICLE	The driver always controls all driving functions.	The vehicle can operate steering **OR** acceleration/deceleration in specific use cases.	The vehicle can operate steering **AND** acceleration/deceleration in specific use cases.	The vehicle can operate steering **AND** acceleration/deceleration in specific use cases. The system can recognize its limits, alert the driver and maintain control until the driver takes over.	The vehicle can operate under limited driving conditions.	The vehicle can operate all driving conditions.
BASt	Driver only	Assisted	Partially automated	Highly automated	Fully automated	–
NHTSA	0	1	2	3	3/4	3/4
SAE (J3016)	No automation	Driver assistance	Partial automation	Conditional automation	High automation	Full automation
VDA	Driver only	Assisted	Partly automated	Highly automated	Fully automated	Driverless

Figure 2.1: Six levels of Automation driving levels

- Level 3 (Conditional driving automation): This level presents a forward step from a technological point of view. The car is equipped with logic and sensors that can take decisions based on the external environment and substitute some driver commands. This means that the car in a particular Operational Design Domain (ODD) can perform lateral and longitudinal control and provide a suitable time to the driver to regain control of the vehicle in case the system is not able to continue alone. A good example is an automatic overtake system, that can evaluate the traffic conditions and, after the approval of the driver, perform the maneuver automatically.
- Level 4 (High driving automation): The automated system takes care of the entire driving mechanism including monitoring the current environment for detection of dynamic changes and controlling of motion as per the changes. This would mean that in a specific ODD, the vehicle can drive alone. In case of an emergency or the occurrence of a strange situation, it can do some safety fallback maneuvers like stopping at the side as a condition of lower danger. The vehicles in this level can already be set in self-driving mode, where often the human action is not necessary

at all.

- Level 5 (Driverless): This level represents the full automation of vehicle driving, where steering wheel and pedals can be removed, since no input is ever required from the driver. All the failures and dynamic decisions are also controlled by the system throughout the trip. These systems are still under development, and are one of the most discussed topic in the automotive field.

In this context, in the following we are going to describe 2 systems directly related to pedestrian protection: Advanced Emergency Braking (AEB) and pedestrian Forward Collision Warning Systems (FCWS) in the next subsection.

2.2.3. Autonomous Emergency Braking and pedestrian Forward Collision Warning Systems

According to EU legislation, Advanced Emergency Braking (AEB) is defined as the system comprised of exteroceptive sensor(-s) and the control module which can automatically detect a potential collision and activate the vehicle braking system to decelerate the vehicle with the purpose of avoiding or mitigating a collision. Herein, exteroceptive sensors measure the state of the environment (mapping, temperature, etc.). From an engineer's point of view, exteroceptive sensors are mainly absolute measurement sensors, which generally have a lower acquisition frequency than proprioceptive sensors. The best known example is probably the GPS.

The terms "Advanced", "Automatic" and "Autonomous" in the context of emergency braking for low-level vehicle autonomy seem to be used interchangeably [3, 4].

According to Euro NCAP, AEB has three characteristics:

- Autonomous: the system acts independently of the driver to avoid or mitigate the accident.
- Emergency: the system will intervene only in a critical situation.
- Braking: the system tries to avoid the accident by applying the brakes.

Regulation No. 131 of the Economic Commission for Europe of the United Nations (UN/ECE) states that the emergency braking phase is the interval starting when the AEB system emits a braking demand for at least $4m/s^2$ deceleration to the service braking system of the vehicle [1]. Society of Automotive Engineers (SAE) organization, in SAE J3016 (Levels of Vehicle Automation) defines Automatic Emergency Braking as a function that is limited to providing warnings and momentary assistance to a modern car [4].

AEB differs from pedestrian-forward collision warning (FCW), which only warns the driver and does not automatically apply the brakes to the vehicle. FCW systems make use of auditory, visual, and haptic interfaces and it is required to balance driver acceptance with effectiveness in terms of allowing time for a driver to brake the vehicle. Studying brake reactions of distracted drivers to pedestrian Forward Collision Warning systems, Lubbe [48] concludes that the most successful FCW setting for preventing collisions in comparison to any other settings was an audio-visual warning to the driver with an added brake pulse. This setting ensured that all the drivers reacted to the collision warning. The collision avoidance was most successful when brake pulse warning was deployed as it had the quickest reaction times and the slowest driving speeds upon break application. Consequently, it was taken into account while designing our P-ICWAS, that it would initially warn the driver, followed by taking over and braking autonomously, if the driver fails to react to the warning in order to prevent collision.

2.2.4. Pedestrian Crash Prevention System

Figure 2.2: PCP System: A V2N-less Architecture

In earlier years, an alternative to ADAS was The Pedestrian Crash Prevention (PCP) system *(Ref Fig. 2.2)*. It is a safety technology utilized in on-road vehicles with a low level of automation and no external connectivity. The PCP system identifies pedestrians who are about to enter the vehicle's path with the help of forward-facing cameras, radar sensors, or LIDAR. The software of the system employs algorithms to determine whether the object is a pedestrian or not, warns the drivers of a possible pedestrian-vehicle collision, and applies the brakes more quickly than a driver would have. However, and not all pedestrian crashes can be avoided by PCP systems [29]. The effectiveness and reliability of PCP systems rely on many factors such as sensor accuracy and cover area [35], system activation time and latency [29], and maximum deceleration [35].

The empirical results of the research work [49] conducted to check the effectiveness of these systems with no external connectivity indicates that in hazardous pedestrian-vehicle conflict situations, the success in avoiding the crash has been 70 percent. Furthermore, the test data shows that some pedestrians went undetected in these tests. In another article by Shetty et al [69], it has been demonstrated that without connectivity, even fully autonomous vehicles are unable to ensure safety, challenges being;

1. Occlusions,
2. Traffic Violation,
3. Behavior Prediction Uncertainty.

To this end, an I2V communication of data is all the more essential to higher driving automation.

2.2.5. Vehicle to Pedestrian Collision Prevention Systems

In a V2P approach to protect VRUs from collision *(Ref Fig. 2.3)*, smartphones of pedestrians and moving vehicles must communicate periodically in order to allow collision detection, and after obtaining the beacons, a Collision Detection Algorithm (CDA) is used to detect collisions. These tasks may not be a big problem for cars, but for smartphones with limited resources, they may present a significant challenge. Especially when more data from other vehicles is required and a more complex CDA is used, it would be difficult on smartphones in terms of battery consumption and processing time.

Nguyen [57] has explored the possibility of using V2P communication to prevent collisions using Multi access Edge Computing (MEC) approach. In their approach, they need to run the collision detection algorithms on the VRU's smartphones in order to determine the criticality of the situation. While using MEC approach provides them some relief by improving system latency, this approach still uses the 4G LTE networks. In our case,

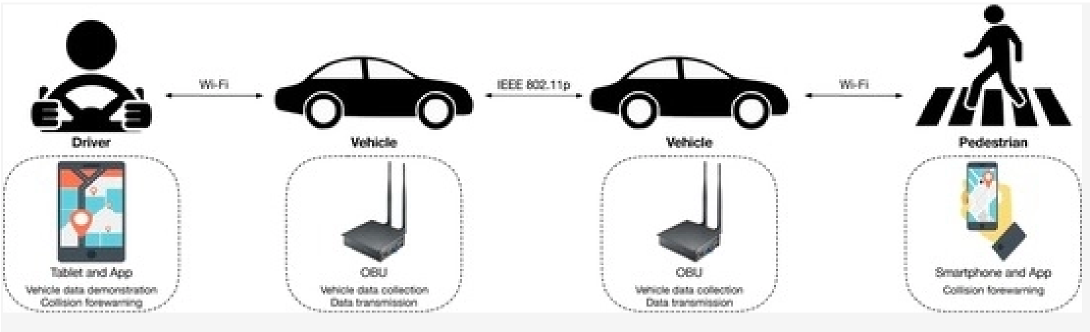


Figure 2.3: V2P Collision Prevention System Architecture

owing to the incorporation of the 5G network to transfer data, we aim to solve the issue of latency and efficiency. Also, in comparison, our research is independent of the VRUs possessing a smartphone in working condition to get detected. Various pre-crash scenarios and varying capabilities of VRUs impose the constraint of functionality and accessibility of smartphone. The system that we aim to design (P-ICWAS) overcomes this problem by evaluating collision with external infrastructure, focusing on an I2V infrastructure to prevent pedestrian collision, and not a V2P collision prevention system.

2.2.6. Choice of Time to Collision as our parameter

The driver-pedestrian encounter, i.e., the simultaneous arrival of a driver and a pedestrian at the crosswalk, is a traffic event characterized by a continuous interaction over time and space between the two road users [74]. In actuality, the pedestrian decides whether to cross at a zebra crossing based on the perceived speed and distance of the incoming vehicle. At the same time, the driver decides whether to give the pedestrian priority based on the projected time of arrival at the crosswalk. Such a disagreement has the potential to result in a collision since the two traffic participants may move into a collision path during the encounter phase.

The collision would occur if, for example, the driver's attention levels, his/her ability to control the vehicle, or the vehicle's dynamic state were not adequate for a safe stopping behaviour [13]. Therefore, since the goal of our thesis was to develop an efficient and effective Collision Warning system for assisted or autonomous driving, there was a need to use a Risk Assessment Model (RAM) that can objectively and quickly capture the severity of the encounter process. In fact, a RAM that can fully understand the relationships between behavior and risk is essential to adequately judge the system's intervention timing [77].

Collision Risk of a VRU may be assessed using various indicators based on collision closeness. These indicators utilize time-based, distance based, declaration based, probability based calculation or other miscellaneous calculation to identify the closeness of a collision. Some of the commonly used indicators for Vehicle - Pedestrian Interaction are[61]:

- Time-To-Collision(TTC) - It is defined as the time left for the vehicles moving at constant speed without altering the trajectory to reach the point of conflict. It can be calculated using the relative distance and the relative velocity. If the the TTC falls below a threshold (TTC_{min}), a critical event is triggered.
- Modified Time-To-Collision(MTTC) - Time-to-Collision may overestimate or underestimate the closeness of collision depending whether the vehicle is decelerating or accelerating. MTTC takes into account the acceleration/deceleration of the vehicle to provide a more accurate TTC.
- Time-To-Steer(TTS) - It is defined as the time to reach the last point on the trajectory at which it is plausible to perform a steering maneuver to avoid Collision
- Time Advantage (TADV) - It represents at each instant the amount of time that would pass between the passage of the first and second users through the same conflict zone if both continued on their current trajectories and relative speeds. It is the temporal extension of the Post-Encroachment Time (PET) concept. Indicators over 2-3 seconds show that a user has a temporal advantage over his opponent in a race across the same spatial zone and is likely to pass first.
- Time-to-Zebra (TTZ) - It is the Time to Collision of a Vehicle where zebra crossing is the point of conflict. The pedestrian velocity is equal to zero. TTZ also considers the reaction time of the driver/AV and the deceleration capabilities of the vehicle.

Referring to the Risk Assessment Model developed by Baldo in 2021 [13], we chose to use the parameter of Time to Collision over Time Advancement to design our Collision Warning System. We utilize a modified version of TTC that combines the MTTC and TTZ calculation methods for calculation of Warning time and Collision time for multiple, moving pedestrians, described in the next section.

2.3. Pedestrian Collision Detection

2.3.1. Curvilinear Coordinate System

A detailed road map is essential for an optimised performance of certain ADASs and navigation of CAVs. Road maps can be used to implement platooning operations, describing road boundaries, etc. It can help in the right positioning and trajectory planning in case of complex scenarios like roundabouts, where the distance of an object perceived by sensors like LIDARs and camera may not be the actual distance to reach that object. [31, 53]

In our specific implementation, a local curvilinear road map is generated from Cartesian global reference for the development of the algorithm. Different models can be employed for the task. Cartesian coordinates (X-Y) of the map are fitted using third order polynomials that locally approximate the road centerline angle θ_c as a function of the curvilinear abscissa s. Even though Cubic splines model are computationally demanding and difficult to use in real-time applications[75], they are suitable for our algorithm as they provide smooth continuous and differentiable curvilinear coordinates and map data is an initialization parameter for the algorithm and is not needed to be updated in real time. In case the algorithm is used simultaneously with other functions like lane change which have dynamic path generation, a simpler model like poly-line or Lanelet method may be used to save computation time and power.[31] It is assumed that complete data of road map is available, which is a suitable assumption, as discussed in [37]

Curvilinear pose is defined as curvilinear abscissa, a signed lateral distance and a relative orientation with respect to a reference path describing the center of the lane as shown in *Fig. 2.4*.

The single track dynamic model has two translational degrees of freedom, X & Y, and one rotational DOF about the Z axis. The longitudinal and translational velocities (V_x, V_y) can be represented in s-y coordinate system using the the *eq.* (2.3) *[52, 63]*

$$\begin{aligned}
\dot{s} &= \frac{V_x cos(\xi) - V_y sin(\xi)}{(1 - \theta'_{cs} \cdot y)} \\
\dot{y} &= V_x sin(\xi) + V_y cos(\xi) \\
\dot{\xi} &= \omega - \theta^{'}_{cs} \cdot \dot{s}
\end{aligned} \tag{2.1}$$

Here ξ , heading angle error, is calculated as the difference between the heading angle(ψ)

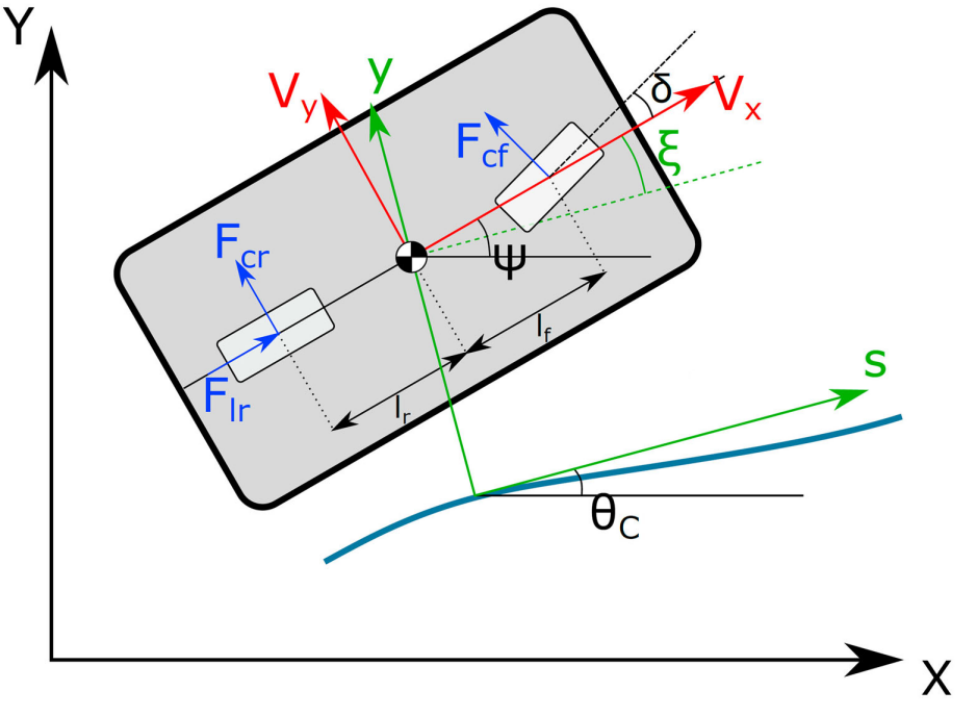


Figure 2.4: Representation in S-Y coordinate system.
Source: NMPC trajectory planner for urban autonomous driving[53]

and the angle of tangent of the path. θ'_{cs} is the curvature of the path at the s coordinate of the point of tangent. In the single track dynamic model, the acceleration of the vehicle along the path can be derived by differentiating *eq.*(2.3).

In an ideal case, where the vehicle is able to follow the planned path precisely at a constant velocity i.e. $\xi, y \to 0$, we have

$$\begin{aligned} \dot{s} &\simeq V_x, \\ \dot{y} &\simeq V_y, \\ \omega &\simeq \theta'_{cs} \cdot \dot{s}, \\ \ddot{s} &= 0 \end{aligned} \tag{2.2}$$

More in general, a vehicle which is able to maintain a heading angle error equal to zero with a constant offset from the path, y_0 (can be equal to zero), at a constant speed, the state of the vehicle can be represented as,

$$\begin{aligned}\dot{s} &= \frac{V_x}{(1 - \theta'_{cs} \cdot y_0)} \\ \dot{y} &= V_y \\ \omega &= \theta'_{cs} \cdot \dot{s}\end{aligned} \tag{2.3}$$

2.3.2. Pedestrian Collision Calculation

It is important to identify the critical point/area along the path of the vehicle where there is a risk of collision. The calculation of collision risk of a pedestrian is done using the following steps:

1. Calculate the distance between the Vehicle and the pedestrian along the path.
2. Calculate the time to reach the pedestrian.
3. Calculate the position of the pedestrian at the arrival of vehicle.
4. Check if the pedestrian is in the obstruction boundary of the vehicle.

Conversion to the curvilinear coordinate system allows to use equations of linear motions in the longitudinal direction of motion, for calculation of future position of the pedestrian and the vehicle as depicted in *eq.*(2.4).

$$s(t) = u \cdot t + \frac{1}{2} a \cdot t^2 \tag{2.4}$$

The time that a vehicle takes to reach, Time-To-Reach (TTR), can be calculated using the relative distance along the path, Δs, the relative velocity in s-coordinate and the relative acceleration in s-coordinate.

$$\Delta s = s_{ped} - s_v \tag{2.5}$$

$$TTR = \begin{cases} -\dfrac{\Delta S}{v_{r,s}} & \forall v_{r,s} < 0, a_{r,s} = 0 \\ -\dfrac{v_{r,s} - \sqrt{v_{r,s}^2 - 2\Delta s \cdot a_{r,s}}}{a_{r,s}} & \forall v_{r,s} < 0, a_{r,s} \neq 0 \\ -\dfrac{v_{r,s} + \sqrt{v_{r,s}^2 - 2\Delta s \cdot a_{r,s}}}{a_{r,s}} & \forall v_{r,s} \geq 0, a_{r,s} \neq 0 \end{cases} \tag{2.6}$$

Here, s_{ped} and s_v are the s-coordinate position of pedestrian and vehicle respectively and $v_{r,s}$ and $a_{r,s}$ are the velocity and acceleration of the vehicle w.r.t. the pedestrian respectively. TTR can not be calculated for $v_{r,s}$ & $a_{r,s} \geq 0$ as the relative distance between the pedestrian and the vehicle does not decrease and for $v_{r,s}^2 - 2\Delta s \cdot a_{r,s} < 0$. It is to be noted that the s_v in *eq.* (2.5) is the s-coordinate of the front end of the vehicle. The calculated TTR is used for predicting the pedestrian position along the y-coordinate. It is assumed that the pedestrian walks at a constant speed.

$$y_{ped}(TTR) = y_{ped}(t) + v_{y,ped} \cdot TTR \tag{2.7}$$

Where, y_{ped} is the y position of the pedestrian and $v_{y,ped}$ is the velocity of the pedestrian in y direction.

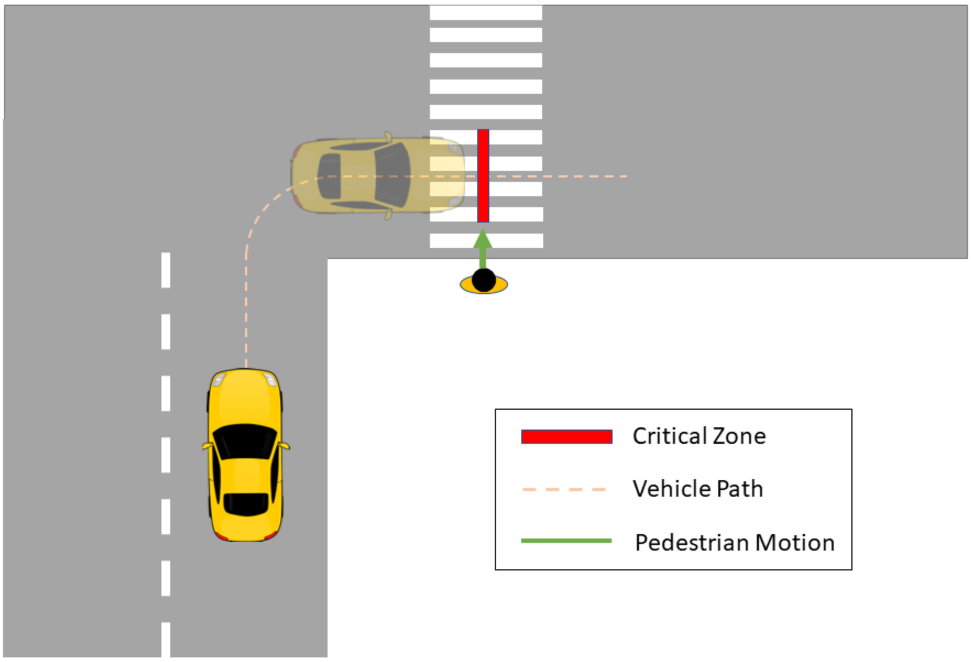


Figure 2.5: Critical Zone

We assume a critical zone in the y direction along the crosswalk. The critical zone consist of the points $(y_v(TTR) + \frac{w}{2} + w_{sz}, y_v + \frac{w}{2}) + y_{sz})$, where y_v is the position of vehicle along the y coordinate, w is the width of the vehicle and w_{sz} is the width of the safety zone around the vehicle. $y_v(TTR)$ can be calculated from velocity and acceleration of the vehicle using *eq.* (2.4). for our case we assume that these quantities are negligible. TTR becomes TTC if the predicted y coordinate of the pedestrian, $y_{ped}(TTR)$ lies within the critical zone, i.e. in TTR amount of time the vehicle will reach the pedestrian and collision will occur. The safety zone can compensate for the real world inaccuracies of the system as well as may prevent starting of the VRU from close passage of the vehicle. Sander et al have demonstrated that having a safety zone of 0.2 m around the vehicle can increase the efficiency of the AEB system significantly at 100% market penetration [67].

If multiple pedestrians are present, above calculations are done for all the pedestrians and the TTC is set equal to TTR of the pedestrian with earliest chance of collision.

$$TTC = min\{TTR_{P1}, TTR_{P2}, TTR_{P3}, ..., TTR_{Pi}, ..., TTR_{Pn}\} \tag{2.8}$$

wherein, n is the number of pedestrians.

Deviation from the designated path

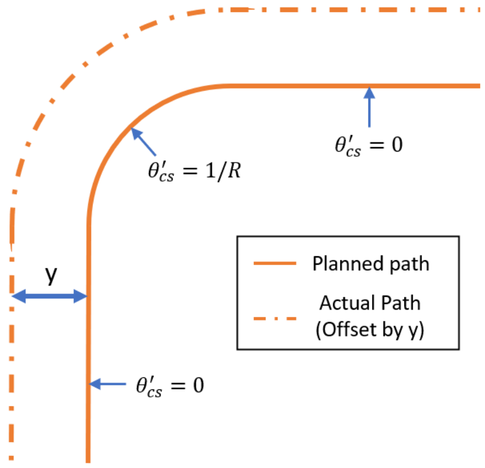


Figure 2.6: Deviated path

If the vehicle deviates from the desired trajectory, we see that velocity along the s-direction varies from the longitudinal velocity of the vehicle, *in reference to eq.* (2.3), even if the longitudinal velocity of the vehicle is constant. This is because $\dot{s}$ depends on the trajectory features θ'_{cs}, vehicle lateral error$y$, and heading angle error ξ. Thus, calculation of relative velocity using $\dot{s}$ may lead to over estimation or underestimation of TTR of the vehicle. For e.g. consider the situation in the *fig 2.6.* The path of the vehicle consists either straight lines or constant radius curves($\theta'_{cs} = \frac{1}{R}$) and the longitudinal velocity is constant. In this scenario, the vehicle is able to follow the path with zero heading angle error but there is an offset in lateral position of the vehicle. The velocity of the vehicle along the s direction is equal to the longitudinal velocity of the vehicle where $\theta_{cs}^{'}$ is equal to 0, but where $\theta_{cs}^{'}$ is finite, the $\dot{s}$ varies by a factor of $\frac{1}{(1-\theta_{cs}^{'} \cdot y)}$.

In the case of underestimation of TTR, it may be treated as added redundancy but in the cases of overestimation, it can be critical. Parameter values related to overestimation can be identified and modified TTC threshold can be used if the those values are observed or else it may be taken care by the added safety distance, discussed in next chapter. If the vehicle is able to follow the path closely or if the trajectory data is updated frequently or updated for large deviations such that the path passes close to the Center of Mass of the vehicle then the effect of the this factor is insignificant.

3 | Pedestrian-ICWAS

Interaction of motorized and non-motorized road users is unavoidable, especially in urban scenarios. Some of these interactions may not always lead to positive outcomes, see 2.1. Both legislators and the automotive industry, are constantly working towards improving VRU road safety. Although, passive safty implementations like helmet, involvement of collision mechanisms in design process etc. help in minimizing the consequences of accidents, but they are effective only in mitigation of damages. Active Safety aims at avoiding the occurrence of accidents. Equipping vehicles with systems like Autonomous Emergency Braking (AEB) can reduce the number of vehicle-to-vehicle as well as vehicle-to-pedestrian accidents by 22%-30%. [50]. Recognizing the benefits of such systems many regulatory bodies have mandated their inclusion in new vehicles being manufactured and have also setup standard testing criteria. Simple Collision warning systems have been identified as an effective technique for avoiding accidents. Perception errors may lead to overestimation of TTC by drivers for objects below certain height. Warning systems can help alert the drivers that the collision may occur sooner than expected. [70]

Active safety systems usually depend on information from On-Board sensors like camera(s), LIDAR, Radars, etc. to predict possible hazardous situations. These sensor rely on Line-of-Sight perception and their performance and be affected by weather, time of day[25] and Occlusion. These issues can be addressed by sensor fusion approach and/or utilizing sensors with better operating range and performance. This may increase the cost of the system for not so substantial improvement. Field of View (FOV) of these sensors may be occluded by moving or parked vehicles, vegetation or other stationary occlusions like buildings as shown in *fig. 3.1*

AEB can still avoid collision or mitigate its severity despite of occlusions but its effectiveness is reduced. A trade off between performance and severity of collision is observed in certain scenarios of occlusion while tuning TTC parameter. [8]. Collision risk in occluded scenarios can be estimated by probabilistic collision risk assessment [43, 46]. These algorithms are computationally demanding as they predict trajectory possibilities without any behavioural data.

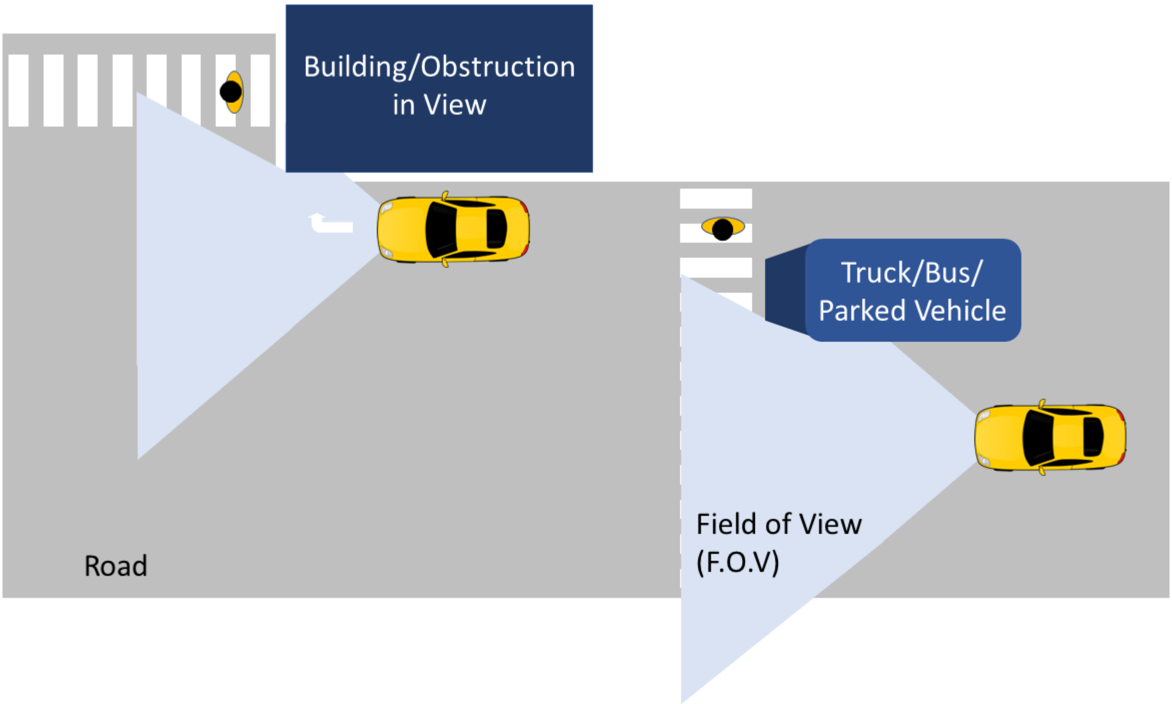


Figure 3.1: AEB Occlusion Scenarios

Another approach to improve collision avoidance is to use Non-Line-of-Sight communication techniques for vehicles and VRUs to notify each other of their presence along with additional information about their state, also known as Cooperative Collision Avoidance(CCA). With the introduction of V2X communication, it is possible to augment the functioning of On-Board sensors and further improve the performance of AEB systems in occlusion scenarios. Min et al use a Bike-to-Vehicle(B2V) communication to calculate collision chances between bike and vehicle traversing through a straight path at an intersection[54]. Similarly, V2P communication is utilized for predicting collision and to avoid collision the local trajectory is modified either on the basis of elastic band type representation, cost function based approach or a potential field approach [28, 42, 51, 76]. In Case of automatic maneuvering to avoid collision, additional road constraints like adjacent lane traffic and road boundaries need to be considered, therefore a detailed knowledge about the environment is required.

To achieve V2P communication, *(see 2.2.5)* VRUs equipped with a dedicated electronic device can actively make themselves aware to approaching vehicles. Smartphones have a high-level of computational power with the ability to communicate over several types of technologies like Wi-FI, Cellular communication (LTE, 5G) and Bluetooth and the ability to localize and calculate the state using global navigation satellite system (GNSS) receivers and motion sensors thereby making them a suitable way of exchanging information between VRUs, vehicles and infrastructure. Additionally, VRUs do not need to adjust to using a new device as they are already using smartphones which used for this purpose by deploying some apps or with little modification. Smartphones can also provide a variety of haptic feedback (Sound, Vibration, Light) to the user to warn them about possible collision. But the effectiveness of these warning may be significantly affected by the position of the smartphone and VRUs' usage of the same. The limiting factor of using smartphones for cooperative VRU protection is however still the size and weight of the devices, for them to be "on" and the battery consumption. Additional, the accuracy of the localization may vary according the price of the smartphone. These limitation may not be as applicable for other VRUs like e-scooter, e-bikes, motorbikes, etc. as the have relatively larger supply of power and a more visible HMI.

The active role of VRU in CCA is an enabling as well as a limiting factor. Alternatively, Infrastructure-side awareness represents a paradigm shift in VRU protection. Here, the road infrastructure is primarily responsible for VRU detection and state calculation. By using a suitable perception system, as for instance a camera installed on a nearby pole, road users, including VRUs, are detected, localized and tracked, as depicted in *fig.3.2* . This information can be encoded into a Collaborative Perception Message (CPM) and transmitted over V2X communication. A fused technique may also be realised which utilizes information other sources like smartphone and perception of other vehicles for accurate and reliable calculations.

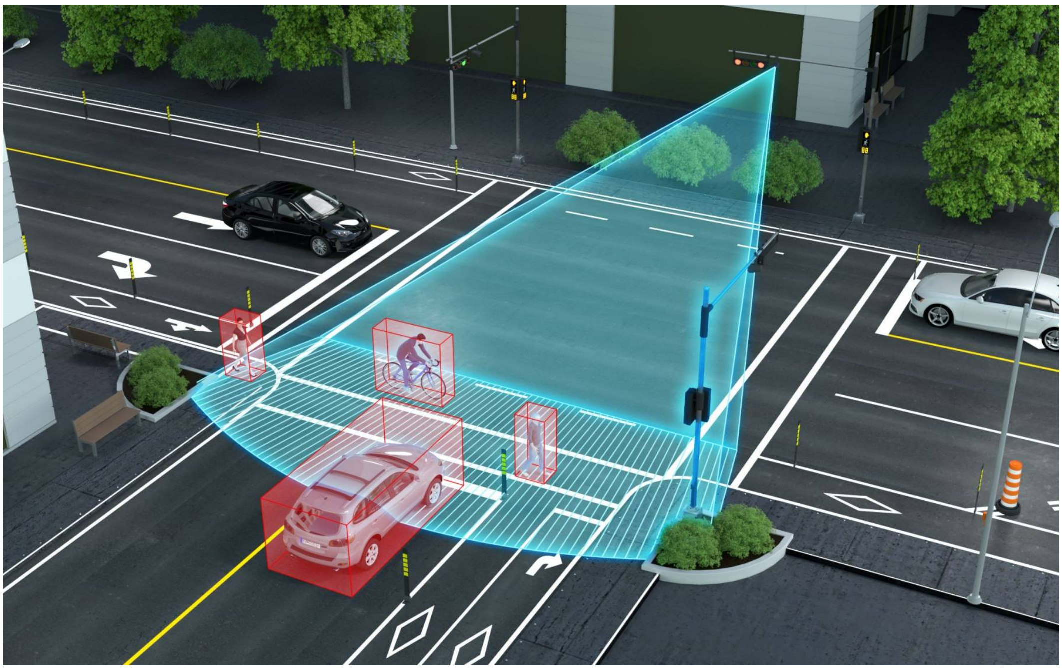


Figure 3.2: Vision based detection of different elements of traffic at intersection

Not only cameras are suited to detect VRUs at urban intersections. In the frame of the German-funded project VIDETEC, DLR and IMST have tested radio-based detection systems for VRU protection. Another very promising technology based on processing radio signals is termed Joint Communication and Sensing and it is foreseen to be a key technology for the future 6th Generation cellular communication. Every node of a distributed array of antennas around the intersection transmits periodic beacons that are received by all other nodes. By intelligent signal processing of the distorted incoming signal, the location and speed of road objects can be obtained.

An Infrastructure based Collision Awareness (V2I) is more objective when compared to smartphone based collision awareness system (V2P) as the hardware used for detection in V2I does not vary. In comparison to a smartphone based V2P, V2I does not suffer from power limitations and the computational power can be optimized better as it only serves a few specific tasks. The architecture, components, and the algorithm of the proposed 5G-based Pedestrian-Intersection Collision Warning and Avoidance System (5G P-ICWAS) are described further in the chapter.

3.1. System Architecture

Intersections are one of the essential components of road networks and they deal with high volume of vehicle and VRU traffic coming from different direction, This makes them an accident-prone zone. While AEB can reduce accidents by 53 - 93 % in case of intersection in turning scenarios in an unbostructed FOV(100deg - 210deg), occlusions are a very common occurrence at an Intersection. A connected- ICWAS has great potential to reduce the number of accidents by timed warnings and AEB. Architecture of P-ICWAS developed is shown in *fig.3.3*.

V2X-based pedestrian collision avoidance system includes pedestrian information acquisition and processing, longitudinal speed planning, longitudinal speed control and vehicle implementation. The pedestrian information is used as the input of the system.

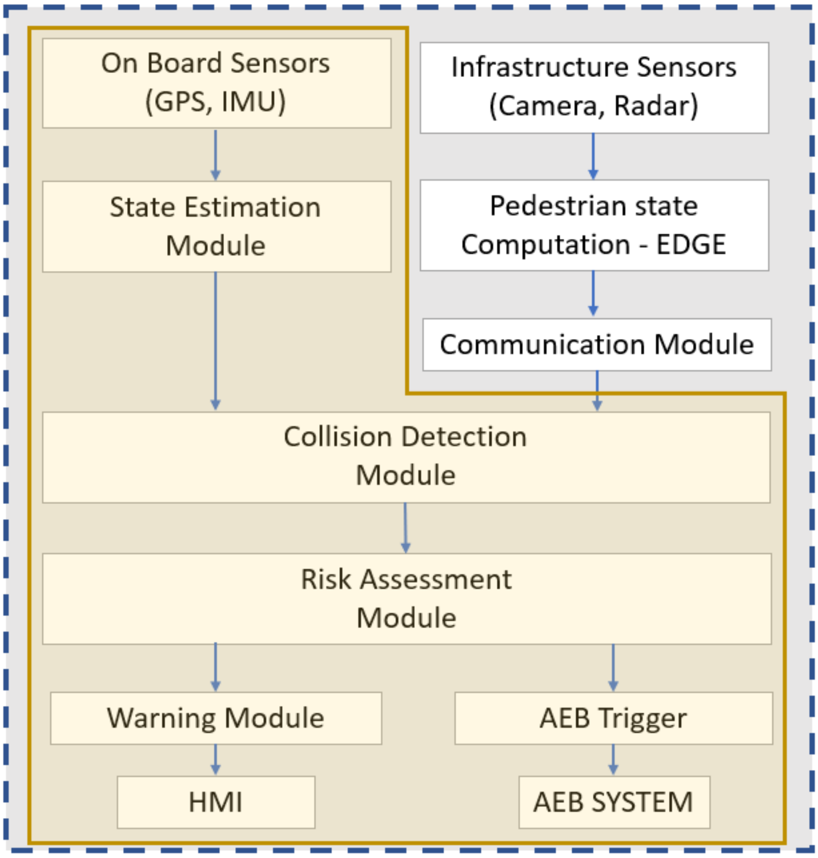


Figure 3.3: P-ICWAS System Architecture
. Yellow shade implies the modules are present on the vehicle.

Pedestrian Information acquisition and processing is done using a camera mounted at the edge of the road and a laptop. This information is then published using MQTT protocol. The On-Board Unit (laptop) subscribes to this message with the help a 5G User Equipment provided by Vodafone. The OBU also subscribes to the information published by onboard sensors. These act as an input for the Simulink based Collision Warning and Avoidance algorithm. The algorithm publishes warning and AEB trigger messages on the ROS network for the HMI and the AEB actuation system.

ROS

The Robot Operating System (ROS) is a set of software libraries and tools that help you build robot applications. It is open source and its simple publisher-subscriber based communication of information makes it easy to use as a communication mode when a lot of different type of devices and architectures of several CPUs and sensors are present on the network. ROS Bags are an easy way to log and reuse information.

3.2. The Scenario of data acquisition

The scenario was designed as follows:

1. The driver arrives at an unsignalized right-turning intersection approximately 200 m from the pedestrian crossing, of which (s)he does not have a clear view, as (s)he is approaching the right-turning intersection.
2. as the driver starts driving, the pedestrian (initially hidden) walks at a 90° angle towards the road and then stops at the edge of the curb.
3. At the moment the vehicle, based on its current speed, is about 4-5 seconds away from the unsignalized pedestrian crossing, the pedestrian enters the zebra crossing and maintains an average walking speed.

3.3. Algorithm

In this section, we will analyse in detail the sub parts of the proposed architecture.

3.3.1. Map Data Initialization Block

In this block, the map data of the route to be taken is initialized from a saved database of data in matlab format (.mat file) at the start of the algorithm and the outputs are UTM coordinates(XX,YY) and their corresponding discretized s-coordinates and θ_c. The map data is initialized at the start of the algorithm. Therefore, If the trajectory is updated frequently, which is a plausible scenario, the map data will be needed to be updated again by restarting the algorithm.

3.3.2. State Estimator Block

The state estimator block *refer fig. 3.4* uses an unscented Kalman filters(UKF) based on single track kinematic model to estimate the velocities, heading angle and positioning of the vehicle in real-time. As expounded in [39], the underlying idea behind UKF is that it is simpler to estimate a probability distribution than approximating a non-linear function or transformation. UKF accounts for the ease of perform a nonlinear transformation on a single point rather than an entire distribution. The magnitude of the error can be expected to be lower in UKF, since the sample of points which belong to the transformation includes contributions of a higher order. The single track kinematic model is reliable for speed range of interest, even though it neglects the effects of rolling radius variation, longitudinal slip and geometrical non-linearities. [66].

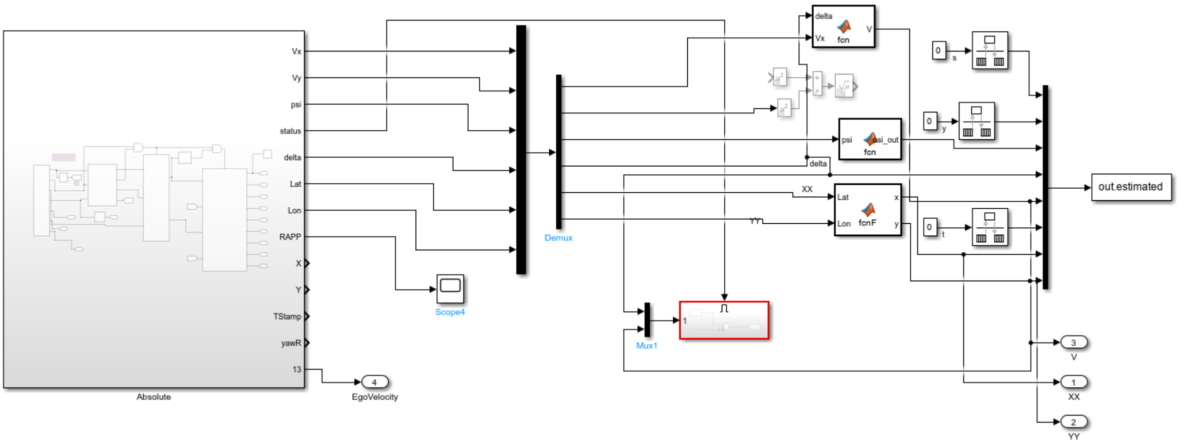


Figure 3.4: State Estimator block

The estimator uses measurements from the following sensors for estimation:

- One GPS receivers located along the longitudinal axis of the vehicle;
- An automotive IMU placed in the estimated centre of gravity (cog);
- Two tone wheels installed within the disk brakes on the rear shaft;
- An incremental optical encoder connected to the DC motor of the Electronic Power Steering (EPS) system of the vehicle.

Real-Time Kinematic(RTK) correction is accounted by the GPS receivers when connected to a ground station. An error of the order of 0.8m/s and 0.03 m/s is observed for position and velocity in East-North-up reference system respectively. The automotive IMU is a 5-axis sensor that provides the linear accelerations along the three principal axis of the vehicle and concurrently the rotational speed around the x and z axis (i.e. the roll and yaw rate respectively). The incremental optical encoder on the EPS system provides the measurement of Steering angle and the tone wheels at the rear axle provide the measurement of longitudinal Velocity of the vehicle. The communication system and update frequencies are shown in the Table 3.1

Inputs from the IMU are considered for the kinematic model of the vehicle and the measurements from the GPS, tone wheels and EPS encoder are used for estimation. State

SENSOR	COMMUNICATION	FREQUENCY
GPS	ETH	10 Hz
IMU	CAN Bus	100 Hz
EPS	Serial Communication by Hard Real-Time System	20 Hz
Tone Wheels	Serial Communication by Hard Real-Time System	20 Hz

Table 3.1: Sensor Frequencies

estimation is to be provided at least at 20 Hz for real time implementation of closed loop control systems in an Autonomous Vehicle [12]. Oversampling of the position is handled by switching between two similar filters triggered by the input of serial data. The first one accounts for GPS measurements and the second one provides the position by integration based on kinematic relationships. The estimator can provide an estimate within 25 ms [16].

3.3.3. Co-ordinate Conversion block

In this block, the UTM Coordinates and velocities are transformed to s-y coordinates, Fig.2.4, according to the data from the Map Data block and State Estimator block respectively. To convert the position coordinates, the function searches for the nearest discrete s-coordinate and its corresponding UTM coordinates with respect to the input UTM coordinates. The function then adjusts the s-y coordinates considering the relative distance between the two UTM coordinates. The velocities are transformed using the equations mentioned in 2.3. The output of the block is position in s-y coordinates and v_s, v_y.

3.3.4. Pedestrian Collision Detection Block

Pedestrian Collision Detection block receives input from Map Data block, State Estimator Block and ROS Network and outputs the value of TTC. The block subscribes to the ROS message that publishes information of pedestrians (upto 6 pedestrians) present at the cross-walk. The message is split and the data — Pedestrian_id, GPS coordinates (Latitude, Longitude), Absolute Velocity and Heading Angle w.r.t. the road,Timestamp— for each pedestrian. Average speed with which pedestrian crosses a crosswalk varies depending the age, gender, time of day, and other factors. A general range of speed is 0.95-1.5 m/s[59]. If the pedestrian speed is found to be deviating from these values, counter based warning can be triggered in order to warn the driver and slow down the vehicle after several frequent occurrences. The GPS coordinates of each pedestrian are then converted to UTM coordinates and later to s-y curvilinear coordinates using the output from the Map Data Block for calculations.

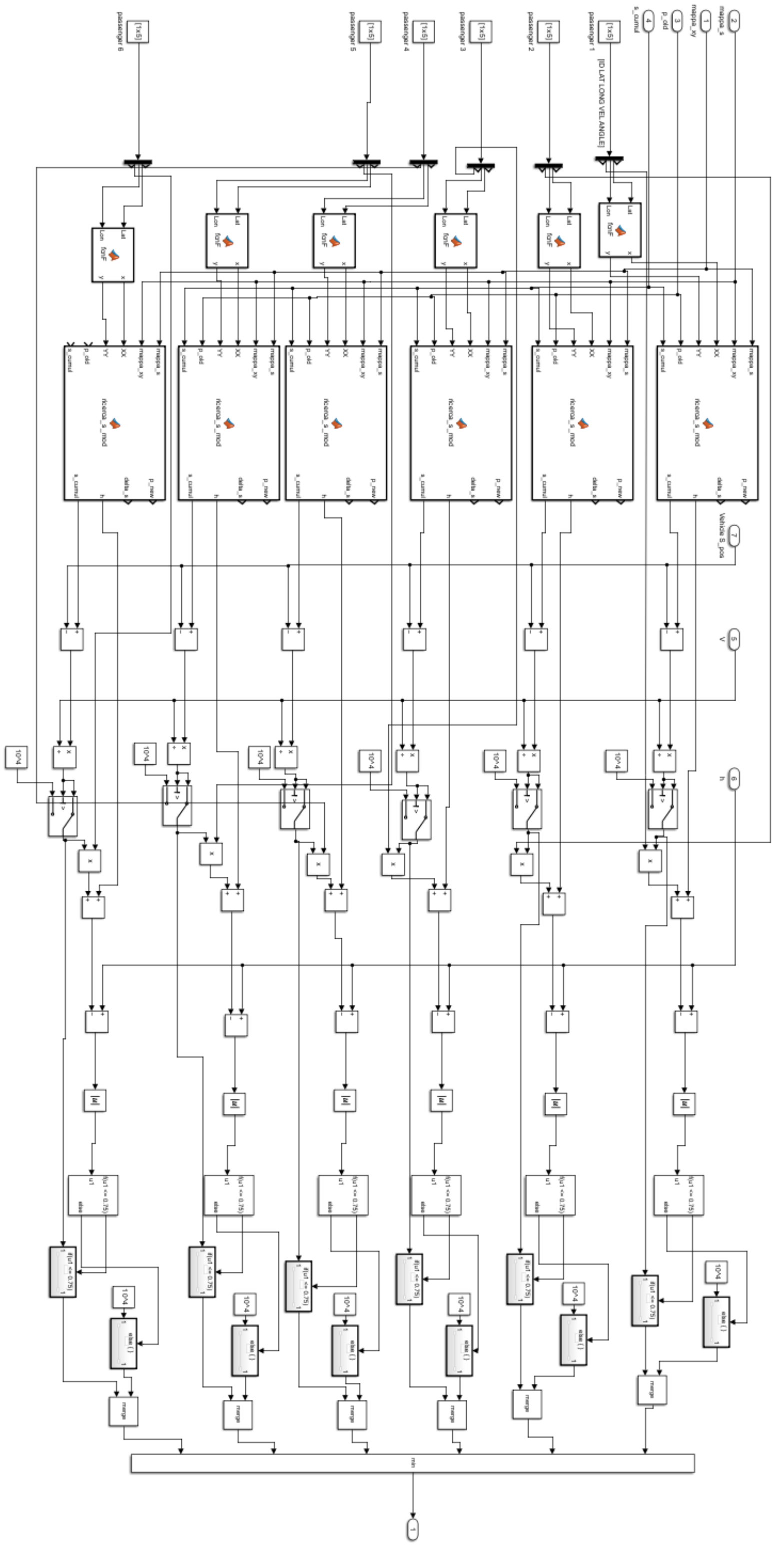


Figure 3.5: Pedestrian Collision detection block

Using the calculations mentioned in 2.3.2, the block decides TTC to be given as output.

If the timestamp of incoming message is sufficiently old, TTC should be adjusted for the elapsed time. In the case of no collision, the block outputs an arbitrary large value.

3.3.5. Collision Warning and Braking Decision Block

Collision Warning and Braking Decision Block consists of two parts: One that decides whether to warn or not and the other makes the decision to brake based on the TTC value received as input. There are two Thresholds (TTC_1, TTC_2) required to be initially given as input for this block to function.

The warning function utilizes both TTC_1 & TTC_2 whereas the brake decision uses only TTC_2. If the TTC falls between TTC_1 and TTC_2, the warn function alerts the user about the possible collision with the pedestrian (Yellow Warning). If the TTC falls below TTC_2, the functions alerts the driver that Autonomous Emergency Braking is active in order to avoid/mitigate the collision damage to pedestrian (Red Warning).

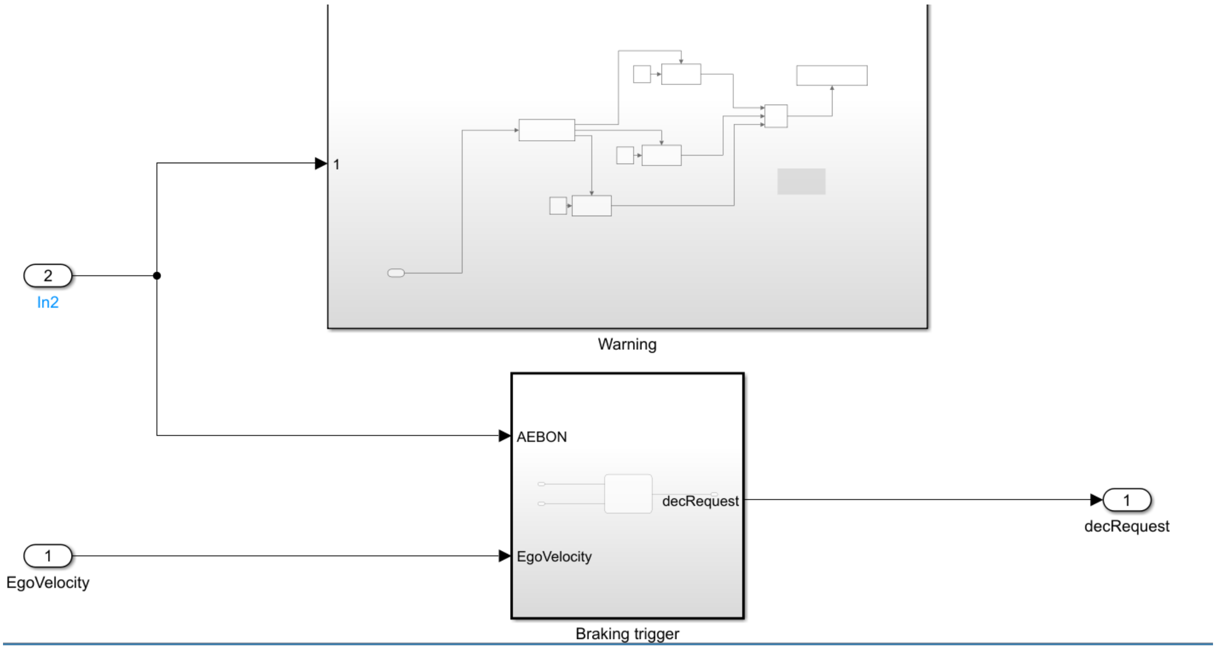


Figure 3.6: Collision Warning and Brake Decision Block

The brake decision function triggers a braking state if the value of TTC is less than TTC_2. The function also decides what should be the output value of deceleration request depending upon the vehicle longitudinal Velocity. The braking deceleration values are based on the discussion presented in [40]. The AEB deceleration logic , Fig. 3.9, is as follows:

- if $v_{car} \leq 30$ km/h , $acc_{req} = -10m/s^2$,
- if 30 km/h $v_{car} \leq 50$km/h, $acc_{req} = -3.5m/s^2$ for 300 ms, followed by $acc_{req} = -6m/s^2$
- it $v_{car} \geq 50$km/h , $acc_{req} = -3.5m/s^2$,

Once a deceleration state is entered then it will only exit if TTC exceeds a certain exit threshold. The exit threshold is set to a very high value, attainable only if the vehicle comes to a halt i.e. velocity = 0, or if the path is clear ,i.e. the pedestrian is out of the critical zone. Further, the deceleration values requested are tuned according to the vehicle and the braking system. NO_TE: While in a real situation the driver will probably increase braking pressure, (s)he cannot interact with the brakes when AEB is active.

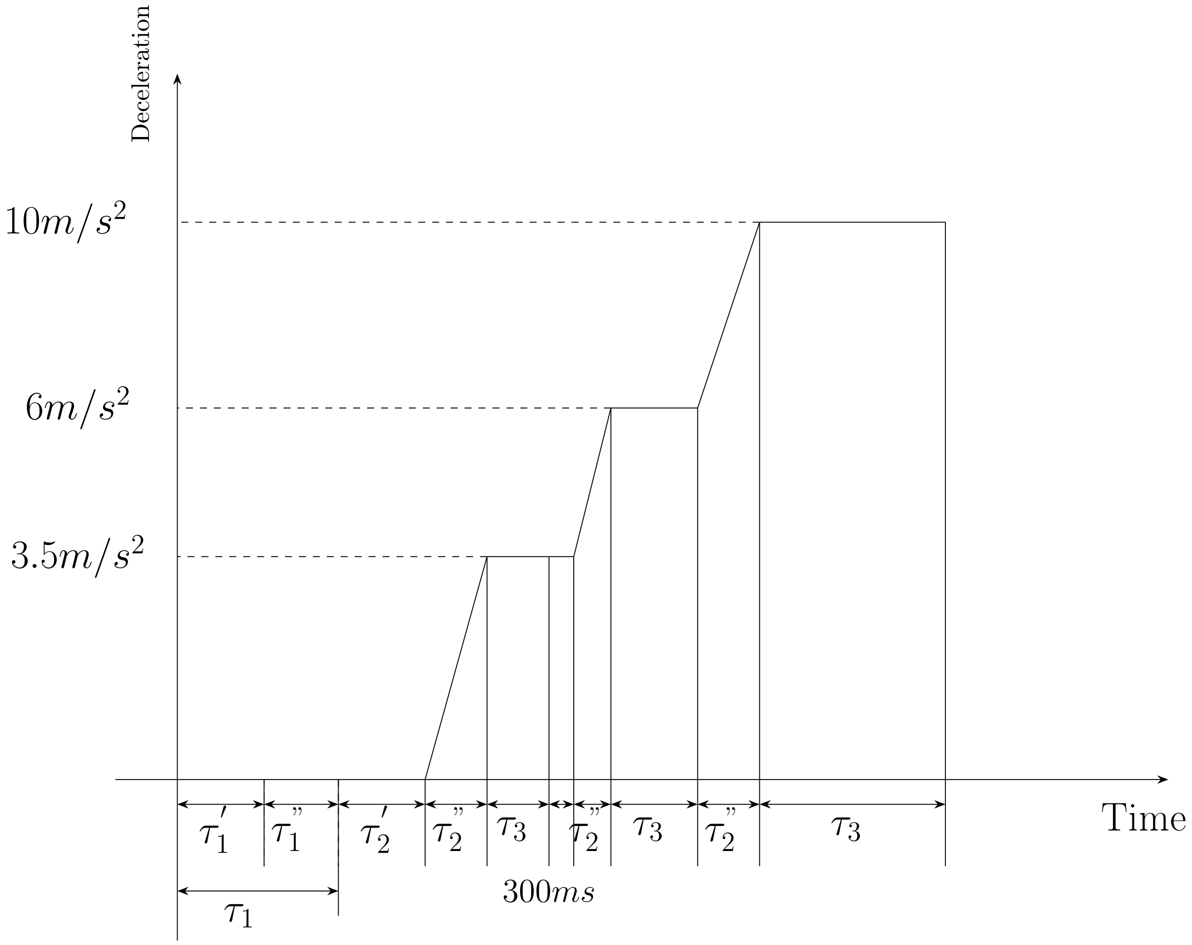


Figure 3.7: Braking process

The values of TTC_1 and TTC_2 are decided according to the braking process which involves the driver and the braking system of the vehicle. The braking process is shown in Fig. 3.7. τ_1 is the driver's response time. It consists of τ_1', the time driver takes to comprehend the warning, and $\tau_1^{"}$, the time taken to respond and brake. $\tau_2^{'}$ is the time taken by brake clearance and time taken by AEB to recieve information and actuate. $\tau_2^{"}$ is the taken by the braking system to build up to the desired deceleration value.

Time to warn (TTC_1) should be decided such that the driver has sufficient time to take responsive action but not long that the warning is triggered frequently for low/manageable risk, distracting the driver and instilling distrust in the warning system. Li et al. found that a flashing brake warning system can improve drivers response time by 0.14-0.62 s [44]. Studies show that driver response time τ_1 is below 1 sec for a alert driver for an expected event and around 1.5 - 2 secs for and unexpected or surprise event. Thus we can set the TTC_1 threshold as TTC_2+2 seconds.

In order to set the threshold value of TTC_2, we need to take the braking distance into consideration. Safe braking distance consists of 3 parts, as shown in Fig. 3.8:

- Actuator Response Distance
- Braking Distance
- Safety Distance

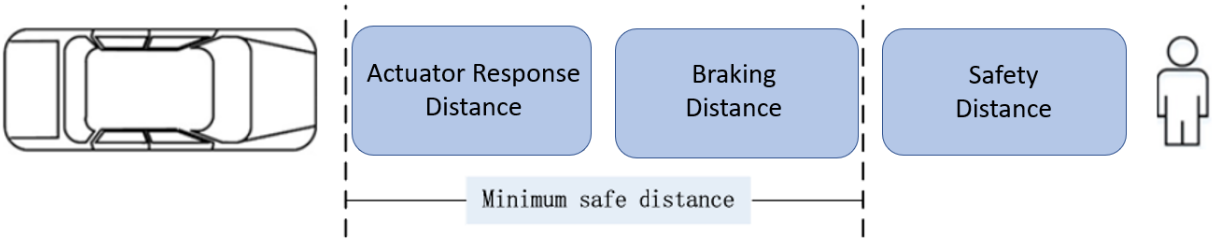


Figure 3.8: Minimum Safety Distance

Actuator Response Distance is the distance traveled by the vehicle in the time interval from when the braking action is initiated and the time when desired deceleration is achieved.

Braking distance is the distance travelled by the vehicle at the desired acceleration request.

Safety distance is a safety measure that adds additional redundancy to the system. It is essential in order to avoid braking too close to the pedestrian and startling them causing panic situation. It also compensates for inaccuracies that may occur in sensing, assumptions and variation in vehicle dynamics due to change in environmental and temporal factors. For a safety distance of 2m, the minimum safety distance, d, is given as,

$$d = \begin{cases} \frac{v}{3.6}(\tau_2' + \frac{\tau_2''}{2}) + \frac{v^2}{259.2} + 2 & for\ v \leq 30kmph \\ \frac{v}{3.6}(\tau_2' + \frac{\tau_2''}{2}) + \frac{v^2 - u^2}{90.72} + \frac{u^2 - 30^2}{155.52} + \frac{30^2}{259.2} + 2 & for\ 30kmph <\ v \leq 50kmph \\ \frac{v}{3.6}(\tau_2' + \frac{\tau_2''}{2}) + \frac{v^2 - 46.22^2}{90.72} + \frac{46.22^2 - 30^2}{155.52} + \frac{30^2}{259.2} + 2 & for\ v \geq 50kmph \end{cases} \tag{3.1}$$

where, $u = v - 3.78$ (kmph). The value of minimum safety distance is then substituted for Δs in eq.(2.6) to obtain the values of TTC_2. TTC_2 indicates that for a TTR value less than TTC_2's value, the vehicle will reach sooner to the the desired position before it can come to a complete stop. In the algorithm a fixed value of TTC_2 equal of 2s to reduce the complexity for initial validation.

3.3.6. Brake Actuation Block

This block publishes a ROS message calibrated according to the Braking system to achieve the desired braking pressure for the deceleration requested.

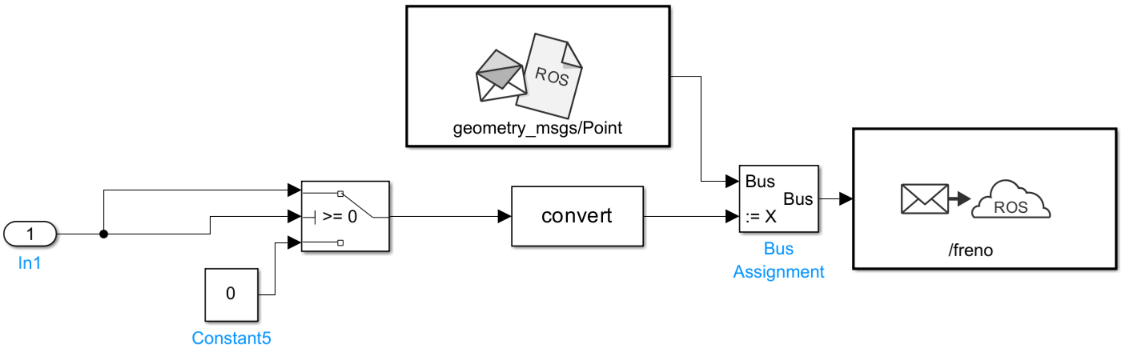


Figure 3.10: Braking Decision Output to ROS

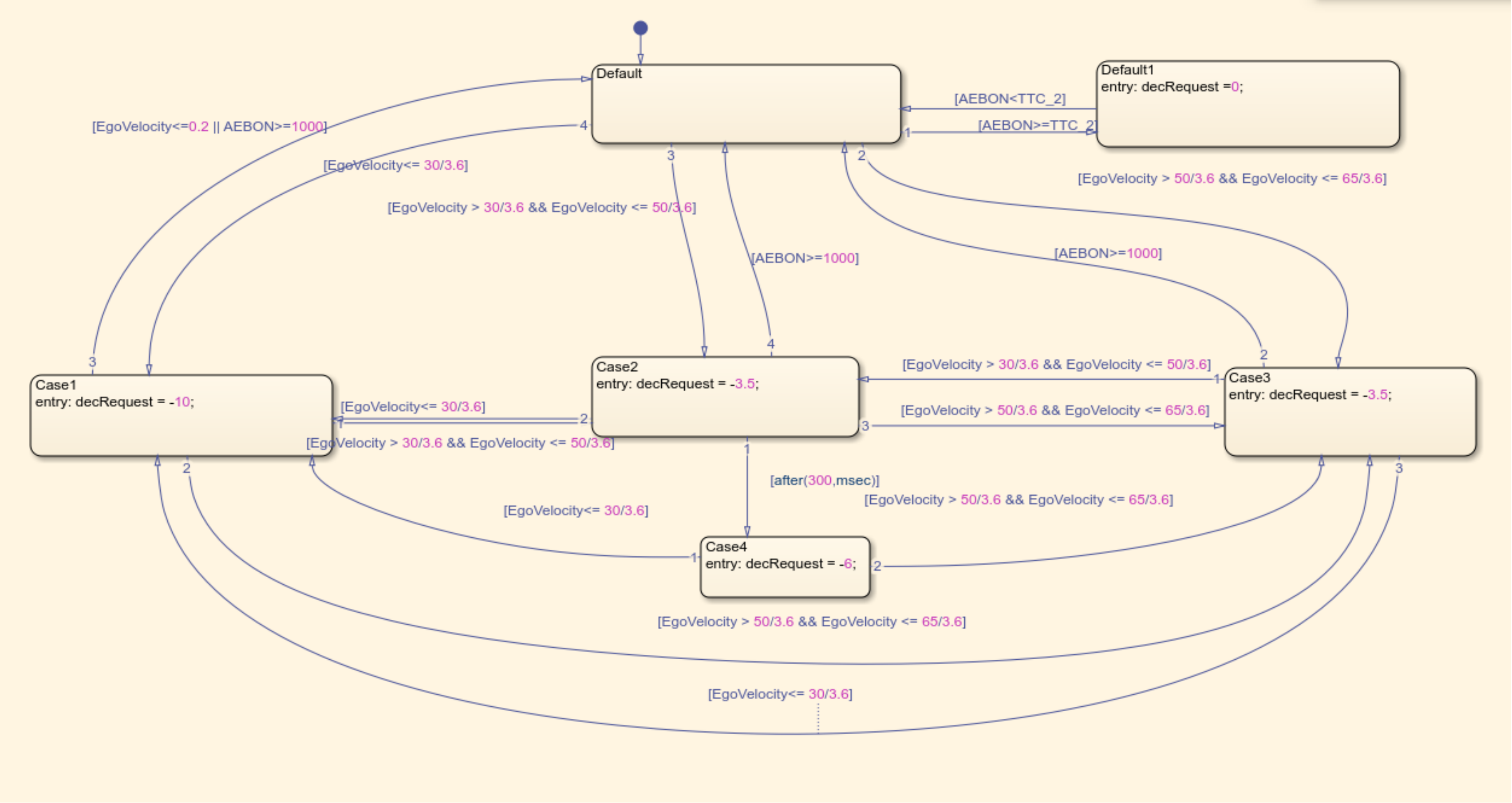


Figure 3.9: AEB Logic

3.4. CWAS Logic

In this section, we will summarize the complete functioning of the CWAS system designed.

The control logic flow of the CWAS system is shown in the fig. 3.12.The Algorithm recieves input from three source: On-board sensors, Pedestrian detection sensor and the map data. These inputs are convereted from UTM coordinate system to s-y coordinate system. The algorithm first checks, if the vehicle is moving or stationary. if the Vehicle is moving it proceeds with TTR calculation based on a s coordinate adjusted for by vehicle length and safety zone, otherwise it outputs an arbitrary TTC Value (high).Next, if the pedestrian and vehicle are moving towards each other, the algorithm calculates the TTR using eq(2.6), otherwise it outputs an arbitrary TTC Value. Based on the calculated TTR, future position of pedestrian is calculated(2.7). If the pedestrian is in the critical zone when the vehicle reaches them2.5, TTR is set as the TTC for that pedestrian instead of an arbitrary TTC. TTC values for all the pedestrians is compared and the minimum value is sent to Collision Warning and Braking Decision block. Futher actions are decided by the block based on the rules mentioned in 3.3.5.

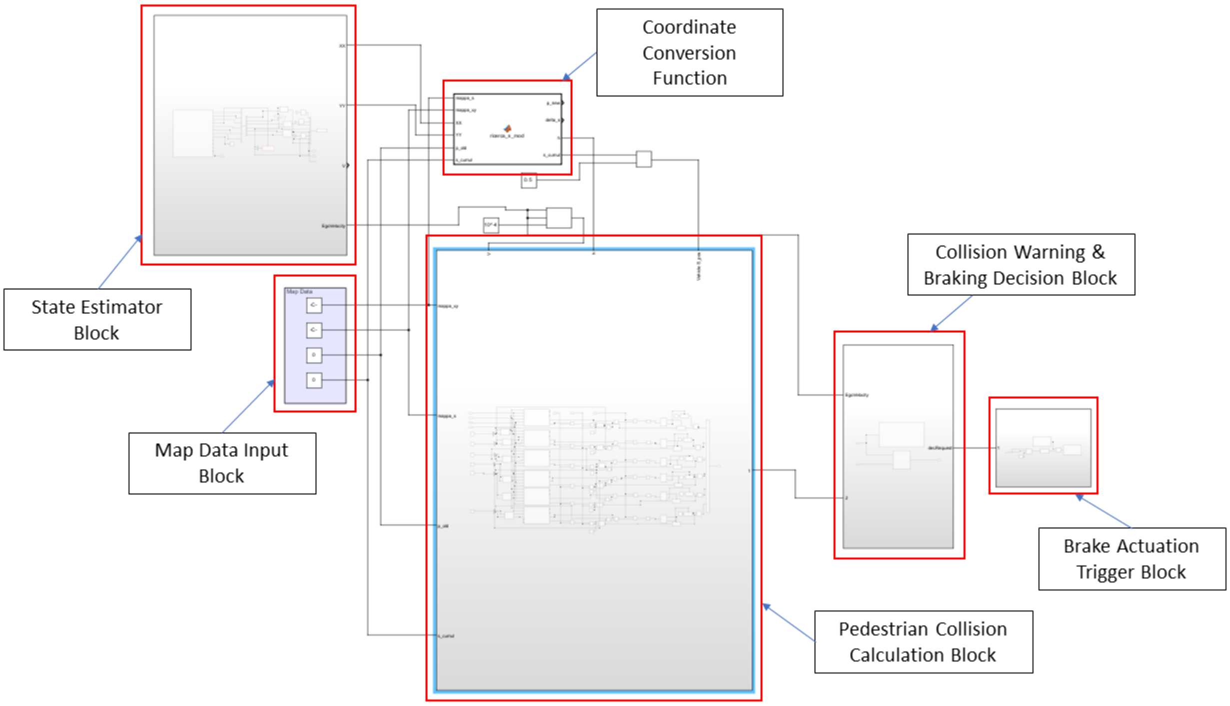


Figure 3.11: Simulink Schematic of Blocks

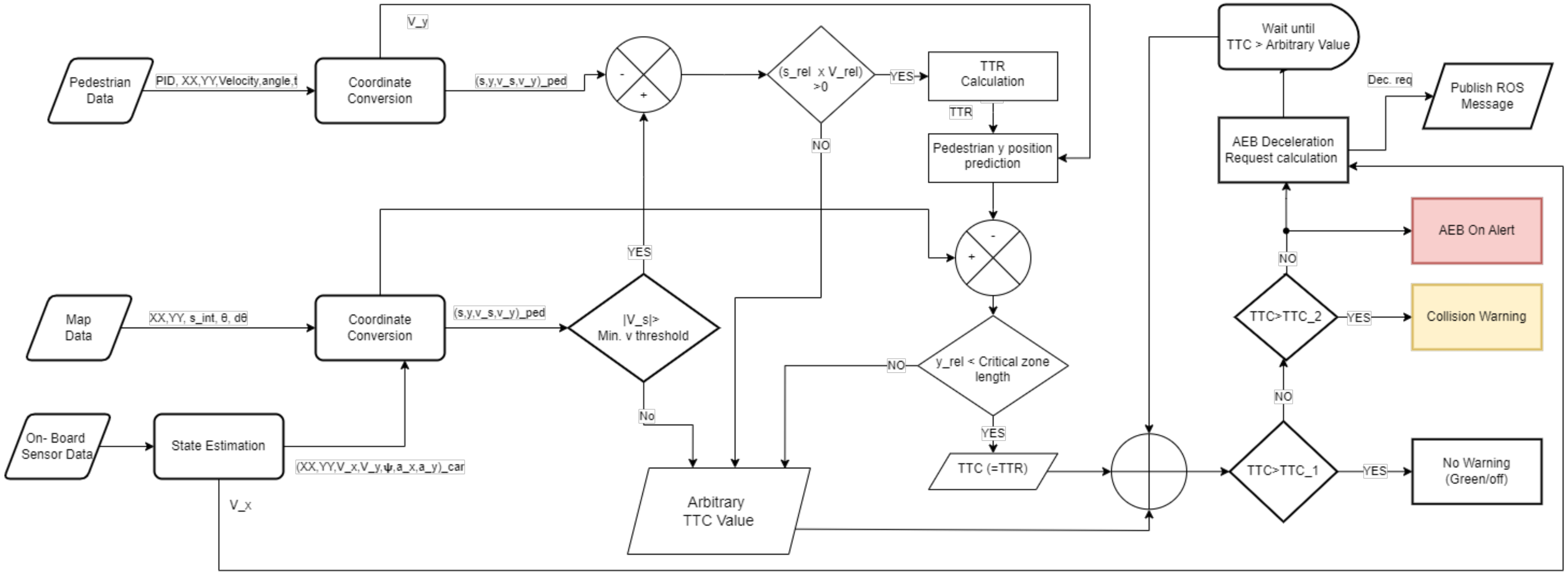
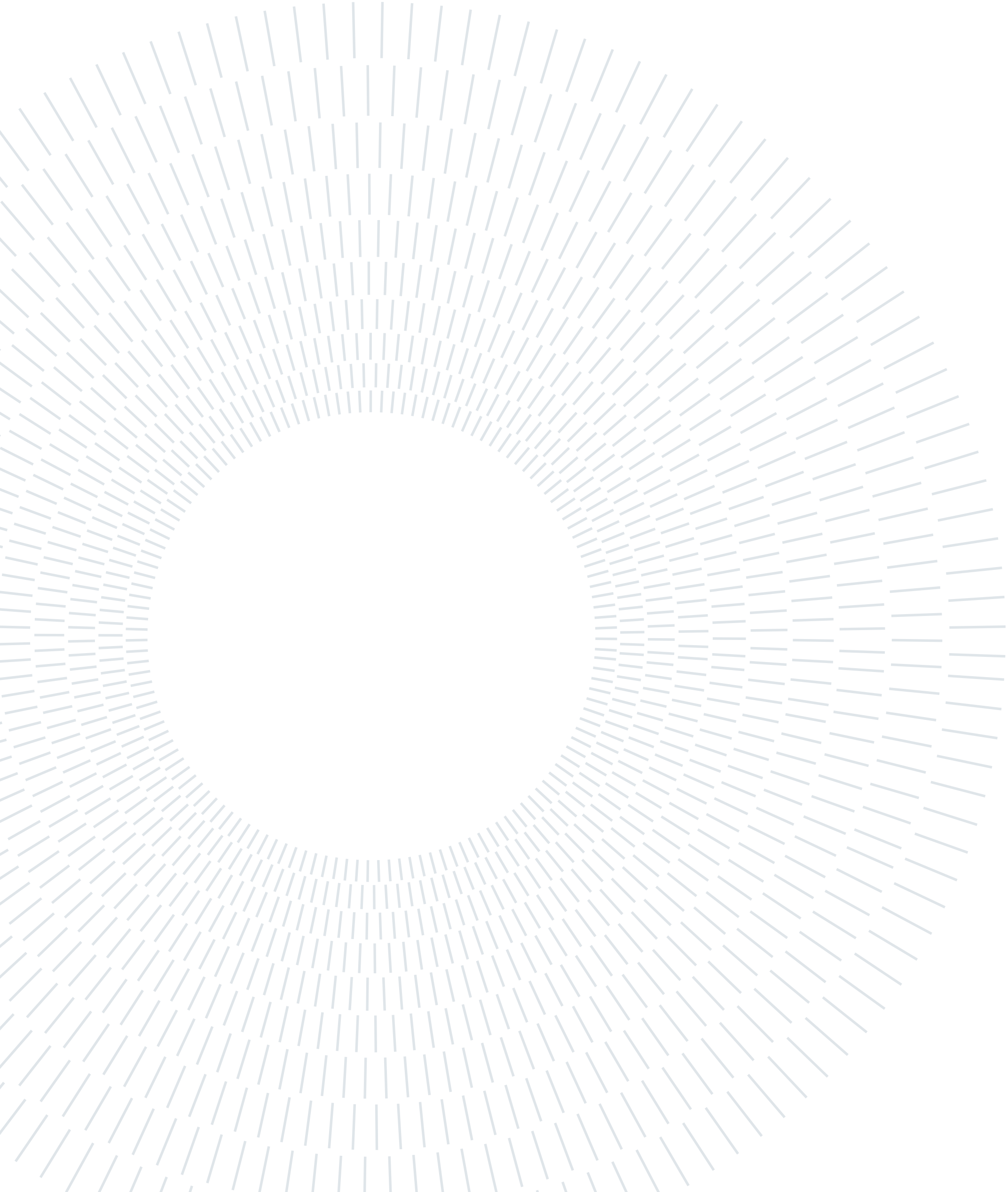


Figure 3.12: CWAS Algorithm



4 Shared Mobility

The concept of sharing is not new to humans. It has been and is still instilled in humans since birth. Thus it is only natural that it influences various aspects of our lives at an individual as well as at an institutional level. The term shared economy has been gaining momentum in recent years. Also referred to as "collaborative consumption", it is a socio-economic system that allows the users to share their underutilized resources with others. It may be of profit or non-profit in nature. The system leverages the capabilities of Information Technology and the Internet to ensure a more efficient use of resources and services.

Sharing economy has found its way in almost every sector including the Mobility sector. Shared Mobility is an emerging business mode of the shared economy. It is an innovative transport strategy, in which services and resources are shared among users, concurrently or sequentially, to gain short term access to transportation according to their needs. Shared mobility includes public transport, taxi, ridehailing, ridesharing, ridesplitting, carsharing, bikesharing (includes regular bikes, e-bikes and pedel-electrics), scootersharing, e-scooter sharing, shuttle services and other micro-transit services. Some of the modes have been present for decades and are being enhanced by the technology advancements, while others have been made possible because of them. Sometimes there could be certain external factors that might lead to higher or lower adoption of certain modes. The concept of resource utilization by sharing is not limited within a sector, it can be also across sectors. For e.g. Crowdshipping, in which underutilized resource of transportation sector is utilized to fulfill the tasks of shipment and cargo sector. In the coming sections, we discuss further about Carsharing, its impacts and its adoption.

4.1. Car Sharing

One form of shared mobility that offers short-term access to a vehicle is CarSharing (CS). It began as cooperative community effort motivated by its economic benefits. Later, business models based on vehicle fleet which can be rented on hourly/daily basis were adopted. Recent technological developments has made car sharing popular and more such vehicles are being observed on the road [24, 79]. A user can typically access the service with a smartphone with zero to minimal human interaction. Car sharing business models are of four types: Business-to-Customer (**B2C**), Business-to-Business (**B2B**), business to government (**B2G**) and peer-to-peer (**P2P**). There are three types of service modes in B2C model:

1. Round trip services - Vehicle is returned where it was picked from.
2. One way, station based - Vehicle can be returned at a partner station.
3. Free Floating Car Sharing (FFCS) - Vehicle can be dropped anywhere in a designated geographical area.

FFCS is a more recent form of service model, but it gives the user more flexibility than other models. To avoid clustering of vehicles in one or few popular location and maintain availability of vehicle all over the designated geographical area, relocation incentives are provided by the carsharing companies.

4.1.1. Impacts of Carsharing

Carsharing allows an individual or an household to gain, maintain or extend their access to different types of vehicles without bearing the cost of owning them. It also allows them to assess their need for car-based mobility. Alternatively, car owners can monetize their idle assets while reducing their ownership costs as hosts in a P2P model. Several studies have documented the socio-economical and potential environmental benefits of carsharing. [68] presents a summary of the literature present on the outcomes of carsharing. Some of the collectively studied outcomes of carsharing are:

- Reduced Vehicle ownership - Round trip carsharing services have found to reduce 6-20 vehicles from road whereas one way carsharing have reduced 3-11 of them. On Average 25% of users of round trip carsharing service have sold their vehicles.
- Adoption of other modes of transport - Adoption of carsharing services have led to users utilizing other modes of transportation too. Walking, Bike use and public transport have increased by 6-14%. increased use of active modes of mobility may also have certain health benefits.
- Reduced Vehicle Miles/Kilometers Traveled (VMT/VKT) - Adoption of CS can reduce VKT by 27-80
- Reduced emissions and energy usage - Combined effect of reduced cars and VKT can

in turn reduce the Green house gas emissions. As the fleets of carsharing companies are relatively newer than average privately vehicle, equal utilization can also lead to reduced emissions. Apart from emissions, sharing of vehicles can reduce the amount of levels of eutrophication, ecotoxicity, and human toxicity caused due to manufacturing of electric vehicles and reduce the overall energy demand of autonomous vehicles

- Increased access to mobility - All sections of society can benefit from the opportunities that come with owning a car without actually bearing the cost of them.

Another potential impact of carsharing is reduction of land use for parking. A reduced number of cars traveling and parked on road will then lead to lower congestion and improved traffic flow, especially in urban areas. The resulting increase in available land may be utilized for economic activities or to facilitate other modes of mobility. Carsharing also allows users to expose themselves to newer technologies on a personal need basis without purchasing them. For instance, consider the case of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). the popularity of EVs and HEVs is increasing as their pricing is becoming more and more attractive. A user who plans to switch to a greener vehicle can make a better judgement of which vehicle is more suitable for them by accessing the them via carsharing before making the switch. Increasing environmental and social awareness among the public and the ease of access make carsharing a sustainable and favoured mode of transport.

4.1.2. User Adoption

Since private vehicles stand idle for an average of 92% of the time[2, 41, 56], the primary reason for impacts of carsharing is improving vehicle utilization and reductions in private car use but the magnitude with which these impact can affect the society depends on the utilization of of carsharing service itself. Although some impacts like lesser road parking requirement seem less likely at the beginning as both private and shared vehicle compete for parking space, its effect is more observable in the long run. However, Simply pushing out the fleets of shared vehicles without any actual demand for them may add to the problems that it tends to solve and even form a distrust in the community which would further delay their adoption. Therefore, generating and addressing the demand properly becomes crucial.

Mobility and travel decisions are impacted by psycho-social constructs which can be categorised as instrumental, affective and symbolic (Steg, 2005, Sovacool and Axsen, 2018). Instrumental or functional constructs relate to the functions of an object and include practical considerations (e.g. time savings, money savings, etc.). Symbolic-affective constructs relate to how an object makes someone feel and include psychological or emotional considerations. While functional constructs can incentivize and influence the use of carsharing, emotions can influence the perceived effective effort which leads to continual use of service. Macro-level analyses of the adoption of carsharing is essential but “only one side of the coin”, where investigations into micro-level aspects of how shared cars are experienced and used can provide complementary understandings on adoption of carsharing from a subjective lens. Thus understanding of the psychological drivers of behavioral intention is crucial for service operators to address more efficient deployment strategies and ad-hoc promotional campaigns.

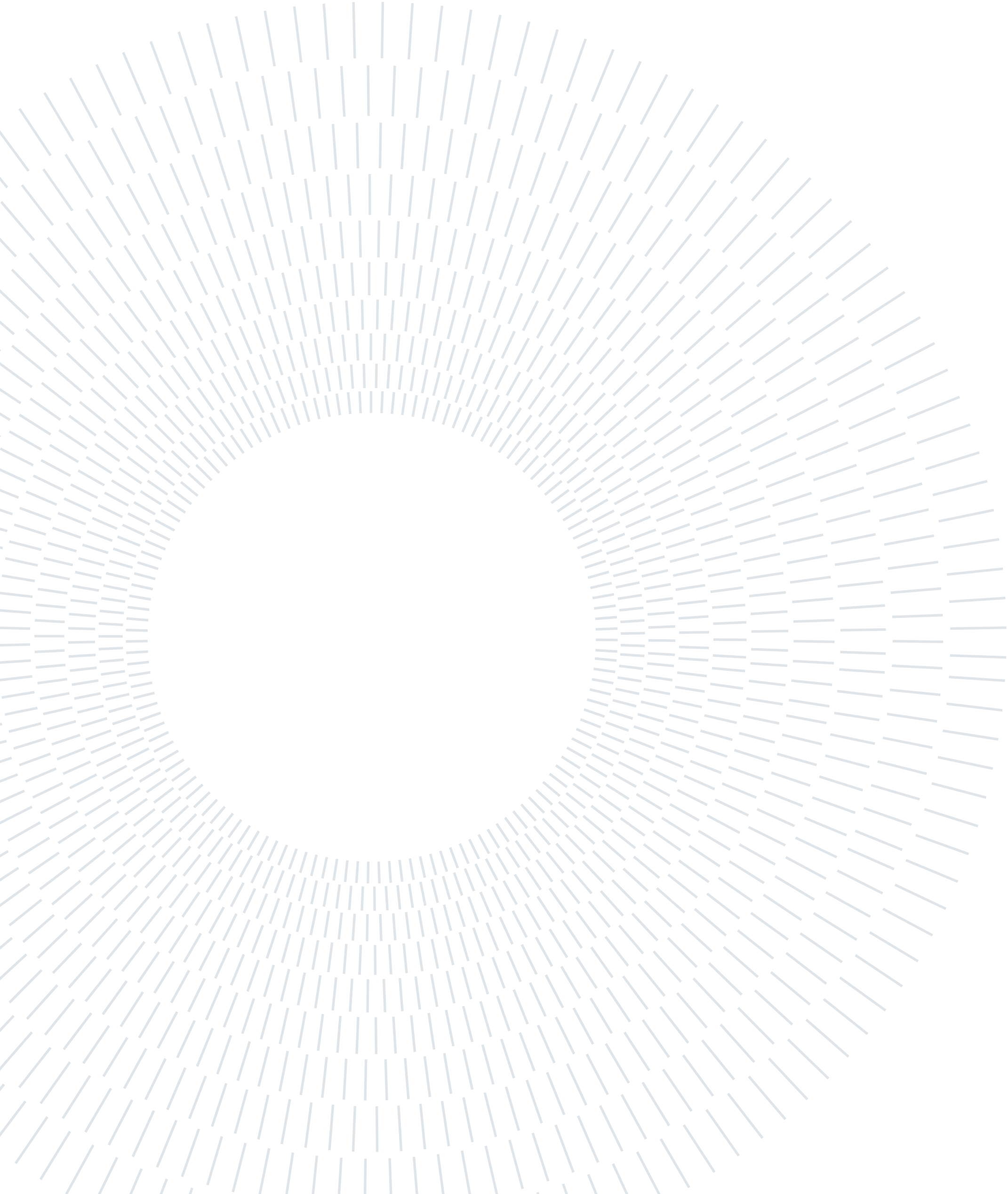
Pierce et al. define psychological ownership as a “state where an individual feels as though the target of ownership or a piece of that target is ‘theirs’”. Psychological ownership differs from legal ownership is an ownership formally acknowledged by others where as psychological ownership is an individual experience. People can develop psychological ownership towards objects they do not own as well as develop psychological ownership to an object only by imagining that they touch that object [62]. Personalization is associated with high psychological ownership as it is an expression of owner’s intimate relationship with the object [64]. Moreover, people high on psychological ownership typically feel the responsibility to protect, maintain, care for, and possibly even defend their possessions when necessary[20]. Lower psychological ownership may be able to explain why people are less reckless while driving their private car than a shared car[14]. It may be necessary to account for psychological ownership in this area, because these two transportation modes differ mainly in people’s feelings of psychological ownership to their own car. People develop feelings of heightened attachment to their private cars, whereas shared cars merely offer instrumental utility[14]. It follows that people with high psychological ownership would value the possessive quality of the car, whether it is a privately owned car or shared with other people, higher than the other instrumental car attributes. Psychological ownership can thus influence on people’s intention to select a shared or private car.[60]

Jain et al. and Doody et al. surveyed users of carsharing services entry, continuation and exit from the service. While critical and gradual life events like moving to a new location, having children, increasing age of children etc, had impacts on the entry and exit, one another factor was convenience and annoyance. Some users endured them, while others discontinued the use of service. For some members, the annoyance and the lack of convenience gradually built up the dissatisfaction which was enough that a minor life change event led to their discontinuation.

While carsharing companies and governments are making changes at a systemic level to motivate the use of carsharing and other shared mobility modalities, it is also necessary to consider the psychological and emotional aspects of using these services to increase adoption and observe significant benefits

Driver Profile Load System

The research shows the more trips a user makes, the more likely they are to take quicker and shorter trips[17]. Frequent use of services like FFCS and one -way sharing may not guarantee that the user may use the same car every time. The feeling of getting into a new car and the inconvenience of setting every thing according to personal preference can lead to low level of psychological ownership and increase dissatisfaction which may lead to discontinuation of use of the service. A system which can automatically load the driver's preferred configuration, i.e., seat position, sidemirror position, climate control settings, etc. can instill a feel of a personal vehicle to some extent and thereby improving the sense of psychological ownership. It also saves time of the user, prevents the user from driving in an uncomfortable position and reduces the implications of improper posture. Such a system is discussed in the next chapter.



5 | Driver Profile Load System

Personalized internal vehicle setup and memory features are common in private vehicles. These system improve comfort and convenience. Although not currently unavailable in present carsharing fleets, such kind of systems can improve adoption and continuation of carsharing services. The second system that we have designed and implemented tends to bring similar comfort to carsharing users as well as user of private vehicles.

5.1. Introduction

Seat and side-mirror memory systems are being offered by Original Equipment Manufacturers like Volvo, MG, Mazda etc. since early 2010s. However these OEMs have limited their system to two to three profiles. These profiles can be saved by pressing Memory button, usually labelled as 'M' or 'SET', along with the profile button, usually labeled as ['1','2','3'] or ['A','B','C'], as shown in *fig. 5.1.* The position of seat and side-mirrors is stored either mechanically with the use of locking mechanisms, similar to the ones found in numbered pad-locks or by using a position detection sensor that electronically saves the sensor output upon pressing the memory button [18, 19, 22]. Some OEMS also use machine learning to set an optimum based on the height input of the user.

These functions provided are of great convenience to the privately owned vehicle owners, driven by 2 to 3 individuals. As the number of unique individual drivers or the number of unique vehicles a driver drives increases, as seen in case of shared mobility, the above mentioned systems has its limitations.

1. Local data storage, and
2. Inability to identify the drivers.

Malneedi et al address the driver identification using a facial recognition system,raspberry pi and a pulse counting based feedback system [73], but discuss about the recording profile data or connectivity. We managed to provide solution to these limitations by eliminating these factors altogether, along with a Proof-of-Work demonstration.

Figure 5.1: Seat memory function

We have developed a system that integrates Cellular Communication Technology and Driver Identification primarily utilizes facial recognition program. Additionally, this system can also be implemented on vehicles with legacy motorized components, i.e. powered seats and mirrors without position memory sensors, as it neither requires any of our focus components, seat and/or mirrors, to have integrated sensors nor does it require installation or mounting of sensors for position memory. The designed system architecture is shown in *fig.5.2* and will be discussed in the next chapter.

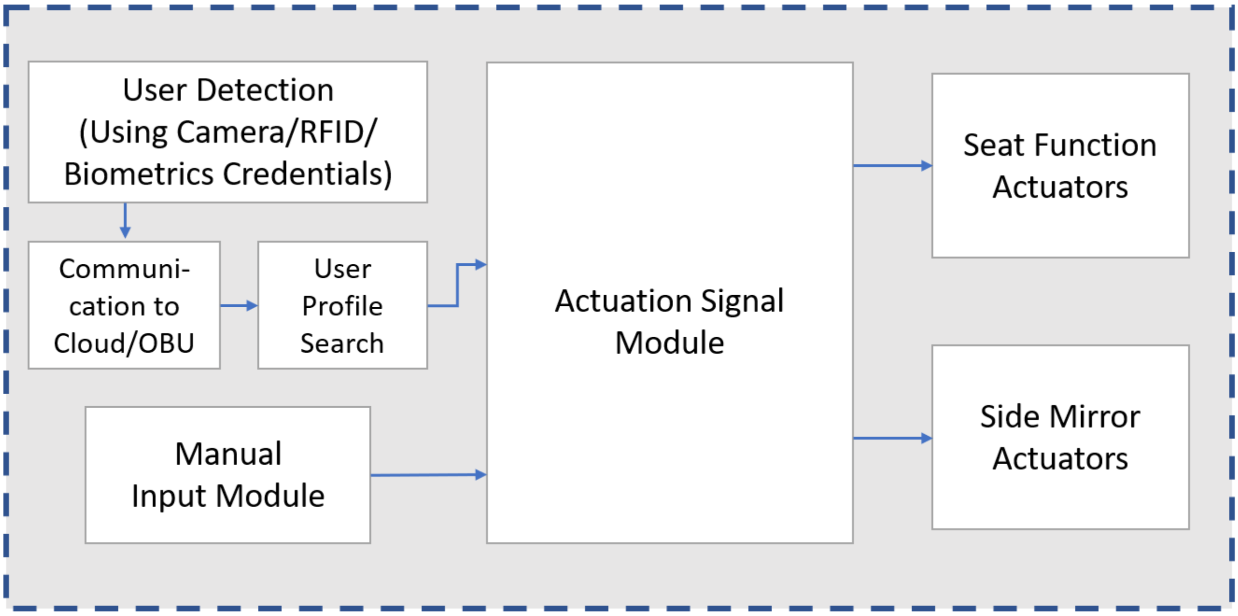


Figure 5.2: Profile Load System Architecture

5.2. System Components

5.2.1. Vehicle and Seat

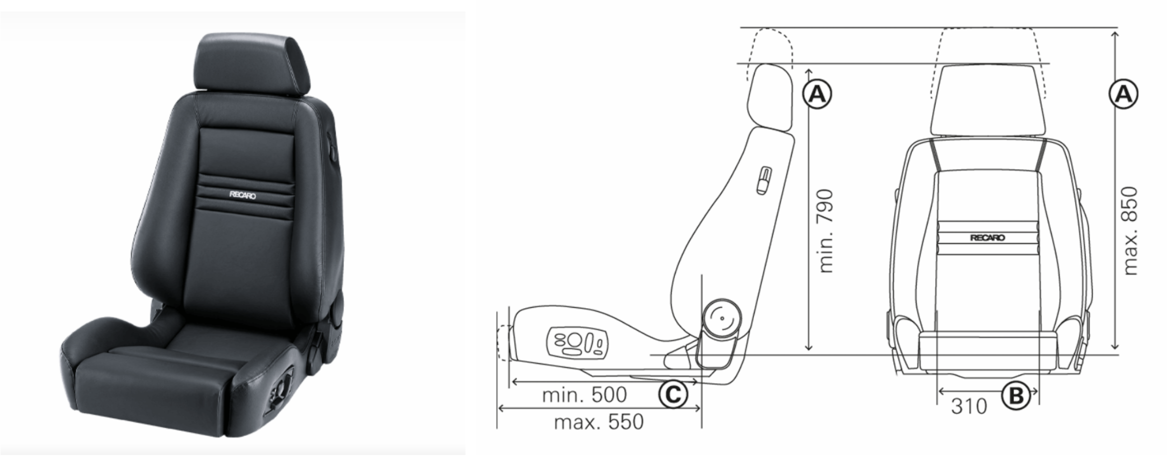


Figure 5.3: Recaro Ergomed E, dimensions in mm

The Vehicle utilized for this system is the same that we used for Pedestrian-ICWAS, the details of which is provided in *Appendix A*. A suitable motor-powered seat, Recaro Ergomed E *(fig. 5.3)* , was mounted on the vehicle. The height of seat and the bulge of the lumbar support can be electronically controlled using the side control panel of the seat, as shown in the *(fig. 5.4)*. The seat requires a 12V DC supply, which is same as other electronic functions of the car.

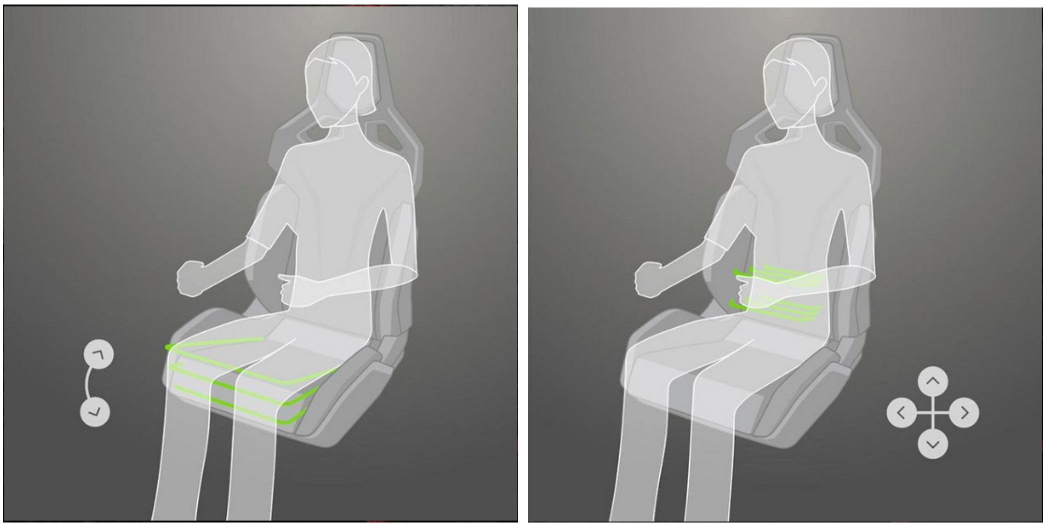
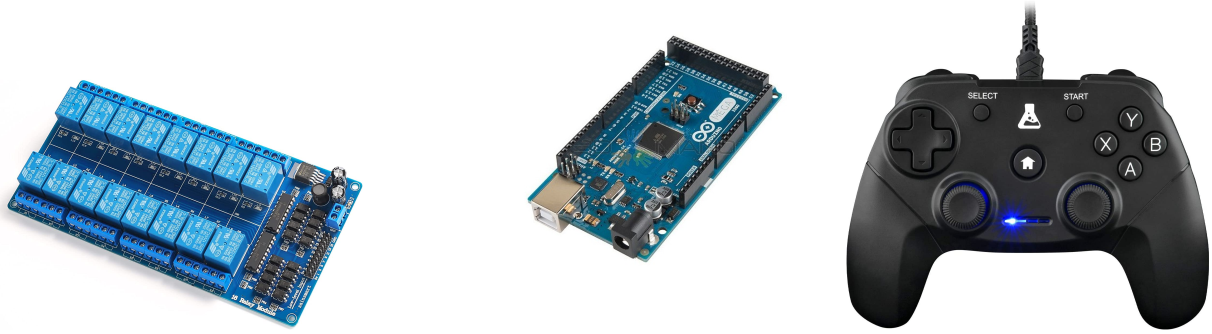


Figure 5.4: Electronic Height Adjustment and Lumbar Support of the Recaro ErgomedE.

5.2.2. Control Components

The Electric control circuit comprises of a 12V Relay board, Arduino Mega 2560, 12V DC battery, a standard game-pad/joystick and a computer with Simulink and Stateflow as reported in *Fig. 5.5*



(a) Relay Board (b) Arduino Mega 2560 (c) Gamepad

Figure 5.5: Components required for electronic control.

5.2.3. Driver Identification Components

A camera and 5G - cellular User Equipment(5G-UE) provided by Vodafone and ROS network is used to transmit the information about the identified driver. This specific task of the work was developed by the research team involved and it's not aim of our thesis.

(a) Camera for facial recognition (b) 5G User Equipment

Figure 5.6: Components required for identifying the Driver.

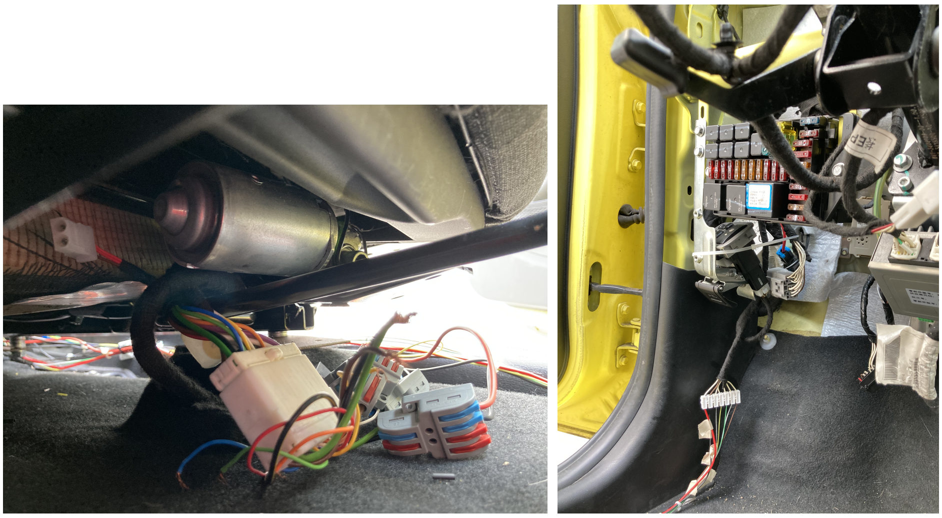


Figure 5.7: Seat and Mirror connections

5.3. DPLS System

The design of the DPLS system developed will be discussed in this section in detail.

5.3.1. Circuit Identification and Mapping

The Side-Mirror and Seat electronic circuits consist of eight wire connections each as shown in the *Fig. 5.7*

1. First step for installation of the system was to identify the connections required to actuate the required functions - Vertical and horizontal movements of left and right mirror and Vertical Height and lumbar support adjustment.

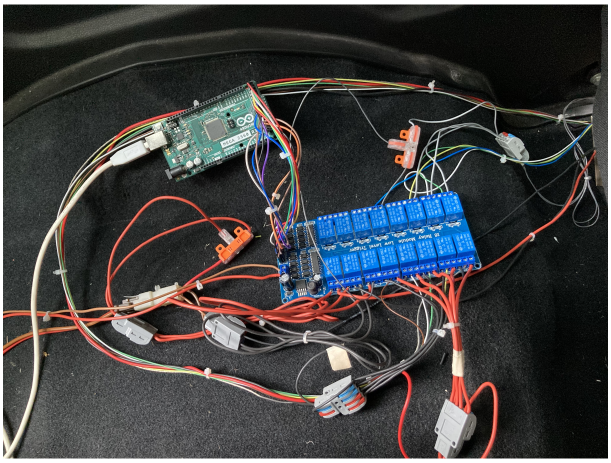


Figure 5.8: Final connections of the DPLS system

2. Then, the circuits were redesigned to integrate Relay board and Arduino Mega-2560 This was done to enable control using Joystick with the option of enabling/disabling control panel provided with seat and mirrors, as depicted in *Fig. 5.8*
3. In the last step, some connections were remapped with the use of AND and NOT gates. In case simultaneous control is on, an additional digital circuit should be used to prevent short-circuiting of the motor.

In order to facilitate the manual input by the driver for the first time, as per his preference, the Controls were mapped to joystick as shown in the *fig. 5.9*.

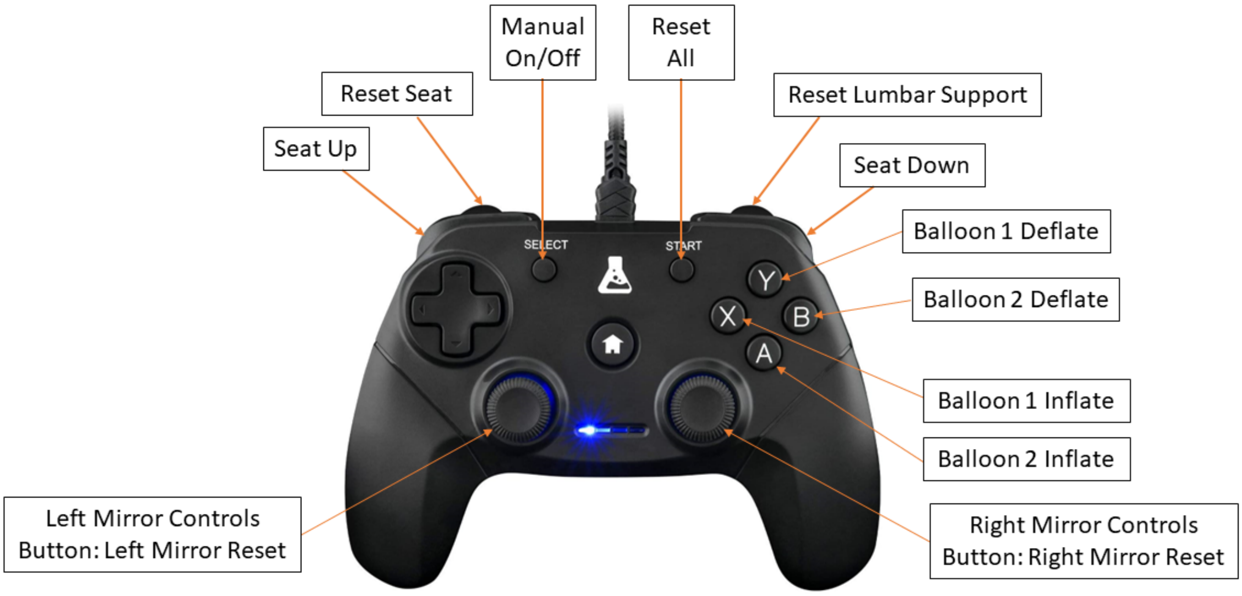


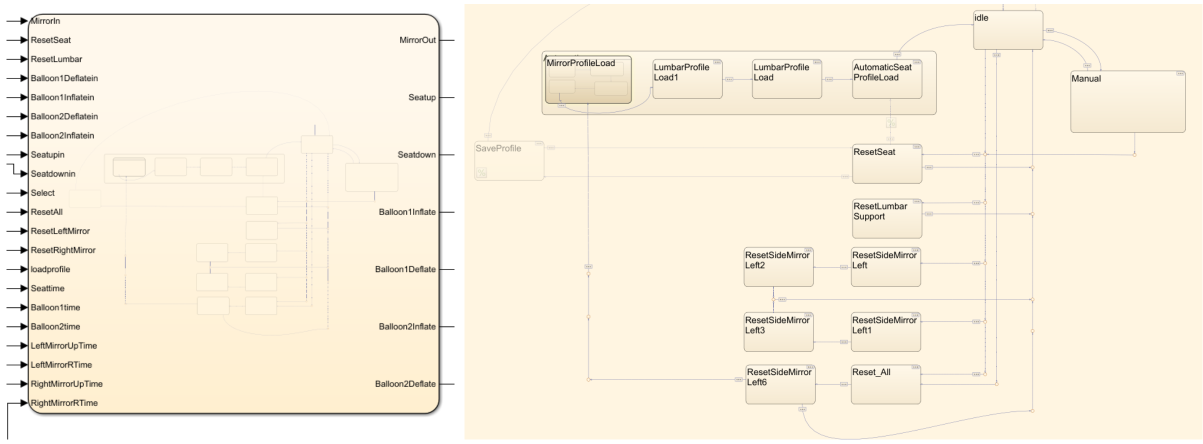
Figure 5.9: Map that we coded onto the joystick for Manual Input.

5.3.2. Control States

Stateflow

Stateflow provides a graphical language that includes state transition diagrams, flow charts, state transition tables, and truth tables. Stateflow enables us to design and develop supervisory control, task scheduling, fault management, communication protocols, user interfaces, and hybrid systems. Combinatorial and sequential decision logic can be simulated as a block within a Simulink model or executed as an object in MATLAB using Stateflow.

The Stateflow Control algorithm receives 21 inputs and provides 7 outputs to the Arduino. The inputs and output of the control are shown in *Fig. 5.10a* The input being read actively depends on the current state of the system. The output is either a high or a low level value, designated to Arduino pins. The output then triggers the relay circuit, thereby connecting the desired circuit and actuating the desired function.



(a) Stateflow Inputs and Outputs (b) Control States

Figure 5.10: Stateflow IO and States

There are four states in which the system can be;

1. Manual,
2. Reset,
3. Profile loading &
4. Idle.

The default state of the system is Idle state, i.e. the system always returns back to its idle state from the profile loading state. The system can go to manual state if and only if the manual button is pressed on the joystick. The manual state allows the user to move the seat and the mirror as they desire. The reset state is triggered if a new profile is being set, or by the user when they press the reset button. The reset position is down-left for the mirrors, lowest height and bellows in completely deflated state for the Seat. The reset will loop back to Idle or Manual state, depending on the state from which it was triggered . The profile load State will set the seat and mirrors according to the input profile variables, if the profile is not already loaded.

The profile loading and resetting of position happens in sequential manner. The order followed is mirror vertical position, horizontal position, seat lumbar bellow actuation and seat vertical motor actuation. The order is reversed while resetting. When the user is in save mode the, the input of the user is recorded using the Duration function of Stateflow. Movements away from the origin point is considered positive and movements towards the origin are considered negative. After selecting the preferred position the sum of all the positive and negative movements is stored as the profile value for that function.

5.3.3. Calibration

Since no position memory sensor are present, saving and loading process is done with the help of system specific calibrated time. Thus after a proper calibration, time of actuation can be used as a way to measure distance. For every motion of a single degree of freedom, the time to reach from one extreme position to another extreme position is observed and entered into the Stateflow. The extremity of the functions set as origin and the time to reach from the set origin to the other extreme positions are mentioned in *table 5.1*.

Function	Origin	Time (from extremity to origin)
Seat Height	Lowest seat point	3.5 s
Seat Lumbar	Maximum Deflation	3.5 s
Left/Right Mirror Horizontal Motion	Inward Extreme Position	5 s
Left/Right Mirror Vertical Motion	Downward Extreme Position	5 s

Table 5.1: Function Origin and Time from Origin to Extreme for Recaro ErgomedE

Alternatively, these values can also be taken as input variables receiving data from cloud, as these values will depend on model of the vehicle and/or seat for further development in scale.

5.4. Work Flow

The driver identification module developed by our colleagues from the IOT department is integrated into this system for identification purpose. It uses face recognition program to identify driver from cloud database over 5G connection and relays the driver ID number to the on-board computer running profile load script as a ROS message. In case the driver is unidentified, the incoming message will have a default value of '0'. Next, the user can choose to save a new profile or continue as "Guest".

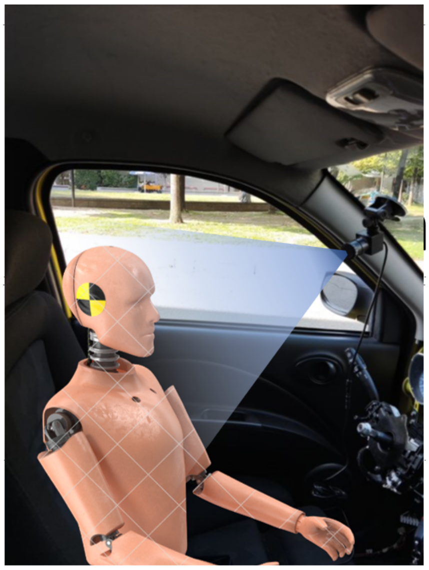


Figure 5.11: Driver Recognition

As stated earlier, the system does-not use any sensors to remember the position of the seat or the mirror. Instead, as the input is given from the joystick via the computer, the time for which a user gives a particular input to perform a function is saved using the duration function of Stateflow. The convention for the memory variable is such that the default reset position is the origin and the upward and rightward movement of the mirrors, upward movement of the seat and the inflation action corresponds to positive value. The maximum and minimum value these variables can attain is the value equal to Reset time value mentioned in Table 5.1, and 0 respectively. The user can manually set the most preferable position and the variables will be stored in profile data array with a new profile ID. The following shows the structure of profile data array:

$Profile = [Pid, Seat\ time, Lumbar\ balloon\ 1\ inflation\ time, Lumbar\ balloon\ 2...$
$...inflation\ time, Left\ mirror\ horizontal\ time, Left\ mirror\ vertical\ time, ...$
$...Right\ mirror\ horizontal\ time, Right\ mirror\ vertical\ time]$

If the user wants to continue as "Guest", the configuration will be set as "Default", i.e. reset position. If the Driver is identified, the script will check if the profile is already loaded or not. If yes, then the system stays in idle state, or else the system will reset the position and then actuate the functions according to values (time in seconds) in profile data array in the sequence mentioned in 5.3.2

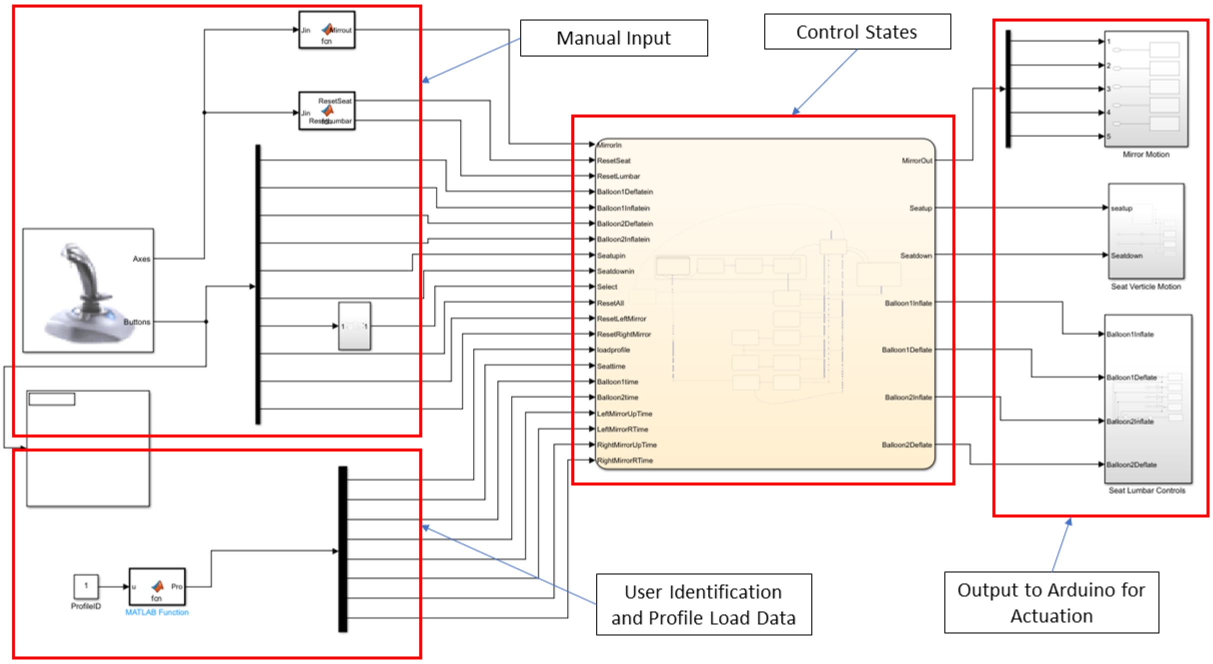


Figure 5.12: Simulink Schematic of Profile Load System

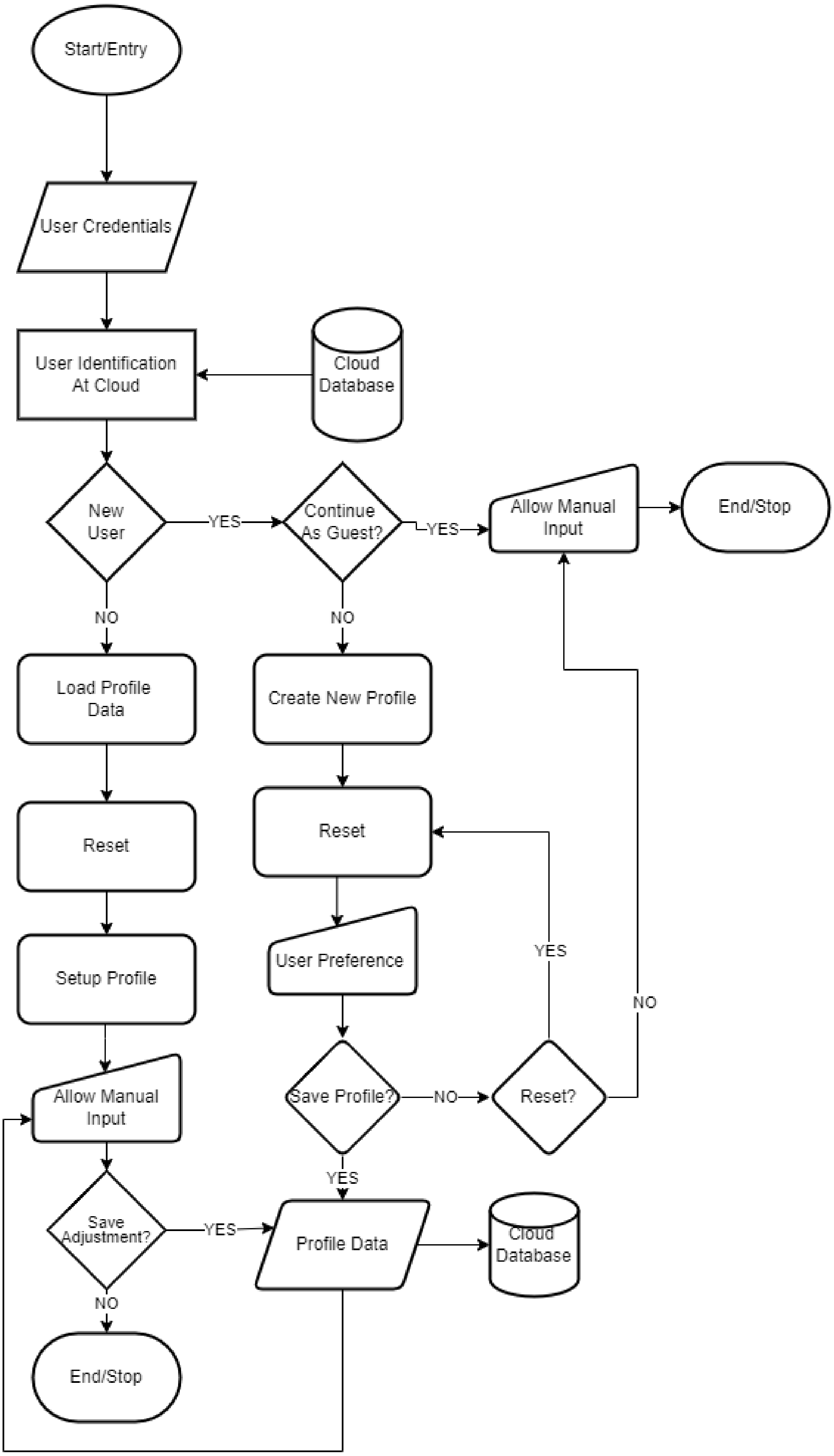
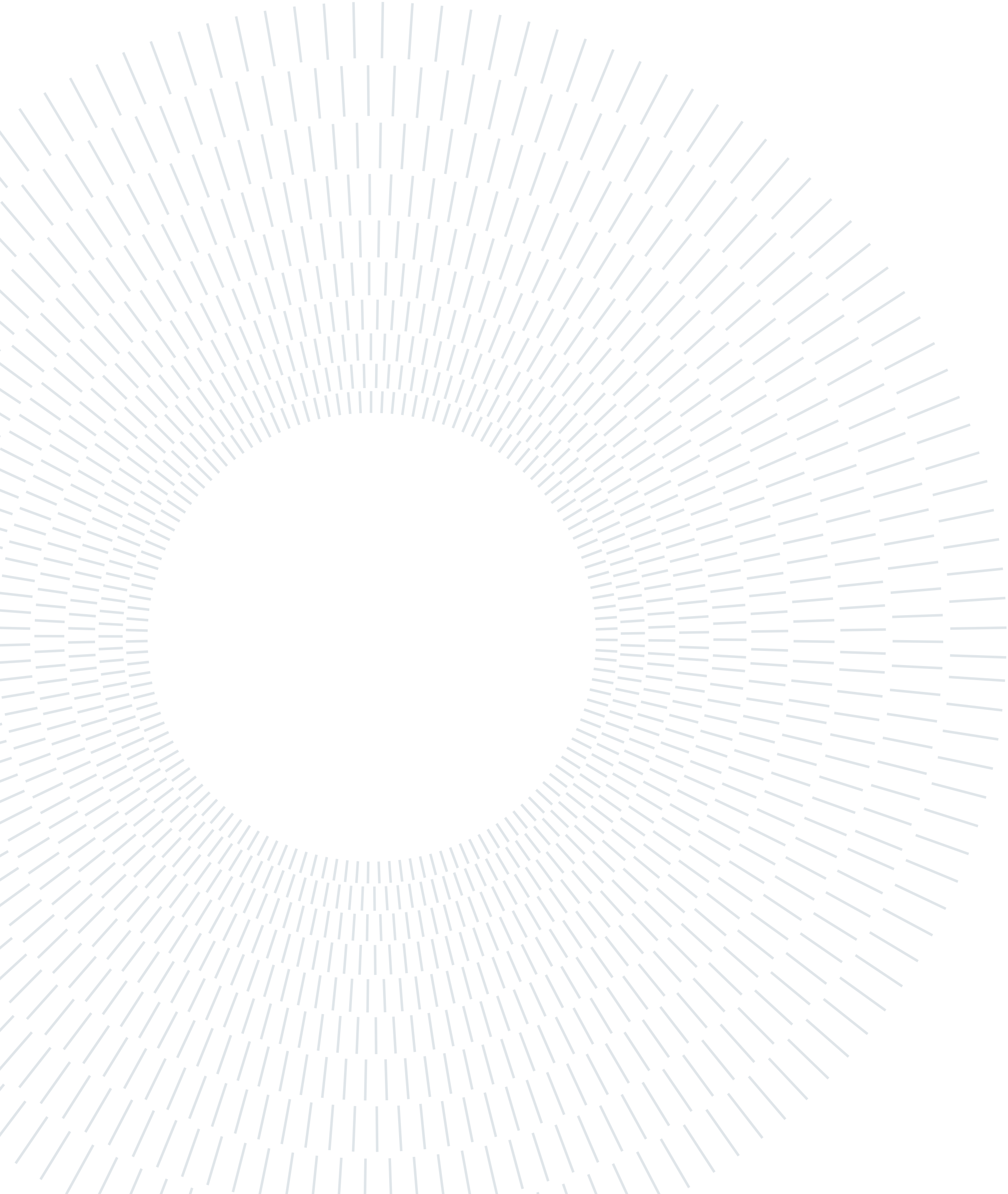


Figure 5.13: Work Flow of Profile Load System



6 | Experimental Results

Experimental tests were performed to test the functioning of the P-ICWAS and identify its limitations, if any. Functionality of both P-ICWAS and DPLF were tested using the test vehicle A. Finally, both the systems were demonstrated in a recreated real life scenario at Project Base 5G seminar held at Politecnico di Milano, Durando campus.

6.1. Experimental Setup

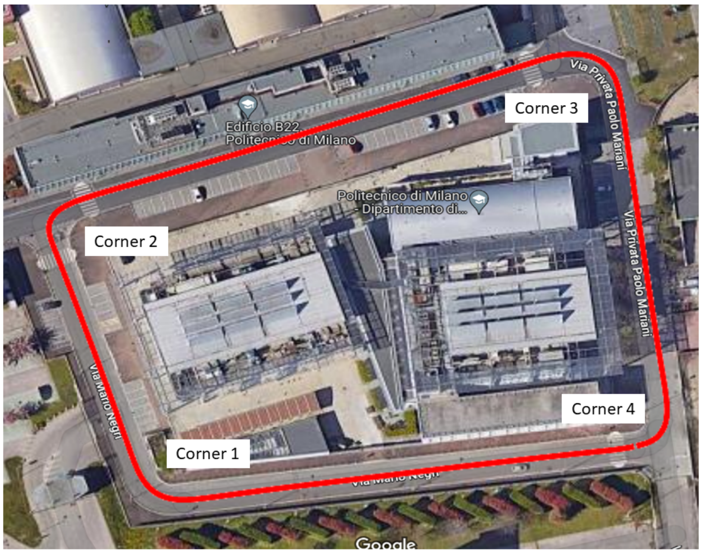


Figure 6.1: Test Map and Path

The path around the Mechanical department (B23) of Politecnico di Milano was used for testing as depicted in *Fig. 6.1.* A base station at the department was used for for RTK correction of GPS coordinates. Due to issues with other sensors, input from GPS was considered only after comparing the GPS output and the absolute velocity output of the estimator saved in a ROS bag. Corner 1 was selected for testing the P-ICWAS function. The test vehicle would go around the path in a clockwise direction. A pedestrian was placed along the path of the vehicle at the end of the curve after corner 1, depicted as a red point in *Fig. 6.2.* The aim of the test was to verify if the HMI warning provided to the driver was in time, and to check the AEB trigger functionality of the system. The AEB should get triggered at a sufficient distance from the pedestrian in order to come to a complete halt following a deceleration profile as shown in *Fig.3.7*.

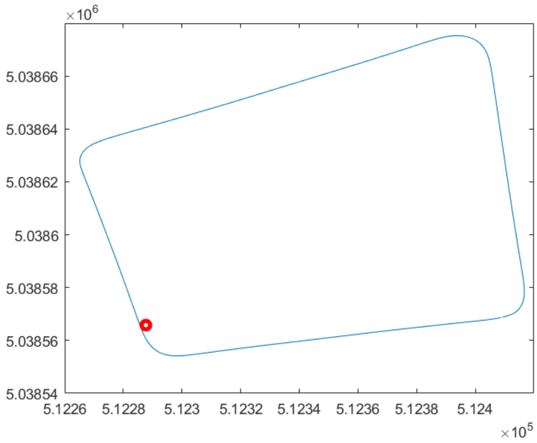
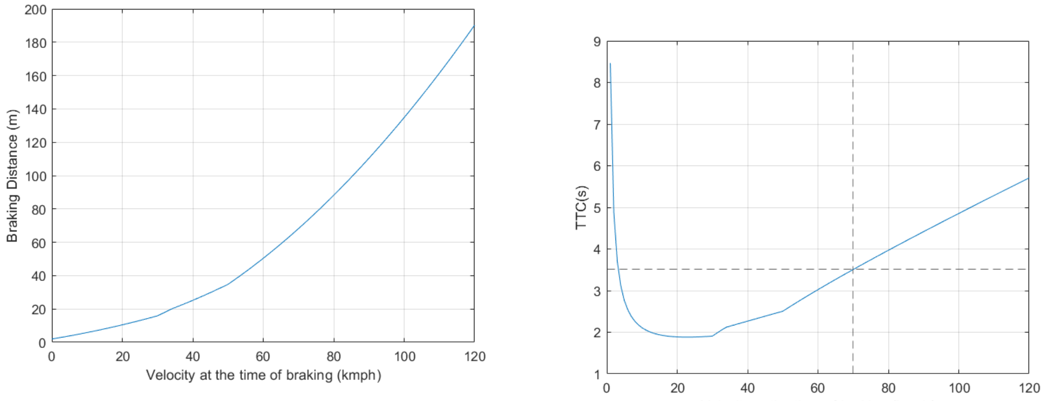


Figure 6.2: Position of the test pedestrian along the test track with GPS coordinates.

Fig. 6.3 shows the braking distance and TTC for different vehicle velocities when $\tau_1 = 1s$ and $\tau_2 = 0.5s$. These values are determined by the brake actuation system. The Time to collision threshold used for the experiment were decided using the plots shown in *Fig. 6.3b*. Instead of using a dynamic TTC_2 threshold, a value corresponding to vehicle speed of 70 kmph was used. This was done to gain initial confidence in the system. the warning time TTC_1 was set as $(TTC_2 + 3\ seconds)$ for the same reason. The data acquisition for the test started with the vehicle being at an arbitrary location before the Corner 1.



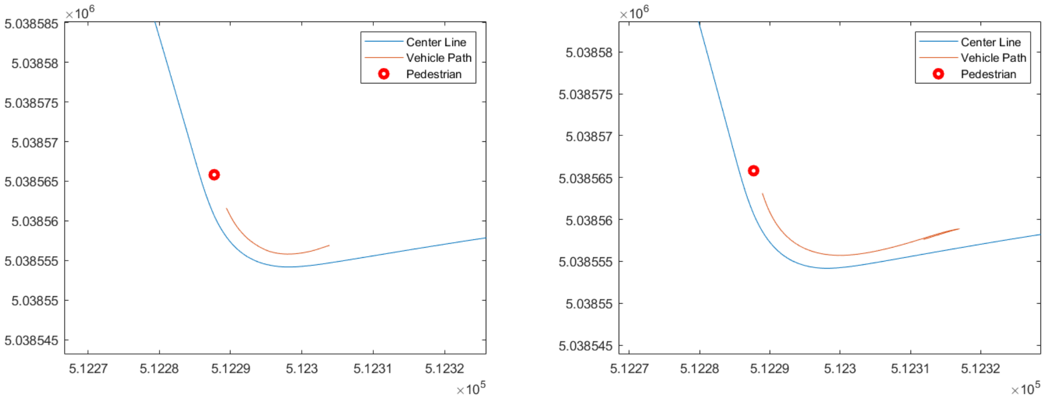
(a) Braking Distance as per deceleration profile vs Velocity

(b) TTC vs Velocity

Figure 6.3: Braking Distance and TTC vs Velocity

6.2. Results

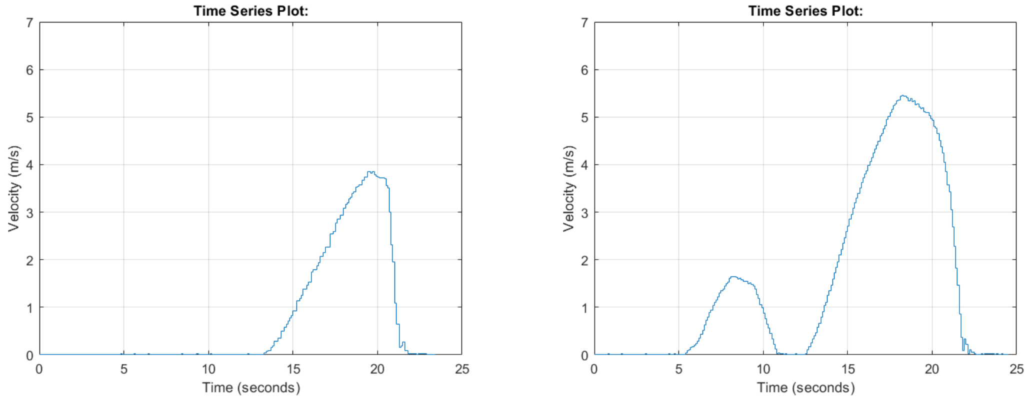
Fig. 6.4 shows the path our test vehicle took during the tests. The velocity profile of the test vehicle observed during the test are shown in *Fig. 6.5*. Warning regarding the presence of pedestrian at the crossing in a staggered form from Green to Amber to Red was relayed via the Human Machine Interface (HMI) to the driver. Green indicates when the TTC is in safe zone and the driver need not reduce the velocity of the vehicle to ensure safety of the pedestrian present. Amber is relayed to the screen on board in front of the driver when the TTC is in a warning zone, wherein the driver can react and brake accordingly on his own without the AEB taking over. As soon as the TTC is in the danger zone, depicted by red warning light on the HMI screen, the AEB is triggered forcing the vehicle to come to a stop to safeguard the VRU. This system worked with perfection, as depicted in the *fig. 6.10*. Also, the AEB was correctly triggered in time, as validated by the data acquired during the tests..



(a) (b)

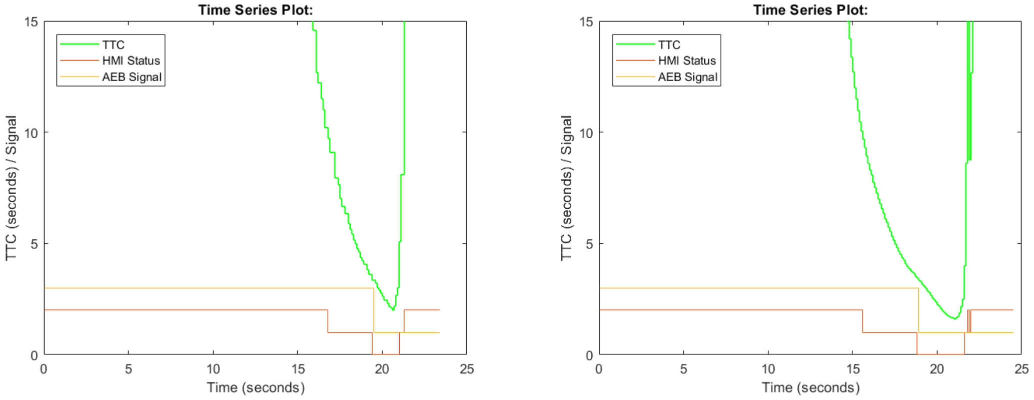
Figure 6.4: Vehicle paths during test

Fig.6.6 shows TTC (green), HMI warning signal (Red) and AEB trigger (Yellow) vs time. HMI displays a warning when the status changes from 2 to 1, as designed in our CWAS algorithm referred to in *Fig. 3.12* , i.e. when TTC falls below TTC_1 but is still higher than TTC_2, as has been described in the *Section 3.3.5* . When the TTC falls below 3.5s, the HMI signal changes its value from from 1 to 0 displaying an alert that AEB is triggered. After delay of 0.1s, the AEB trigger changes from 3 to 1 and braking is actuated, as designed. Triggering of AEB is visible by the change of state in the yellow signal in *Fig. 6.6*. During these tests, manual braking was done upon receiving the HMI alert, instead of autonomous braking to ensure safety. However, during the demonstration the autonomous braking was allowed to take over as the safety protocols were ensured. Warning Time, AEB Alert Time, Velocity, and s-coordinate of the vehicle at the time of trigger were noted and the braking distance according to the deceleration profile shown in *Fig.3.7* was calculated using (3.1). Distance remaining was calculated as the difference between the final braking s-coordinate and the s-coordinate of the pedestrian. The values of these quantities have been reported in table 6.1. It can be observed that the warning signal to HMI and AEB trigger was timely, as designed. Also, the safety distance achieved was more than twice the safety distance used to calculate braking distance and TTC_2 threshold, as referenced in *Section 3.3.5*.



(a) (b)

Figure 6.5: Velocity profiles



(a) (b)

Figure 6.6: Time history of TTC collision, HMI Warning Signal and AEB Trigger

Test	Warning Time	AEB Trigger Time	s-coordinate at trigger	Velocity at trigger	Braking Distance	Remaining Distance from the pedestrian
Test 1	16.8	19.5 s	116.3	14 kmph	7.55 m	5.7 m
Test 2	15.5 s	18.9 s	110.6	20 kmph	10.5 m	8.5 m

Table 6.1: Remaining Distance to Pedestrian

6.3. Demonstration at Project Base 5G Seminar

6.3.1. Project Base 5G

Project Base5G [5] is a research and innovation project funded by the Lombardy Region and coordinated by Politecnico di Milano (Departments DEIB, DESIGN, MECC, DASTU) and a pool of Lombardy companies (Vodafone, LIFE, AnotherReality, Yape and AKKA).

The Base5G project aims to create advanced services for the citizen whose use is increasingly automatic and “easy”, with focusing on prototyping and testing of the new use cases "Smart Parking, Smart Direction, and Smart Personal Bubble", connected to 5G technology in the Smart Cities and Smart Campus areas. Thus the project has three macro objective:

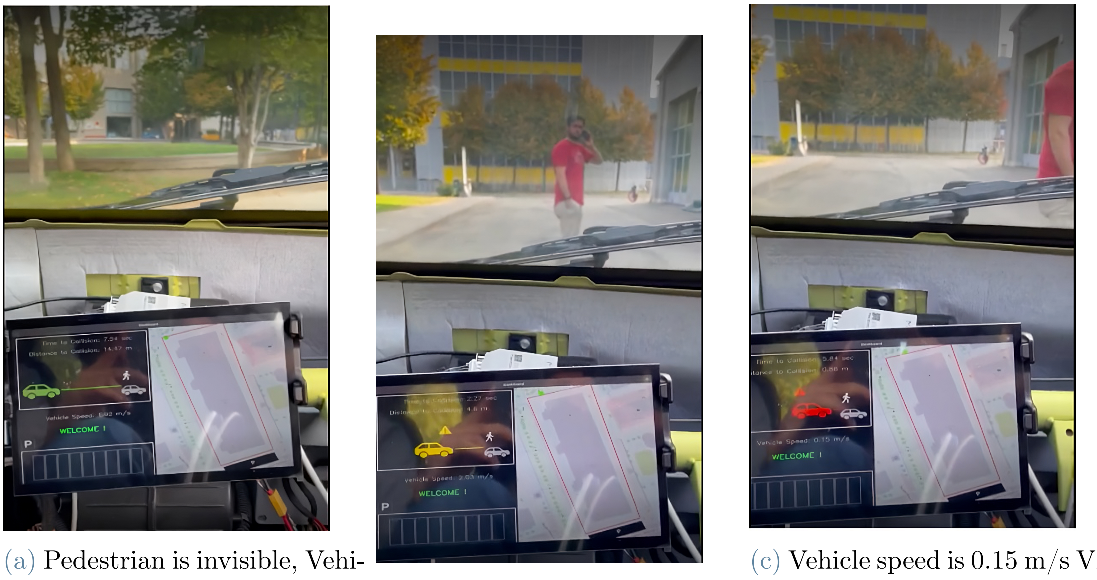
- Design of services based on intelligent environments
- Vertical integration of 5G technology with IoT platforms to support advanced services
- Development of simple interfaces for the end user

Figure 6.7: Demonstration of P-ICWAS at Base5G Seminar. A distracted pedestrian can be seen crossing the road at an unsignalised pedestrian crossing.

6.3.2. Demonstration

The systems developed in this thesis were part of the second objective of the Base 5G project. A proof-of-work for the two systems designed, P-ICWAS and DPLS was also successfully demonstrated at the Project Base5G seminar held on 8th October 2022, at Politecnico di Milano Durando Campus as depicted in *Fig. 6.7*.

P-ICWAS



(a) Pedestrian is invisible, Vehicle speed while negotiating the turn is 2.02 m/s, Visual Warning is Green, TTC is 7.54 seconds, Distance to collision is 14.47 m.

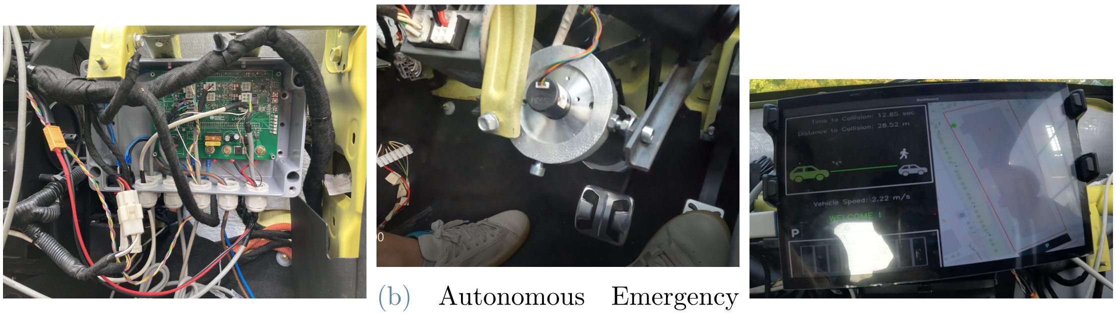
(b) Pedestrian is visible, Vehicle speed is 2.03 m/s Visual Warning is Amber, TTC is 2.27 seconds, Distance to collision is 4.6 m.

(c) Vehicle speed is 0.15 m/s Visual Warning is Red, TTC is 0.84 seconds, Distance to collision is 0.86 m. The brake has been applied autonomously, and the pedestrian is safe.

Figure 6.8: Driver's Point-of-View with TTC On Board Display including visual and audible warning.

The demonstration was done in collaboration with IoT lab of Politecnico di Milano and other PhD colleagues of our research group. The camera system, as depicted in *Fig. 6.9* was setup, which could track upto 6 moving pedestrians at a time and relay their motion information over the Vodafone 5G network. The same test vehicle as referenced in Appendix A was also used for this demonstration purpose. Upon receiving the data of the moving pedestrians over the 5G-V2I network, our algorithm was able to calculate the collision possibility, asses the risk and transmit information to the driver. If the driver could not respond in time, and in case of a risk of collision, signal to trigger AEB was sent by the developed algorithm and AEB was actuated, as depicted in *Fig. 6.10b* via communication through a CAN network, further depicted in *Fig. 6.10a*. A Human machine interface (HMI) was also setup, as depicted in *Fig. 6.10c* which displayed the TTC, Distance to collision, current velocity, a map of the path and current location of the vehicle. This HMI warned the user and correctly showed the alerts about AEB being triggered as seen in *Fig. 6.10*

Figure 6.9: Camera Setup at the location of pedestrian crossing that could relay I2V communication over a 5G network.



(a) Controller Area Network (b) Autonomous Emergency Brake Actuator (c) Human Machine Interface

Figure 6.10: Installed Subsystems of P-ICWAS

The three stages of warning and actuation described above has also been captured from the point of view of the driver during the demonstration, as depicted in *Fig. 6.10.*

DPLS

To demonstrate the Driver Profile Load System (DPLS) that we had designed, a 5G enabled camera setup similar to that of P-ICWAS was used, which was designed to use facial pattern recognition algorithm to identify the user, as can be seen in *Fig. 6.11a.* The identification was perfectly carried out on cloud and unique user id was communicated to DPLS via the designed DPLS control module as seen in *Fig. 6.11b.* The system then loaded the user profile according to the pre-saved profile data, as described in the *Section 5.4.* Then the users switched and the system was able to recognize and load the new driver

(a) Driver Identification Using Facial Recognition (b) Driver Profile Load System Control Module

Figure 6.11: Demonstration of the designed Driver Profile Load System

profile in less than 30 seconds. Also, other users who were witnessing the demonstration for the first time were able to manually set up their desired configuration and could store their information on the cloud for saving their user-profile, that could be used anytime later whenever they choose to access their profile through any DPLS enabled vehicle.

Conclusion

Technological advancements in the fields of Vehicular Communication, Sensing Environment and Computational Power are disrupting the way automobiles are being designed, manufactured and used. In this thesis, we leveraged the potential of these technologies to develop and implement systems that can improve safety of Vulnerable Road Users (VRUs), improving driver comfort and enable users to adopt sustainable modes of Mobility.

The first system developed (P-ICWAS) successfully overcame the limitations of a collision warning and avoidance system that would have relied just on on-board -sensors (OBSs) for detection, such as occlusions, traffic violations or pedestrian's behavior uncertainty. To this end,a system which utilizes 5G-network's ultra low latency, high reliability and high peak data transfer for efficient and quick I2V communication has been successfully developed and implemented, for a 5G-V2I pedestrian collision avoidance system. To the best of our knowledge, its the first time such a system has been implemented and demonstrated. An infrastructure-side camera was used to accurately detect pedestrians which successfully communicated this information to CWAS algorithm. The developed algorithm then perfectly calculated the chance of collision using a curvilinear coordinate system and performs risk assessment of the collision. Risk is assessed based on a modified time to collision (MTTC). Furthermore, a suitable warning was issued and an emergency action in the form of triggering the AEB was taken, if the warning was ignored. The TTC threshold for warning and emergency actions was decided based on the minimum braking distance the vehicle should have required in order to perform a relatively smoother braking action than full hard braking. The algorithm was experimentally validated using the test vehicle and found to be effective in warning and taking emergency measures. Experimental tests were conducted with a higher value of TTC_2 in order to build confidence in the functioning of the system. In these tests the vehicle came to an halt with more than twice the distance than of safety distance. Thus tighter TTC threshold values can be utilized. Such a system can be utilized along with present day AEB systems to improve overall road safety of both vehicle users and VRUs.

The Second system (DPLS) developed was successful in leveraging the identification technology to recognize users using facial recognition by automatically loading the drivers preferred driving configuration in much less time than they would do manually. We could successfully implement the DPLS that integrates 5G Cellular Communication Technology and Driver Identification. The system being connected to 5G network and non reliant on position detection sensors implies that the user profile can be loaded on any vehicle of the same model and can be implemented for different vehicles, even ones without any memory function with proper calibration. Such a system has the potential to instill higher level of psychological ownership value in carsharing users and reduce annoyances that may arrive with frequent use of such services. Increased adoption of such sustainable services is crucial for their socio-economical and environmental impacts to be fruitful.

These systems were developed as a part of research project called Base 5G. Functioning of these projects was successfully demonstrated at Project Base 5G seminar. Such work demonstrates it may be possible to actually achieve goals like zero emission transportation and Vision Zero and sooner than imagined.

6.3.3. Future Scope of work

While the systems developed prove to be effective within the relams of the tests performed, it is necessary that they should be tested in varied scenarios, before being deployed on the commercial vehicles. Some of the future work that can be undertaken are:

- To check test network reliability and performance under different load conditions.
- To use a model predictive control to more accurately predict the position of vehicle after the curve.
- To test and adapt the P-ICWAS system performance for VRUs other than pedestrians.
- To test the systems incongruence with other ADAS systems mounted on system to check proper communication of information and hierarchy of action.

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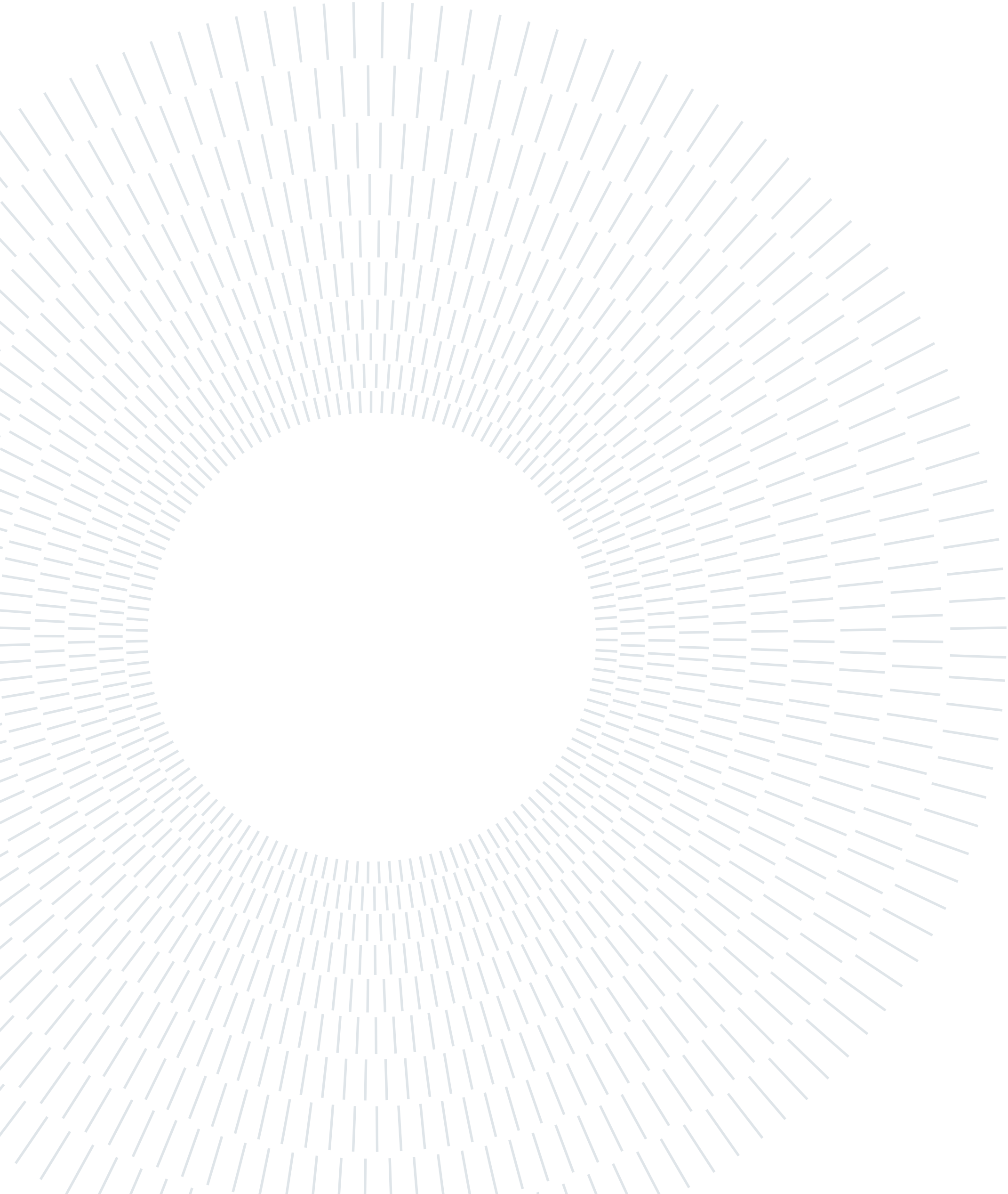


A | Appendix A

A.1. The Test Vehicle

Figure A.1: Test Vehicle used in demonstrating our thesis

General Information	
Brand	Zhidou
Model	D1
Generation	D1
Modification (Engine)	11.5 kWh (24 Hp)
Start of production	2014 year
Powertrain Architecture	BEV (Electric Vehicle)
Body type	Hatchback
Seats	2
Doors	3

Table A.1: General information of the car used in demonstrating our thesis.

A.2. Electric SubSystem Specifications

Gross battery capacity	11.5 kWh
All-electric range	145 km (90.1 mi)
Electric motor power	24 Hp @ 4200-5000 rpm.
Electric motor Torque	82 Nm (60.48 lb.-ft.)
System power	24 Hp @ 4200-5000 rpm.

Table A.2: Electric and Hybrid SubSystem Specifications of the car used in demonstrating our thesis.

A.3. Dimensions and Weight

Length	2763 mm
Width	1539 mm
Height	1524 mm
Wheelbase	1765 mm
Minimum turning circle (turning diameter)	8 m
Kerb Weight	670 Kg

Table A.3: Dimensions and Weight of the car used in demonstrating our thesis.

A.4. Performance Specifications

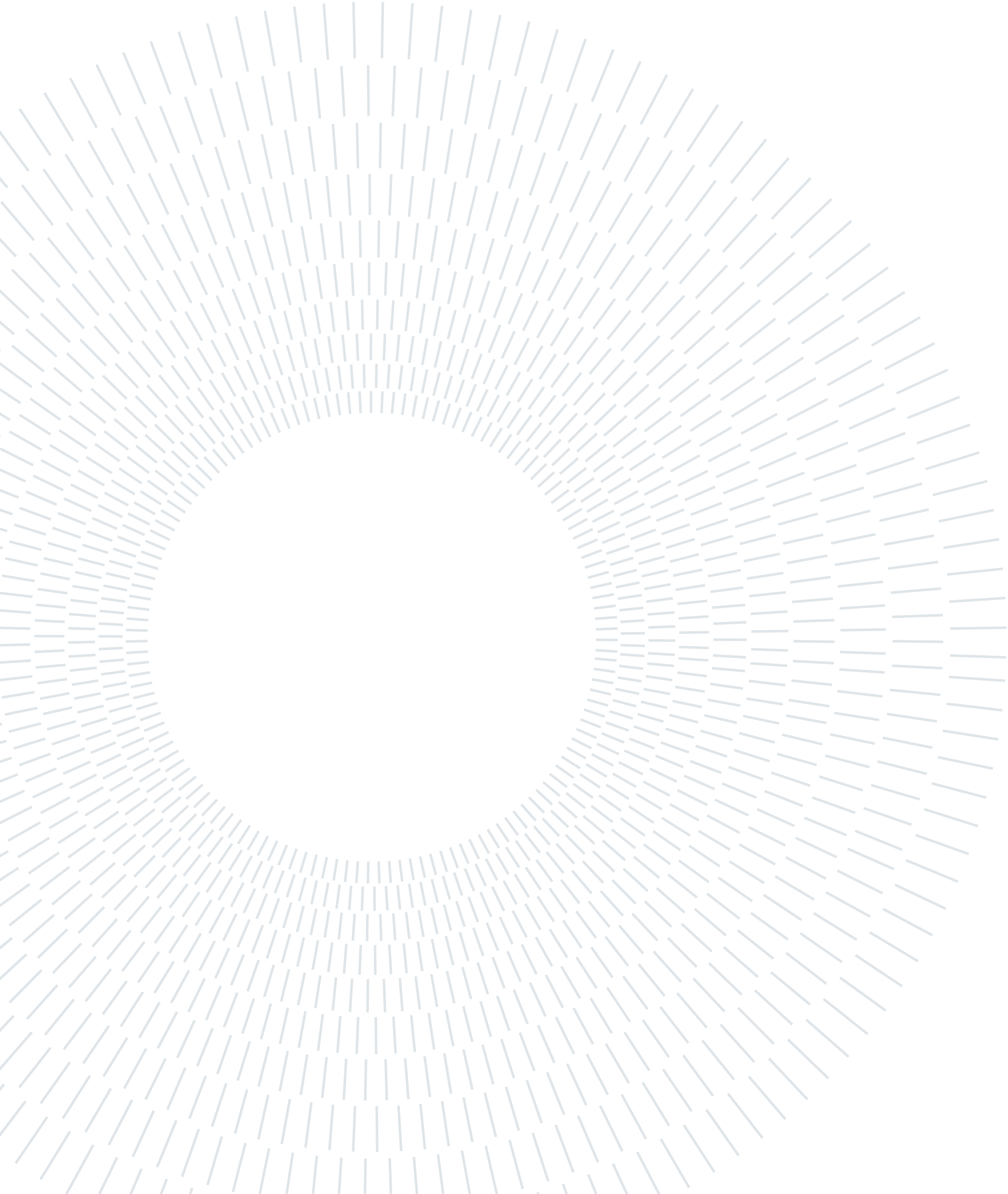
Fuel Type	Electricity
Maximum speed	80 km/h (49.71 mph)
Weight-to-power ratio	27.9 kg/Hp, 35.8 Hp/tonne

Table A.4: Performance Specifications of the car used in demonstrating our thesis.

A.5. Drivetrain, Brakes and Suspension specifications

Drive wheel	Front wheel drive
Number of gears and type of gearbox	1 gears, automatic transmission
Front suspension	Independent type McPherson
Rear suspension	dependent spring suspension
Front brakes	Disc
Rear brakes	Disc
Tires size	145/60 R13; 165/55 R13
Wheel rims size	13

Table A.5: Drivetrain, brakes and suspension specifications of the car used in demonstrating our thesis.



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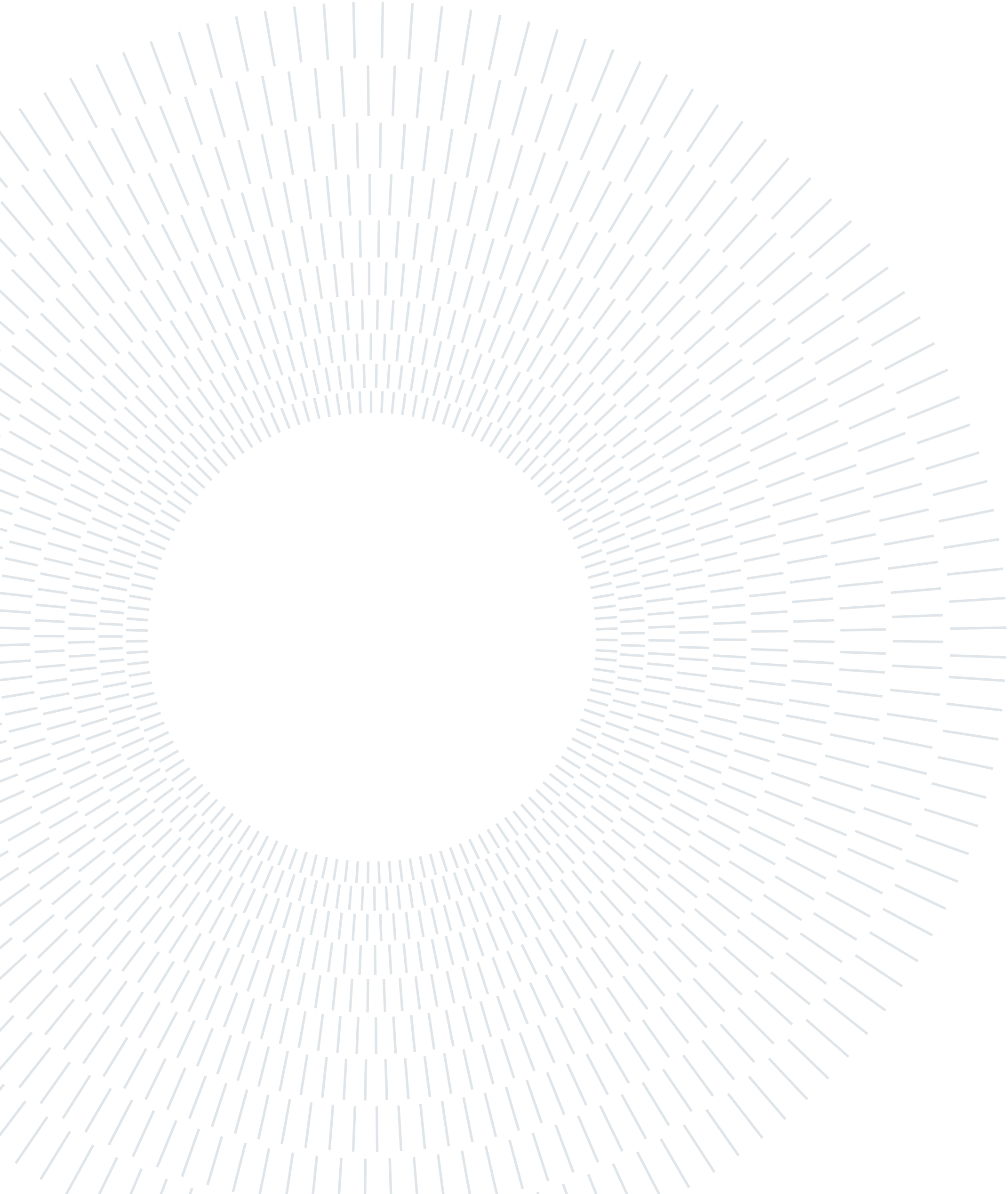

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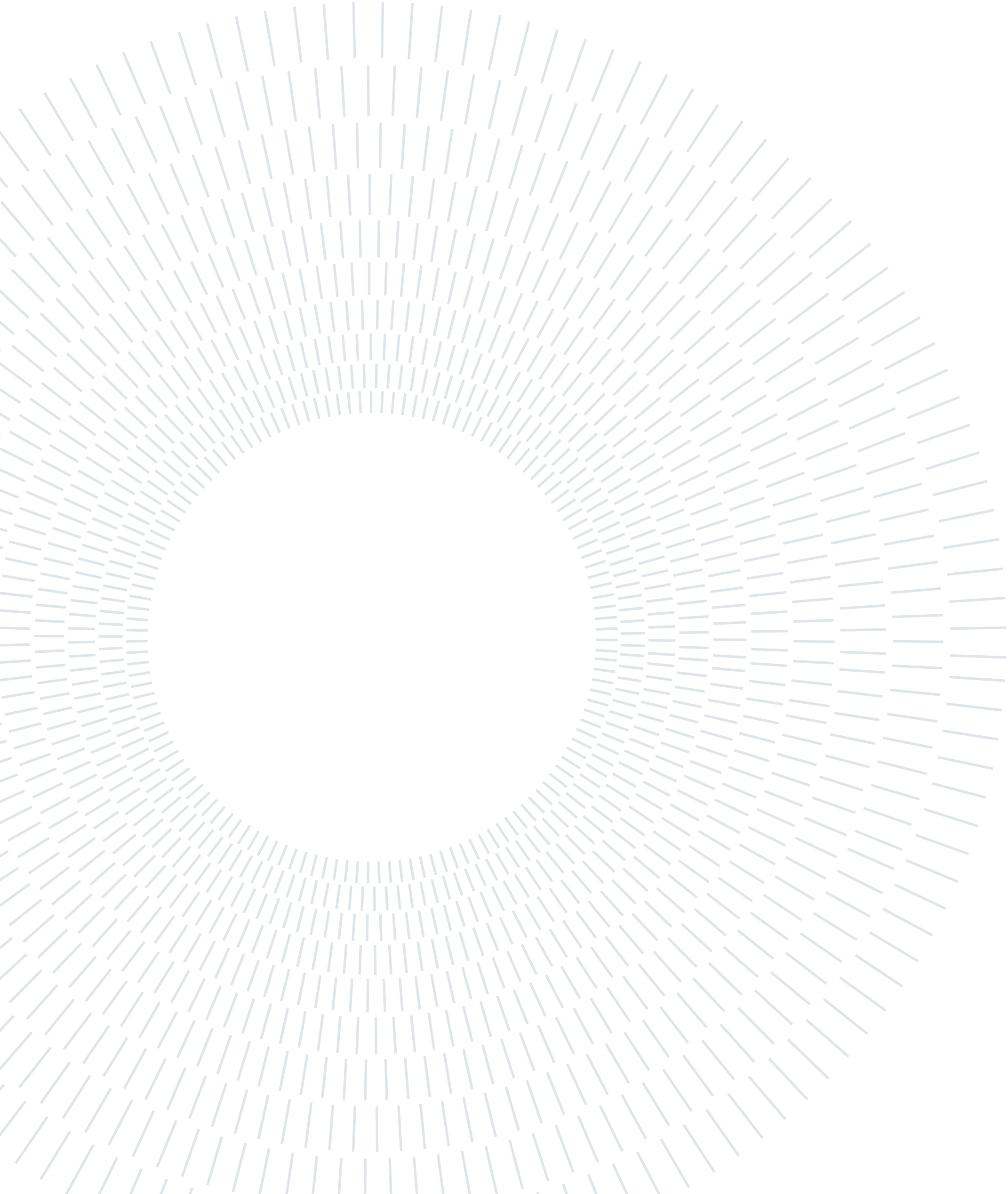

List of Abbreviations

3GPP	3rd Generation partnership Project
5G-NR	5G New Radio
5G-V2X	Fifth Generation vehicle to Everything
ACES	Autonomous driving, Connectivity, Electrification and Shared Mobility
ADAS	Advance Driver Assistance Systems
AEB	Autonomous Emergency braking
AVs	Autonomous Vehicles
C-ADAS	Connected Advance Driver Assistance Systems
CAM	Connected Autonomous Mobility
CAN	Controller Area Network
CASE	Connectivity, Autonomous Driving, Shared Mobility and Electrification
CAVs	Connected Autonomous Vehicles
CVs	Connected Vehicles
CWS	Collision Warning System
D2D	Device to Device
DPLS	Driver Profile Load System
eMBB	Enhanced Mobile Broadband
eNB	evolved Node B
I2I	Infrastructure to Infrastructure
IoT	Internet of Things
ITS	Intelligent transport System
ITU	International Telecommunication Union
MEC	Multi-access Edge Computing
mMTC	Massive Machine Type Comunication
mmWave	millimeter-Wave
MTC	Machine Type Communication
NS	Network Slicing
OEM	Original Equipment Manufacturer
P-ICWAS	Pedestrian Intersection Collision Warning and Avoidance System

PER	Packet error rate
UE	User Equipment
uMTC	ultra-reliable Machine Type Communication
URLLC	Ultra-Reliable Low Latency Communication
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle to Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VRUs	Vulnerable Road Users

Table A.6: List of Abbreviations used in our thesis

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