Enhancing Vulnerable Road Users Safety in the 6G Era: Developing a Sustainable V2X Framework

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***Abstract*—Only the chairs can edit The integration of vehicular communications, 5G mobile networks, and edge computing represents a significant shift in intelligent transportation. Key components of Intelligent Transportation Systems, such as Vehicle-to-Vehicle and Vehicle-to-Infrastructure communications, are essential for this transformation. The introduction of 5G improves connectivity, while edge computing brings processing capabilities closer to data sources. This combination has the potential to dramatically enhance transportation efficiency and safety. We focus on developing a sustainable Vehicle-to-Everything (V2X) framework based on experimentation in the Smart Highway testbed, located in Antwerp, focusing on protecting Vulnerable Road Users (VRUs). This study explores the interaction between vehicular communication and edge computing within a 5G network, focusing on the varying distances between On Board Units (OBUs) and Roadside Units (RSUs). The framework applications involve the development of a VRU Safety Mobile Application (SMA) and a Collision Prediction Edge Application (CPEA). Additionally, the research addresses sustainability by analyzing energy consumption in the context of the Central Processing Unit (CPU) load at the RSU using detailed real-world experiments and simulations. The findings indicate that energy consumption remains stable at shorter distances but shows increased variability at longer ranges.**

***Index Terms*—Vulnerable Road Users, Edge Computing, Collision Detection, Pedestrian Safety, Network Orchestration, Monitoring**

I. INTRODUCTION

In the quest to create robust and secure mobility solutions, the paramount consideration is ensuring the safety of VRUs. To accomplish this, designing an Intelligent Vehicle Infrastructure Cooperative System (VICS) is a cornerstone of smart transportation, exemplifying the collaboration between vehicles and their surroundings. Such a system integrates various communication modes, including vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), and vehicle-to-network (V2N), which are collectively known as vehicle-to-everything (V2X).

An essential Intelligent Vehicle Infrastructure is composed of two key elements: the Roadside Unit (RSU) and the On Board Unit (OBU). The interaction between these units allows vehicles to gain precise awareness of their environment, facilitating decisions that improve traffic safety and efficiency. For example, sensors on RSUs can detect nearby objects, such as pedestrians and vehicles, assess their distance and speed, and relay this information to the RSU. The RSU can then use this data to dynamically adjust the timing of smart traffic lights, thereby optimizing traffic flow and efficiency. Additionally, intelligent parking systems utilize environmental data to assess and model available parking spaces, enhancing user convenience.

CPU load represents the computational demand placed on the RSUs and OBUs as they process and transmit crucial data, such as Cooperative Awareness Messages (CAMs), between vehicles and infrastructure. In a VRU safety context, real-time processing of this data is critical for detecting and reacting to pedestrians, cyclists, and other VRUs. A high CPU load could indicate that the system is processing a large volume of data, but if not managed efficiently, it could lead to delays or system bottlenecks. These delays could compromise the timely transmission of critical safety information, thus affecting the system's ability to prevent accidents or ensure the safety of VRUs.

To ensure optimal safety, managing CPU load is essential to maintain efficient and reliable data flow. Lower CPU load or efficient load balancing would enable quicker decision-making and responses, improving the system's overall safety performance. Response time refers to how quickly the system can detect, process, and react to a potential hazard, such as a VRU entering a vehicle's path. In the Smart Highway solution, fast response times are vital for preventing accidents by alerting vehicles or adjusting traffic signals in real-time. If response times are too slow, the system may fail to provide timely warnings or take necessary actions, thus increasing the risk to VRUs.

By reducing response times through efficient edge computing and 5G connectivity, vehicles and infrastructure can react almost instantaneously to the presence of VRUs, significantly improving safety outcomes. Faster response times translate into quicker alerts to vehicles and smarter decisions made by RSUs, such as adjusting traffic lights or warning VRUs via V2P communication. The paper addresses several critical challenges associated with the integration of vehicular communications, 5G networks, and edge computing within intelligent transportation systems. One major challenge is optimizing CPU load at the Roadside Units (RSUs), particularly as the distance between OBUs and RSUs varies. The research highlights the requirement for optimising CPU load at the RSU in order . This issue is crucial for ensuring that the network operates efficiently across different scenarios.

Another significant challenge involves managing the Central

Processing Unit (CPU) load at the RSU, which is influenced by the communication distance. The variability in performance metrics, such as CPU load, at different distances, presents a further challenge. The research addresses this by ensuring that the vehicular communication network remains efficient and reliable, regardless of the physical distances involved. Balancing the findings from real-world experiments with those from simulations is another challenge the paper seeks to tackle.

Finally, the paper confronts the overarching challenge of designing vehicular communication networks that are both adaptive to varying conditions and scalable to accommodate different infrastructure sizes and traffic densities. By addressing these issues, the research aims to leverage the integration of 5G, vehicular communications, and edge computing to significantly enhance the safety and efficiency of transportation systems, while also identifying potential pitfalls in the practical deployment of these technologies.

DEDICAT-6G explores, amongst others, the use of a Smart Highway[1] (as seen in Fig.1) as part of its proof of concept. The project leverages simulations and field evaluations to advance intelligent network load balancing and human-machine interactions [1]. In the realm of public safety and smart highways, our experiment focuses on improving the safety of VRUs at intersections with obstructed visibility. This is achieved by designing a Safety Mobile Application (SMA) prioritizing VRU safety. The SMA utilizes real-time location tracking, 5G, and C-V2X communication technologies, along with collision prediction algorithms. The goal is to provide timely alerts to both VRUs and vehicle drivers, potentially preventing accidents and ensuring safer mobility. The user-friendly interface of the app changes color to convey safety status based on the situation, making it an indispensable tool for road safety.

In the context of advancing 6G network requirements to enable VICS, the DEDICAT-6G project [2] stands as a significant endeavor, seeking to establish an intelligent connectivity platform. This platform integrates existing communication infrastructure with innovative edge intelligence distribution to facilitate real-time experiences [2]– [4]. Building on the foundations laid by 5G [5], DEDICAT-6G emphasises dynamic connection development, efficient resource utilization, and enhanced privacy preservation. It specifically highlights the importance of security, privacy, and trust assurance in mobile edge services [1], [6].

The low response time is particularly crucial in a 6G system, where VRUs in various locations may have different communication needs, and their positions are constantly changing. By processing data in real time and dynamically adjusting CPU power allocation based on traffic conditions, location data, and network load, the application can ensure that VRUs are notified swiftly and accurately, even in dense urban environments or under heavy network traffic. This synergy between computational power, edge processing, and the intelligent capabilities of 6G networks enables the application to maintain a high standard of safety and reliability, particularly when it comes to protecting VRUs.

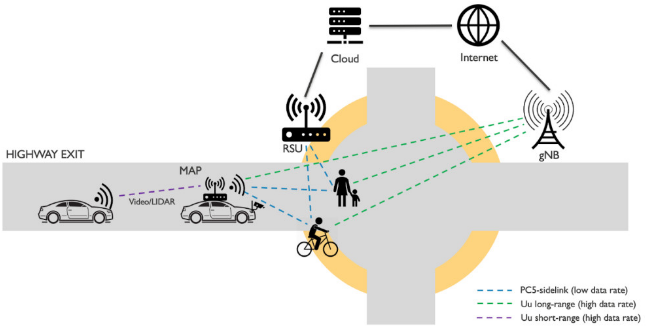

Fig. 1. The Smart Highway scenario.

A late notification in such a system can be arguably more dangerous than not having the application at all. In scenarios where VRU safety depends on timely alerts, a delayed warning could lead to false security, giving road users and vehicles the impression that they are safe when, in fact, a hazard is imminent. This false sense of protection could result in missed opportunities to take evasive actions or slow down in time, leading to accidents that could have otherwise been prevented. Therefore, maintaining low response times is critical, as the value of these safety applications lies in their ability to provide real-time, actionable information that directly impacts decision-making and risk mitigation.

In the pursuit of developing strong and secure mobility solutions, the primary focus is on safeguarding VRUs. Wang et al. [7] present a smartphone app that utilizes the device's camera and a machine learning-based image processing algorithm to monitor approaching vehicles, signaling a potential avenue for real-time hazard detection. The limitation of this solution is the dependency on local processing in the UE which limits the adoption by users with incompatible hardware. Our solution uses edge computing which uses the network to offload computation from the UE to the cloud. This enables our solution to be compatible with a wider range of UEs. Exploring Dedicated Short-Range Communications (DSRC) for V2P interactions [8] demonstrates the adaptability of vehicular communication standards, expanding the range of viable communication protocols for safety applications.

Furthermore, the exploration of specialized hardware, such as sensors attached to the shoes of the VRU [9] and electronic transponders [10], presents tangible possibilities for enhancing visibility for VRUs and crosswalk safety. This lays the groundwork for integrating wearable technologies into VRU safety. However, these approaches face significant challenges, including privacy concerns, high costs, message delays, complexities in firmware modifications, and issues with user adoption. These challenges underscore the necessity for user-friendly safety solutions for VRUs in the evolving urban mobility landscape using edge computing and V2X technologies [11]. V2V communication enables direct communication between vehicles, allowing them to share information about speed, direction, and potential hazards, while V2I communication facilitates communication between vehicles and RSUs, which can process and relay critical information such as traffic signals, road conditions and proximity to VRUs. V2P commu-

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[1] https://www.uantwerpen.be/en/research-groups/idlab/infrastructure/smart-highway/

nication allows vehicles to communicate directly with VRUs, such as pedestrians or cyclists, warning them of oncoming traffic or other dangers. Finally, V2N communication ensures that vehicles are connected to a broader network, which can provide additional data and analytics to support decision-making.

Our solution addresses challenges encountered in previous approaches, with a primary emphasis on prioritizing VRU safety within the urban transportation framework using the technologies described above. Through the deployment of the Collision Prediction Edge Application (CPEA), we aim to minimize computational overhead and ensure accurate real-time collision prediction. Our approach includes the development of a user-friendly mobile app that takes advantage of edge computing and V2X communication over a 5G Standalone (SA) network catering to the needs of both VRUs and drivers. A robust framework for optimizing edge computing in 5G-enabled vehicular communication systems seamlessly integrates advanced technologies to ensure the safety and efficiency of intelligent transportation. At the heart of this framework is the 5G mobile network, which provides the ultra-reliable, low-latency communication necessary for real-time data exchange between vehicles, infrastructure, and VRUs. The network capabilities are further enhanced by edge computing, which processes data close to the source, reducing response times and enabling immediate decision-making in critical situations. Leveraging 5G ensures high-speed data transfer, low latency [12], and increased network reliability. Additionally, V2X technologies reduce costs associated with additional deployments and maintenance by utilizing existing cellular infrastructure, offering a comprehensive network and high-speed communication in populated areas. Its future compatibility with 5G networks and ability to achieve greater range make it a promising technology for the connected vehicles industry. Moreover, our comprehensive monitoring infrastructure enables efficient data flow management, leading to optimized performance.

II. SUSTAINABLE VRU SAFETY FRAMEWORK

A. Overall Framework Architecture

Our solution is intricately designed with a three-layered architecture, each layer playing distinct roles and executing specific tasks. The initial layer, responsible for data collection, involves the Vehicle OBU and VRUs equipped with the SMA. Together, they contribute to real-time location tracking and seamless communication with the Smart Highway, facilitated by the C-V2X communication protocol between vehicles and RSUs and 5G between VRUs and RSUs.

At the core of the system resides the second layer, responsible for data treatment, embodied as the CPEA. This application critically analyzes CAM from vehicles and Global Positioning System (GPS) location data from VRUs. It swiftly identifies potential collision risks and notifies users through the mobile app, ensuring timely alerts within the mobile app interface.

The third layer, tasked with monitoring resources, comprises the Monitoring Infrastructure. Leveraging LXD containerization, this infrastructure ensures seamless management and monitoring across all nodes, including RSUs, OBUs, and the SMA infrastructure. Each container hosts Prometheus servers with key agents, namely Node Exporter and cAdvisor, collecting real-time performance metrics and health statuses. The interconnected Grafana Dashboard serves as a centralized interface for users, offering dynamic performance network (e.g., latency) data (through the monitoring of the CPU load) and status updates. This facilitates informed decision-making on resource allocation, optimization, and scalability of the CPEA.

B. Network and Computing Setup

The network architecture boasts advanced components in both the RSU and OBU (refer to Fig.1). The Smart Highway testbed (where all experimentation takes place) is equipped with advanced components for efficient communication and high-speed data transfer. The RSUs feature the USRP N310 Software-Defined Radio (SDR), which supports rapid data transfer, multiple antennas, and a wide frequency range, enhancing the system's versatility. Additionally, the RSU incorporates the Septentrio AsteRX-m2 for high-precision GNSS reception, ensuring accurate location data.

Similarly, the OBU is designed for high-performance communication within the intelligent connectivity platform. It includes an Intel Nuc 7i7DNKE with an Intel Core i7 processor, providing substantial processing power. The OBU's connectivity is supported by the Cohda MK5 OBU and Cohda MK6c EVK, offering IEEE 802.11p and C-V2X capabilities for robust communication. The USRP B210 SDR further enhances communication flexibility, while the Nvidia Jetson AGX Xavier GPU boosts data processing capabilities. The OBU also includes the Septentrio AsteRX-m2a for precise GNSS data, ensuring reliable location information within the Smart Highway network.

Monitoring Infrastructure: To efficiently manage the network, containers are deployed across all nodes, including RSUs and OBUs (see Fig. 2). Each container runs Prometheus servers with agents like Node Exporter and cAdvisor. A centralized Grafana Dashboard, connected to the Prometheus servers, provides real-time insights into the performance and health of RSUs, OBUs, and the SMA. The dashboard actively displays metrics such as CPU usage, disk space, memory utilization, and data traffic, providing efficient resource management and scalability through containerization.

C. Advanced Applications

VRU Safety Mobile Application: Deployed on both VRU smartphones and vehicles, the SMA utilizes C-V2X and 5G communication for seamless interaction with the Smart Highway. It tracks users' geographical locations in real-time, enabling updates to the CPEA and dynamic display of VRU locations on a map. A message sequence chart depicting our sustainable VRU safety framework is shown in Fig.3. Employing Dart's asynchronous programming capabilities[2], it ensures efficient communication with the CPEA through Hypertext Transfer Protocol (HTTP) and User Datagram Protocol (UDP). The app integrates Flutter's widget tree for a clean and user-friendly interface, allowing easy navigation

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[2] https://dart.dev/libraries/async/async-await

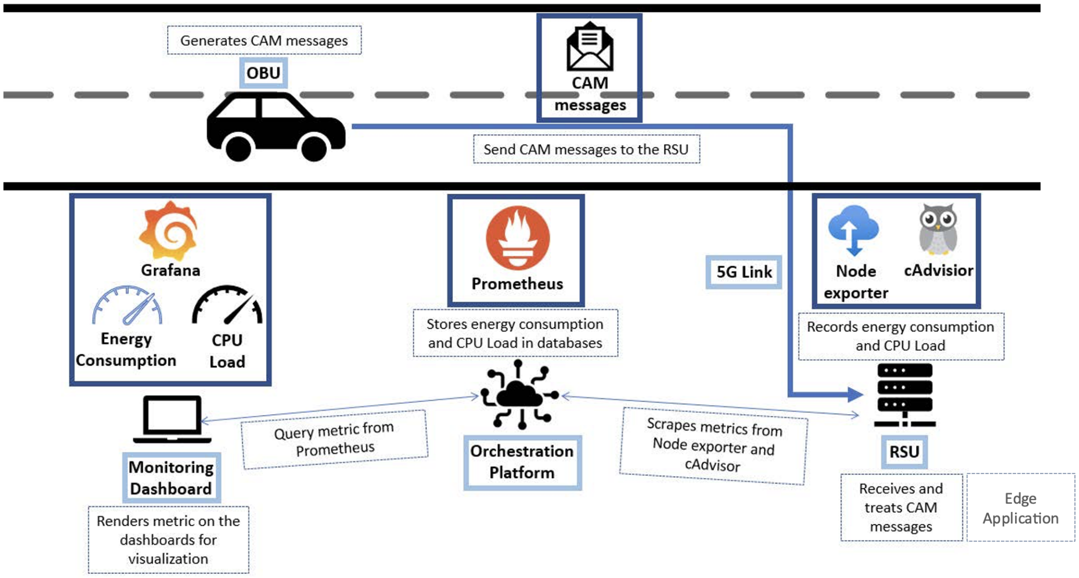

Fig. 2. Experimental architecture of the 5G system in the context of V2X communication.

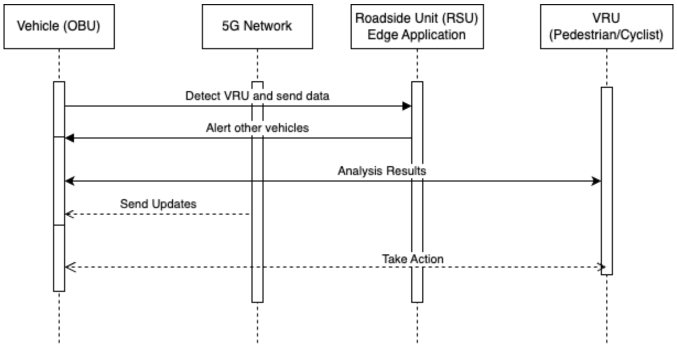

Fig. 3. Message sequence chart of the dynamic V2X framework.

across various sections, such as the home page, log page, and settings. The interface dynamically changes colors to convey safe surroundings (green) or approaching threats (red) when warnings are received (see Fig. 1). The app includes log and history options, utilizing the SharedPreferences package[3] for storing and reviewing important events, providing users the ability to clear the log when necessary. Its robust structure revolves around Flutter's widget tree[4], with state management efficiently controlled through various StatefulWidget[5]classes, enabling seamless navigation between interfaces.

Collision Prediction Edge Application: Positioned at the network edge, this app analyzes CAM messages from vehicles and GPS location data from VRUs to identify potential collision risks. It notifies users through the SMA, utilizing the NotificationService class and Flutter Local Notifications plugin, when a potential risk is detected. The app considers various factors like location, speed, and direction to assess different situations.

III. IMPLEMENTATION

The primary aim of this experiment is to conduct a detailed analysis of the CPU load on the RSU, particularly at the edge node, across varying communication ranges, specifically at distances of 30, 50, 70, and 80 meters between the RSU and the vehicle. By simulating these distances and transmitting data packets from the OBU within a BMW to the RSU, the study seeks to evaluate the effect of distance on CPU load. Through this analysis, we gain critical insights into the behavior of the edge node within a dynamic 5G communication scenario, focusing on system performance.

A comprehensive monitoring system is deployed to record and monitor CPU load. Encapsulated within an LXD container, this system ensures seamless management and monitoring of the RSU. Within this container, a Prometheus server, accompanied by key agents such as Node Exporter[6] and cAdvisor[7], actively collects real-time performance metrics (e.g., latency, throughput, CPU load, etc.) and health statuses (e.g., status of the RSU (ON/OFF)). These components collaborate with a Grafana Dashboard, serving as a centralized interface for visualizing dynamic performance data and receiving real-time status updates.

The experiment setup is carefully constructed to monitor the CPU load in real-time using a Grafana Dashboard, which provides users with a centralized interface for visualizing dynamic performance metrics. This allows for continuous observation of the RSU's CPU load and immediate updates on the performance of the edge node. By evaluating the CPU load under varying communication ranges, the experiment aims to understand how effectively the edge node could process data in real-world conditions.

Conducted at the University of Antwerp's Groenenborger Campus in Belgium, the experiment features a real-world

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[3] https://pub.dev/packages/shared_preferences

[4] https://docs.flutter.dev/ui

[5] https://api.flutter.dev/flutter/widgets/StatefulWidget-class.html

[6] https://github.com/prometheus/node_exporter

[7] https://github.com/google/cadvisor

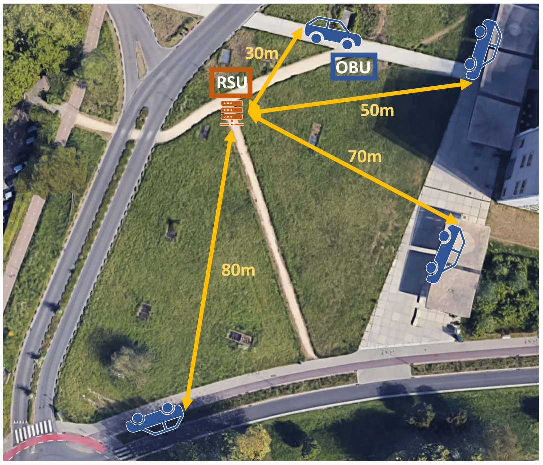

Fig. 4. 5G testbed setup at the University of Antwerp Campus Groenenborger in Antwerp.

TABLE I
CPU LOAD OF THE EDGE.

Time(s)	30 m	50 m	70 m	80 m
0	7.14%	10.89%	12.66%	13.11%
0.5	11.41%	11.79%	17.19%	13.07%
1	12.30%	11.86%	16.78%	13.50%
1.5	12.19%	10.66%	14.91%	17.95%
2	13.07%	15.69%	15.57%	14.67%
2.5	12.93%	15.33%	16.03%	12.24%
3	12.97%	16.58%	17.27%	12.42%
3.5	12.93%	17.75%	17.22%	13.11%
4	12.94%	17.67%	17.49%	13.67%
4.5	13.02%	17.42%	17.87%	19.50%
5	13.09%	16.13%	16.50%	15.72%
5.5	12.97%	15.54%	15.55%	20.02%
6	13.06%	15.49%	18.53%	16.49%
6.5	13.07%	16.55%	18.43%	13.45%
7	10.89%	10.43%	13.41%	13.11%

deployment with an OBU mounted in a BMW (as part of the Smart Highway infrastructure) and a strategically positioned RSU on the campus. The 5G connection is established between the OBU and RSU, enabling the seamless transmission of CAMs, with CPU load at the RSU recorded at different distances.

Importantly, the results demonstrated that if the CPU load at the RSU is sufficiently low, the response time of the CPEA is not compromised. This ensures that timely notifications are sent to VRUs, allowing them ample time to react and preserve their safety. Additionally, the findings confirm that the communication distance —whether 30 meters or 80 meters— does not impact the CPU load significantly enough to affect the performance of the CPEA. Thus, the experiment effectively rules out distance as a factor that could hinder the timely delivery of notifications, reinforcing the reliability of the system in maintaining VRU safety in a real-world 5G communication environment.

The specific focus on generating CAM messages and assessing their impact on the CPU load of the RSU provided crucial insights into the performance of the system under dynamic conditions. This experiment, set within an authentic environment, aims to capture nuanced details about the interplay between communication distances and processing load. The University of Antwerp Campus Groenenborger serves as an optimal location for this real-world deployment, ensuring the relevance and applicability of the experiment in practical urban settings. The monitoring of the CPU Load at the Edge node (RSU) is a key aspect in the experimental setup, specifically focusing on different communication distances: 30, 50, 70, and 80 meters (refer to Fig. 4). The recorded percentages reflect the proportion of CPU load over time during the transmission of CAM.

At a distance of 30 meters, the CPU load exhibits a relatively stable pattern. The initial utilization hovers around 7-8%, indicating a moderate load on the edge node. As the CAM transmission commences, there is a noticeable increase, peaking at around 13.07%. Subsequently, the CPU load gradually decreases, reaching around 10.66% after the transmission concludes. Upon increasing the distance to 50 meters, the CPU load demonstrates a more varied trend. The utilization commences at approximately 12.79%, rising significantly during CAM transmission with peaks reaching 17.75%. Post-transmission, a noticeable decline in CPU load is observed, stabilizing around 11.86%. Extending the distance to 70 meters introduces further variability in the CPU load. The initial CPU load is approximately 13.41%, escalating during CAM transmission and reaching peaks of around 18.53%. The post-transmission period sees a decline in CPU load, stabilizing around 13.50%. The scenario at an 80-meter distance presents distinct CPU load patterns. The initial CPU load is approximately 13.45%, escalating during CAM transmission, with peaks reaching 20.02%. After the transmission concludes, the CPU load gradually decreases, reaching 13.11% and eventually stabilizing at initial values.

The results of the CPU load measurements are summarized in Table I below. In our study, the CPU acts as the primary processing hub, managing the computational tasks required for processing and transmitting CAMs between OBUs and RSUs. The CPU load is particularly critical in scenarios demanding rapid and simultaneous vehicle communication, as it reflects the intensity and efficiency of computation necessary for smooth data exchange in dynamic vehicular environments [13].

These detailed observations of CPU load dynamics across varying communication distances provide valuable insights into the performance of the Edge node (RSU) during CAM transmissions. The experiment allows for a nuanced understanding of how communication range influences CPU load patterns, contributing to a comprehensive assessment of the behavior of the system under diverse scenarios. In a 6G system, an application designed to ensure the safety of VRUs requires a certain level of CPU power to meet the critical demands of timely notifications and low response times. This is because the application must process large volumes of data, such as location information from VRUs and vehicles, traffic conditions, and sensor inputs from the surrounding environment, in real-time. To achieve this, the system must allocate sufficient computational resources to the edge nodes, such as RSUs and OBUs, where much of this data processing occurs.

IV. CONCLUSIONS & FUTURE WORKS

The presented paper explores the development of a sustainable VRU safety framework to enhance road safety through advanced communication technologies, edge computing, and real-time monitoring, as shown in Fig. 2. The study involves the integration of OBUs in vehicles and RSUs strategically positioned in urban settings, establishing a robust 5G communication network.

The architectural design of the system is carefully structured into three layers, each playing a distinct role. The first layer focuses on data collection involving OBUs, VRUs equipped with the SMA shown in Fig. 2, and RSUs. The second layer, represented by the CPEA, critically analyzes CAM and GPS location data, contributing to real-time collision prediction. The third layer monitors resources using containerization and advanced tools for efficient management and evaluation.

The experimentation phase, conducted at the University of Antwerp Campus Groenenborger, delves into the CPU load of RSUs at varying communication distances. The study provides a detailed analysis of how the CPU load at the edge node evolves under different scenarios, shedding light on performance variations with distances ranging from 30 to 80 meters. Notable findings from the CPU load analysis indicate that as the communication distance increases, the CPU load exhibits greater variability. Distances of 50 meters and beyond show a discernible increase in CPU load during CAM transmission, with subsequent stabilization post-transmission. This information is crucial for optimizing resource utilization and system performance in real-world urban environments.

If the application malfunctions, particularly due to high CPU load at the RSU, it could severely compromise the safety of VRUs. A system under strain may delay the delivery of critical notifications, which is arguably more dangerous than not having the application at all. Late notifications could provide VRUs with a false sense of security, leaving them with insufficient time to react to hazards, potentially leading to accidents that could have otherwise been avoided. In the broader context of a sustainable 6G system, intelligence plays a key role in optimizing resources at the edge, ensuring that CPU load remains within manageable limits to prevent such malfunctions. Additionally, advanced AI within the system can dynamically detect VRUs and prioritize resource allocation, guaranteeing that timely notifications are consistently delivered.

In demonstrating the stability of the system, our findings show that the application running within the 6G-enabled network performs consistently, regardless of the distance between vehicles and RSUs. This stability is maintained due to the advanced capabilities of 6G, including its ultra-low latency and efficient edge computing infrastructure, which processes data locally, minimizing the impact of physical distance on performance. Extensive testing has confirmed that whether a vehicle is in close proximity to the RSU or further away, the system's ability to process and deliver critical notifications to VRUs remains unaffected. As a result, we can confidently rule out distance as a factor influencing the performance of the EdgeApp, ensuring that timely notifications and low response times are maintained across varying distances within the network. This highlights the system's reliability in delivering real-time safety alerts, regardless of geographical positioning.

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