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RESEARCH ARTICLE

A Sensing, Communication and Computing Approach for Vulnerable Road Users Safety

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ABSTRACT Most fatal road accidents in urban areas involve vulnerable road users. New solutions for fighting against these accidents can be considered by leveraging connected, intelligent vehicles and smart cities connecting all parts of an urban environment. This work proposes a multi-sensing and communication approach to prevent potential accidents between vehicles and VRUs, by predicting and notifying both about potential collisions before they happen. This approach leverages and aggregates information from smart city sensors, dispersed in the vehicles (and aggregated by the On-Board Units, OBUs), in the VRUs (e.g., smartphones and smartwatches), and on the road itself (e.g. video cameras, radars, lidars). These elements communicate through several message standards and wireless access technologies (e.g. ITS-G5, C-V2X, LTE, 5G and, in the future, 6G). Using both sensing and communication, fusion and collision detection algorithms, this system predicts and notifies potential hazardous situations involving Vulnerable Road User (VRU)s and vehicles. The results in a real scenario with sensors, VRUs and vehicles on the road show that the system predicts potential collisions with high accuracy and low delay. Results also point to some vital deployment decisions that must be made to ensure proper notification timings, such as the usage of multi-homing, 5G and edge computing.

INDEX TERMS 5G, edge computing, ITS, smart city, vehicular ad-hoc networks, vulnerable road users.

I. INTRODUCTION

According to the World Health Organization [1], in 2016 1.35 million people died within road accidents. In an urban environment, roads can be hazardous for Vulnerable Road Users (VRUs), such as children, disabled or impaired people, older people, and other types of pedestrians. In addition, non-human VRUs, such as dogs or wild animals, can pose a danger to vehicles and their occupants.

With the advent of smart cities, more and more data can be obtained from road users, namely vehicles and VRUs. These data can improve urban environments in entertainment, traffic management, urban planning, health, and, more crucially, road safety. At the core of smart cities are road elements connected with a shared infrastructure. A smart city can contain several Intelligent Transportation Systems (ITSs) vehicles (with capabilities for sensing the surrounding environment) and VRUs with smartphones and other connected wearable devices, but also other road infrastructure sensors (such as video cameras, RAdio Detection And Ranging (Radar), LIght Detection And Ranging (Lidar) and other sensors) to create a complete picture of the current status of the smart city. References [2], [3], [4].

The amount of information a smart city can send to vehicles and the vehicle's sensing capabilities is now sufficient to support semi-autonomous vehicles. Vehicles now possess the

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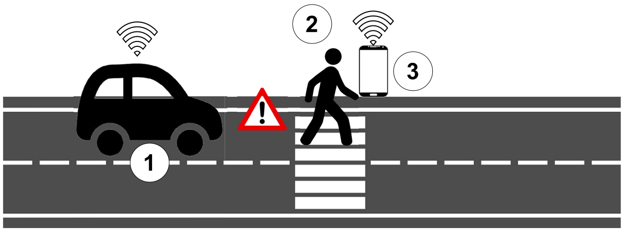

FIGURE 1. Vehicle (1) and a pedestrian (2) are warned about a potential collision. The pedestrian has a ITS-S, e.g. a smartphone (3). Roads have no infrastructure associated.

information to support helping and replacing the driver in several tasks such as park assist, lane merging assist, and keeping a stable distance from another car (adaptive cruise control). These capabilities support the end goal of manufacturers to achieve full autonomy within their vehicles [5], [6], while ensuring the safety of passengers and others VRUs outside the vehicle.

Current solutions to ensure VRU safety focus on the vehicle being able to act and react to its surroundings - and for example, break if a VRU is close - based on the information from the vehicle onboard sensors [7]. However, these solutions require the vehicle to be fully equipped with sensors, not equipped in older or cheaper vehicles. Moreover, they do not fully explore the full potential of smart city infrastructures and available data. Road elements, sensors and infrastructure within smart cities can, in cooperation with intelligent vehicles, provide information about the status of vehicles and VRUs, for one side, and warn them in real time about currently dangerous situations. In addition, smart cities could also power new services to predict dangerous situations before they happen, significantly reducing the risk for vehicles and VRUs.

In this work, we explore and implement a system that focuses on improving the safety of VRUs within a smart city environment by using a multi-sensor system and communication to predict and warn about potential collisions. Figure 1 provides an overview of the system behavior. The system receives as input existing information from intelligent vehicles (①) and the smart cities (②), and implements a solution to obtain the status of the VRUs from their smartphones (③). The system then fuses and processes the information to decide if a collision is likely and, if so, it warns vehicles and VRUs. To communicate with vehicles and VRUs, the system leverages multiple access communication technologies (IEEE 802.11p WAVE (WAVE), Long Term Evolution (LTE), 5G) and edge computing.

More specifically, the proposal of this article is to improve VRU Safety in an active way, using sensor detection in the vehicles, in the VRUs and in the roads and communication between themselves, to predict, warn and prevent potential accidents between vehicles and VRUs. For this approach, it proposes a multi-sensor solution that leverages existing information sources, such as radars, video cameras, messages communication from vehicles and from VRUs smartphones. With this information, gathered through communication technologies such as ITS-G5, 4G and 5G, it proposes a prediction algorithm, in the cloud and in the edge, that assesses collision probability based on kinematics. The results in a real road scenario show that the system can react with low times compatible with ITS services, and that 5G communication and the edge processing can provide great advantages. The results also show how the accuracy of the system can improve with the different sensors and with the sensor fusion proposed, and confirm the scalability of the safety application.

The main contributions of this work can be summarized as follows:

- solution to introduce VRUs in the context of a vehicular network and integrate them in a vehicular network;
- data fusion between the communication data, radars and video cameras to improve the accuracy of the nodes' position and velocity;
- algorithm that assesses collision probability, and that considers the data fusion from the radars, video cameras, the messages from both vehicles and VRUs, and the ITS stations;
- mechanism that prevents and warns about potentially dangerous situations on the road;
- analysis of the edge vs cloud computing in a real vehicular network scenario;
- analysis of the ITS-G5 and 4G vs 5G communications for a VRU warning system;
- usage of data from a smart city in a real context and testing in a real environment.

The remaining of this article is organized as follows. Section II overviews the related work. Section III details the existing solutions to improve VRU safety. Section IV explains the proposed architecture for the multi-sensor collision prediction solution. Section VII evaluates the overall system solutions and compares edge and centralized approaches, LTE and 5G approaches, and the importance of sensor fusion. Finally, Section VIII presents valuable remarks about this work and introduces future work.

II. RELATED WORK

Within the context of Intelligent Transport Systems (ITSs), applications can be considered as safety or non-safety [8]. Non-safety applications are responsible for infotainment and comfort needs or traffic management (optimizing and monitoring the traffic flow). In opposition, safety applications are designed to reduce and prevent accidents and collisions between vehicles and VRUs, and warn about road hazards. Examples of such applications are solutions such as emergency braking, see-through, optimal speed advisory, overtake support, adaptive cruise control, e-calls, and forward collision avoidance [9], [10]. From these, the most important with immediate effects are the forward collision avoidance between vehicles and VRUs.

VRU protection falls within ITS safety applications. Achieving VRU protection can be done by passive VRU protection - the reduction of the impact on a VRU when the accident is no longer avoidable - or active VRU protection - actively avoiding the collision [11]. The current technologies and safety methods for VRU active safety can be divided into three categories [12]:

- **In-vehicle systems**: based on On-Board Units (OBUs) within vehicles;
- **Carried by-the-pedestrian systems**: e.g. based on a smartphone or wearable application;
- **Indirect systems:** based on systems connected to road infrastructure.

The work in [13] surveyed existing V2P solutions for safety applications with VRUs, devices for vehicles and VRUs (smartphones, helmets, tags) and modes of communication (direct / indirect). The conclusion from this study is that safety applications should rely on multiple solutions (hybrid) to ensure better reliability, since the decision systems may need to include also information and sensors from vehicles and the roads. Our proposed solution considers an indirect approach in which vehicles and VRUs communicate with the infrastructure of the smart city of Aveiro to enable the gathering of data from VRUs, vehicles and infrastructure.

Solutions based on the usage of the Vehicular Ad-hoc Network (VANET) infrastructure and information to predict a potential collision between vehicles and vehicles and VRUs, are the most prevalent.

The work in [14] presents a lightweight two stages solution to detect a potential collision between VRUs and vehicles based on 1) radio signal strength and 2) locations of vehicle and VRU, exchanged within a V2P communication. While in this solution a VRU is using a smartphone, this solution fails to incorporate the environmental and mobility smart city sensors information.

The work in [15] considers additional parameters to collision risk, such as weather condition and driving fatigue, through a Hidden Markov Model, and the one in [16] proposes a safety application to classify types of overtaking and send warnings to the vehicle driver, if needed. Finally, the work in [17] introduces a safety system for cooperative lane change using a decision tree to process information about environment, vehicles and V2V information. However, these solutions fail to consider the sum of the environment, vehicles and VRUs information, by not incorporating the VRU information.

On a different side, the work in [18] presents solutions that leverage the information coming from the smartphone of VRUs to obtain their location and predict movements and next steps. Multi satellite and sensor data fusion techniques are considered in order to improve the location accuracy. However, this solution fails to fuse the information from the smartphones with both vehicles and infrastructure.

The proposal in [19] introduces a smartphone based solution for tourism within the city of Lancaster. This solution emphasizes the historical importance and relevance of mobile context-aware applications to interact and serve the user's needs while adapting to the surroundings. A safety application for VRUs must also be a mobile context-aware application and understand the VRU surroundings to better protect them.

Several algorithms are available that can consider information from vehicles, VRUs smartphones sensors and smart city infrastructure, from more straightforward and quicker kinematics-based algorithms to more complex Neural Networks algorithms. However, while all algorithms, to some extent, fulfill the functional requirement of predicting potentially dangerous situations, not all are compatible with timing requirements.

The definition of a potential accident is challenging since a simple change in the vehicle, or VRU dynamics might change the overcome - e.g. the vehicle might turn, or the VRU might run away. In [20], a set of kinematic equations is defined based on Newton's Second Law. These equations can determine the distance and time until the vehicle reaches a collision point with a VRU. In addition, [21] defines the concept of Time To Collision (TTC). TTC is frequently used to measure how urgent a situation is. The work in [22], within its collision risk assessment, presents a trajectory-based collision detection system based on the Euclidean distance between the vehicle and VRU. Vehicle's and VRU position, speed, and acceleration are used to predict future collisions that will happen if the time until the minimum distance between the vehicle and VRU is shorter than the space to collision, s_{col}. This solution, while using some information about the vehicle and VRU, relies too strongly on the correct definition of the s_{col} parameter and ignores crucial information such as the heading of the vehicle and VRU.

Within the definition of the concept of Geographical Destination Area (GDA), *i.e.*, if a vehicle is in this area, pedestrians have to be informed about the incoming vehicle, and [23] defines a time to a collision between VRU and vehicle. Such time is computed based on the subsequent positions of a vehicle represented by a bicycle kinematic model. This model allows taking into consideration the heading information, increasing its precision compared to previous alternatives.

The work developed in [24] considers the characteristics of the vehicles that might affect the braking times and the drivers' reaction times within the computation of zone lengths. These safe/unsafe/potentially unsafe zones, with a centre either in the vehicle or VRU, define a length in which if the distance between VRU and the vehicle is equal or smaller than a specified value, the situation is deemed safe/unsafe/potentially unsafe.

Since the system to be developed is considered critical safety, timing requirements are exact and critical. This criticalness shall be considered during architectural decisions, namely in the decision between edge, centralized cloud, or hybrid solutions or in the choice of both the aggregator and persistence solutions for the information of sensors and VANETs. The work in [25] relates the end-to-end delay (between VRUs and vehicles awareness and notification of potential accident) with the accuracy of its location. If the

VRUs position inaccuracy is 0.5 *m*, the overall end-to-end latency must not exceed 100 *ms*. If the positioning inaccuracy is 1.0 *m*, the overall end-to-end latency must not exceed 300 *m*s. While specific to intersection collision scenarios, European Telecommunications Standards Institute (ETSI) also defines a ceiling of 300 *ms* for the end-to-end latency in safety applications [26].

The proposed solution distinguishes itself from others by the fact that: (1) it uses aggregated data fusion from real sensors, such as video cameras, radars and data from communication vehicular and VRU messages; (2) it extends vehicular and VRU messages to integrate the required sensing data; (3) it proposes an algorithm for data fusion and collision prediction; (4) it studies both edge and cloud-based approaches; (5) it uses both ITS-G5, 4G and 5G technologies; and (6) it is tested in a real environment with real infrastructure and aggregated and processed real data from the Aveiro Tech City Living Lab [27].

III. BASE WORK

The smart city of Aveiro, Portugal, powered by the Aveiro Tech City Living Lab City (ATCLL) infrastructure [27], is an advanced large-scale infrastructure with Smart lamp posts and boxes spanned throughout the city. These edge points connect through fiber to a central cloud where further information gathering and processing can occur, and new services and applications can be developed, tested, and deployed.

Other initiatives exist, including the Smart Road Cortina in the italian state road 51 *"di Alemagna"*[1] or the city of Oulu, Finland, Timo Ojala, which proposed an urban and open testbed with both WiFi and Bluetooth technologies and devices, to demonstrate the potential of such infrastructure [28].

Each smart lamp can contain: multi-radio communication technologies, such as reconfigurable radio units, 5G-NR radio and 5G network services, Wi-Fi access points, Long Range Wide-Area Network (LoRaWAN) gateways and ITS-G5; sensors such as video-cameras, passive Radars, Lidars and environmental sensors; and edge computing units such as NVIDIA Jetsons, PC Engines APUs and Raspberry Pi 4.

Vehicles and VRUs are part of the overall city either by using OBUs, ITSs stations such as smartphones, or by being detected by infrastructure sensors, such as Radars, video cameras, and Lidars. City buses and garbage collectors contain ITS-G5, 4/5G and Wi-Fi OBUs for communication with the infrastructure.

A. VANETs

Vehicular Ad-hoc Networks are a subset of Mobile Ad-hoc Network (MANET), which are networks prepared to manage the high dynamism of nodes - unlike standard IP protocols - where vehicles are capable of wireless communication with the remaining network [29].

[1] https://www.anaspercortina2021.it/smart-road-cortina-2021

TABLE 1. **Network access technologies in VANETs.**

Technology	Communication type	Range	Latency	Reliability	Cost
ITS-G5	Device-device ad-hoc	Short ($< 1\ km$)	Low	High	Low/free
Wi-Fi	Device-device	Short ($< 1\ km$)	High	Low	Free
3GPP C-V2X	Device-device ad-hoc (D2D), device-network (D2N)	Short (D2D), Long (D2N)	Low	High	Low
Cellular (LTE/5G)	Device-network (D2N)	Long ($> 1\ km$)	Medium	Low	High

In VANETs, the vehicles are part of the network by publishing and receiving information from and to other vehicles (Vehicle to Vehicle (V2V)), infrastructure such as Road-Side Units (RSUs) (Vehicle to Infrastructure (V2I)) and VRUs (Vehicle to Pedestrian (V2P)) - overall called Vehicle to Everything (V2X). Vehicles are equipped with ITS equipment, such as OBUs. OBUs contain one or more wireless access technologies and are responsible for processing information from the vehicle sensors, producing messages and transmitting them to other nodes of the VANET, such as RSUs.

Traditional definitions of VANET exclude the VRUs and their equipment. However, they can easily be integrated through wireless access technologies such as LTE and 5G, present in their smartphones or equivalent types of equipment. VRUs can also communicate with other VRUs (Pedestrian to Pedestrian (P2P)), infrastructure such as RSUs (Pedestrian to Infrastructure (P2I)) and vehicles (Pedestrian to Vehicle (P2V)) - overall called Pedestrian to Everything (P2X). VRUs are equipped with ITS equipment, such as smartphones, that contain one or more wireless access technologies.

For nodes within a VANET, and more globally, to exchange information from or to ITS network nodes (*e.g.* vehicles OBUs, RSUs and other sensors), standardized message formats can be used [30]. These standards allow better interoperability between vendors' applicational stacks and hardware since they establish a common information set and format. Examples of such messages are Cooperative Awareness Messages (CAMs) for vehicles, Vulnerable Road User Awareness Messages (VAMs) for VRUs, Collective Perception Messages (CPMs) for the perception of sensor(s), and Decentralized Environmental Notification Messages (DENMs) for road events.

Both vehicular and VRU VANET nodes can use different wireless access technologies to communicate. These technologies can be classified based on their communication range [31], with a summary of the main characteristics of the most used access technologies described in Table 1.

ITS-G5 is based on IEEE 802.11p, a modified version of IEEE 802.11a to support the high mobility of nodes in Vehicular Ad-hoc Networks (VANETs). However, it requires specific hardware, which can be a problem regarding the devices the VRU carries (usually a smartphone). Wi-Fi can be seen as a solution for the hardware support issue; however, it lacks the low latency, high reliability required for safety applications. The work in [32] reviews the C-V2X timeline from LTE up to the 5G-based release, its advantages — rapid development and potential in terms of latency and reliability — while pointing limitations, such as the limited hardware support and the handovers handling. Finally, cellular communications can be used as an integrated solution when vehicular communications are not available, especially with the introduction of 5G with lower latency communications.

B. SENSOR UNITS

One of the main steps of any system to predict potentially dangerous situations on the road will be the awareness/ perception stage, where information about vehicles and VRUs is obtained.

This set of information can be obtained through a wide range of sensors. Some examples include Inertial Measurement Units (IMUs), Global Navigation Satellite System (GNSS) sensors (e.g. Global Positioning System (GPS), GLONASS) sensors, visual sensors (*i.e.* video cameras), Radars, Lidars and infra-red sensors [33], [34]. Table 2 summarizes the main characteristics, advantages and disadvantages of each sensor available within the ATCLL infrastructure.

Each sensor possesses several strengths and weaknesses, but none can be used in all circumstances [35]. Therefore, sensor fusion techniques, either powered by Kalman [36], [37], particle filters or machine learning techniques, are essential to obtain a complete, accurate view of vehicles and VRUs. Such accuracy is especially critical for safety ITS applications, including applications that aim to detect potentially dangerous situations.

A practical example of the potential of sensor fusion is the Fused Sensor Provider API from Google.[2] This API fuses information not only from the accelerometer, gyroscope, magnetometer, and orientation sensors and the GNSS sensor but also Wi-Fi, Bluetooth, and cellular signal strength. At Google I/O 2019,[3] the implementation of the API was given further details, with its inner workings being similar to a Kalman filter by having 2 phases, a prediction phase and an update phase. This API uses models to obtain coordinates based on the sensors' readings in the predict phase like in a typical Kalman filter. Then, the best measurements will be given more weight in the update phase, where all predictions are fused.

IV. VRU SAFETY ARCHITECTURE

Figure 2 presents an overview of the overall architecture for a VRU and vehicle collision prediction and avoidance approach. This includes the *VRU ITS-S* with its application, the vehicles and the edge infrastructure - connected indirectly through the infrastructure (V2I and P2I) to better leverage the ATCLL infrastructure; the *information aggregators* (in the cloud or edge infrastructure); and the *VRU Safety Application*, further discussed in Section VI.

A. NETWORK ELEMENTS

Vehicles and VRU nodes contain sensors to obtain their status information and computing power to process and create standard messages transmitted with the infrastructure. Therefore, these nodes heavily rely on multiple wireless access technologies to transmit these messages, as depicted in Figure 3.

The VRU has a ITS-S, such as a smartphone, while the vehicle also possesses equipment (e.g. OBUs) that allows both to send awareness information to a potential collision detection module periodically. We consider that roads are equipped with video cameras, Radars and other equipment at strategic locations that add information about VRUs and vehicles. A vehicle and a VRU are warned about a potential collision through warning messages.

Each of these nodes communicate using one or more wireless access technologies, most notable short-range standards such as ITS-G5, C-V2X, or long-range technologies such as LTE, 5G and, in the future, 6G. In our work we consider that the VRU communicates through LTE or 5G, and that the vehicles communicate through ITS-G5. However, our platform enables the vehicles to also use LTE and 5G.

In this work, we do not consider the direct communication between VRUs and vehicles. The reason for this is to enable the provision of a better context of the environment. With the different types of communication considered, the edge or cloud can take into account, not only the information provided by the vehicle and VRU directly, but also the information from sensors in the roads. We will show in Section VII that the fusion of all the data, including the static sensors, is very important to improve the accuracy of the system in a large section of the roads, and provide predictions in advance considering all the road context.

Vehicular nodes exchange information using a standardized message format, the Cooperative Awareness Message (CAM). CAMs are periodic messages exchanged between nodes to create and maintain awareness of vehicles or RSUs. A CAM contains status and attribute information of the originating vehicle/RSU [38]. The content of a CAM varies depending on the type of ITS-S: for vehicles, the status information includes time, position, motion state, activated systems (*e.g.*, cruise control, pedals, and others), and the attribute information includes data about the dimensions, vehicle type, and role in the road traffic; for RSUs, it contains information, at least, about the station type and location.

VRU ITS-Ss exchange information using a standardized message format, the Vulnerable Road User Awareness Message (VAM). VAMs are periodic messages exchanged between nodes to create and maintain awareness on VRUs and support the collision risk assessment [39]. Just like CAMs, the content varies depending on the type of VRU, but basic status includes information such as time, position,

[2] Available at https://developers.google.com/location-context/fused-location-provider

[3] Available at https://www.youtube.com/watch?v=MEjFW_tLrFQ

TABLE 2. Main sensors in the ATCLL.

Sensor	Working principle	Immune to	Not immune to	Precision	Complexity	Cost
GNSS	Satellites	Weather, Illumination	Discontinuities	Low	Low	Affordable
Video-Camera	Optical + object tracking algorithms (e.g., YOLO)	-	Non-line of sight. Illumination and weather	Low to medium	Low to high	Affordable
Radar	Doppler property of electromagnetic waves	Weather and illumination, obstacles	Static, stationary objects, coarse resolution	Medium to high	High	Expensive
Lidar	Reflection of emitting pulses of light	Weather and illumination, obstacles	Very coarse resolution, no color data	High	Very high	Very expensive

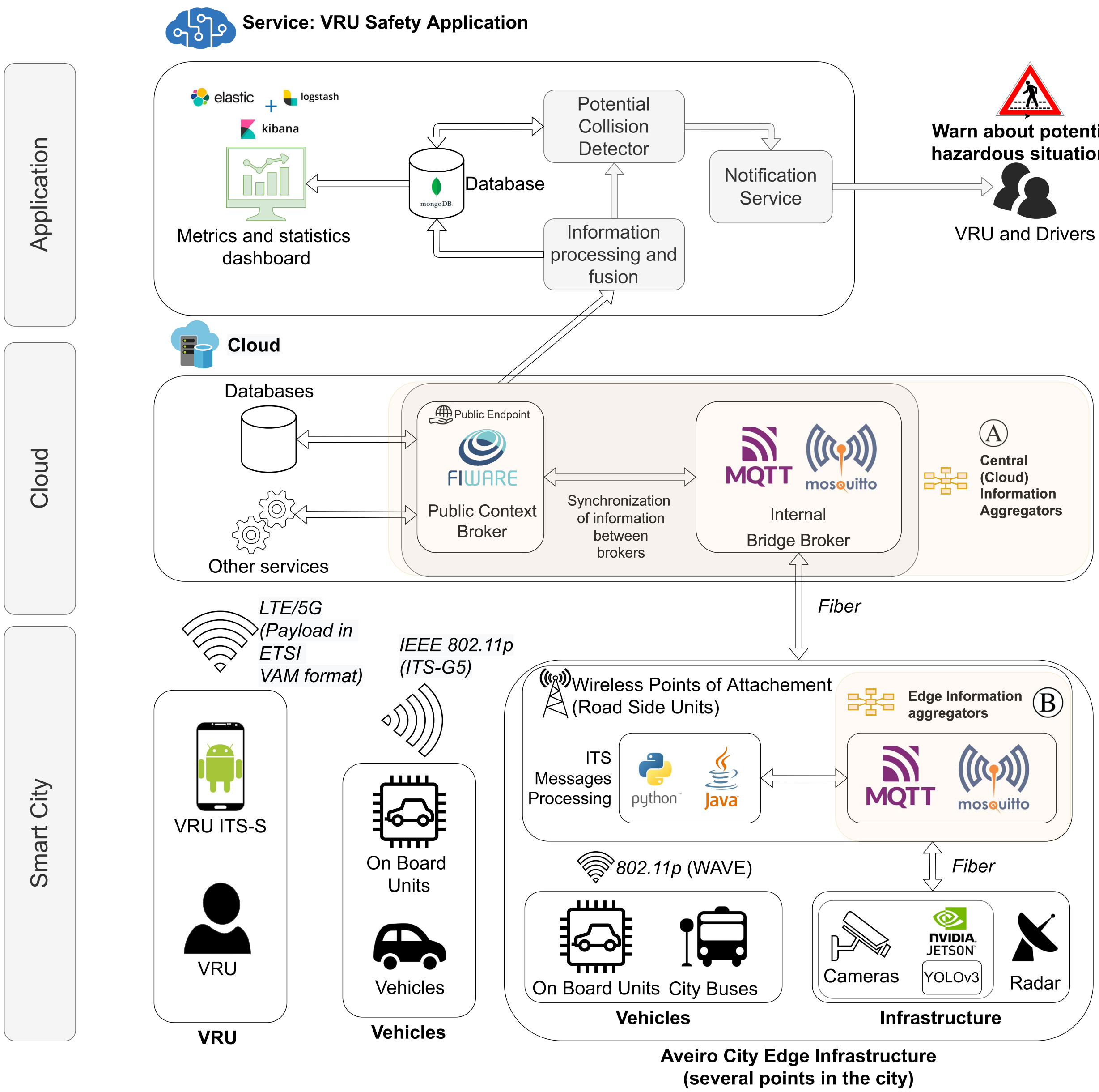

FIGURE 2. Detailed system overview.

speed, heading, yaw rate and acceleration, orientation, lane position, dimensions and VRU type.

To warn about potential collisions, the infrastructure sends to vehicles and VRUs another standardized message, the Decentralized Environmental Notification Message (DENM). DENMs are asynchronous messages exchanged between nodes to create and maintain awareness about a road event - a road hazard or an abnormal traffic condition - such as its type, position, validity, timestamp, and the history of the event [40]. While the content varies depending on the type of

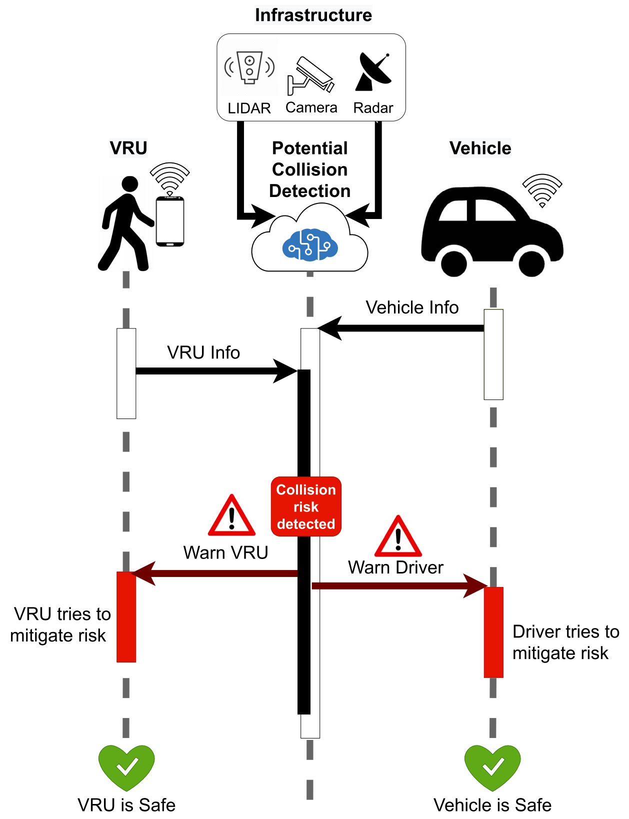

FIGURE 3. Sequence flow of the system.

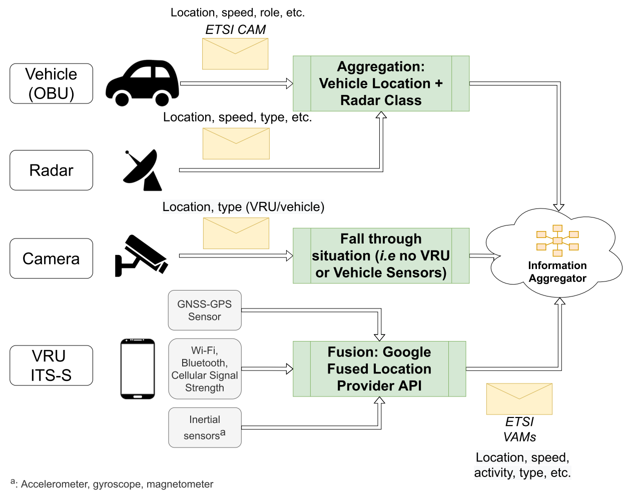

FIGURE 4. Main information sources for vehicles and VRUs.

event, it is expected that at least the detection time, the event's position, the type of the related ITS-S and a set of cause codes identifying the type of event are present.

While standardized messages have a defined set of information, they can easily be extended in the system by adding fields in the messages stored in the information aggregator.

B. INFORMATION AGGREGATION

The information aggregator is responsible for aggregating the information from all nodes – vehicles, VRUs, radars, video cameras – into a single platform accessible by all nodes and potential applications, which shall use the sum up/fusion of all the available information. The aggregation of information from multiple vehicles, VRUs and sensors into information aggregators/brokers is done following an event-driven architecture (publish-subscriber pattern), where information is published into a set of brokers. Since the information is sent asynchronously in this situation, an event-driven architecture based on using an information aggregator is ideal. An event-driven architecture supported by an information aggregator implements a pattern of publishers/generators and consumers/subscribers of events, which can be occurrences in the past, for example, of messages. Unlike patterns like request-response, they allow publishers and subscribers to be loosely coupled and communicate asynchronously through the mediation of a message information aggregator, which is the only node both publishers and subscribers need to know.

A hybrid approach was followed in the presented architecture, with an information aggregator in a cloud ((I)]A in Figure 2) and the edge nodes ((I)]B in Figure 2). Both solutions present different strengths but also challenges. In the edge computing solution, existing infrastructure is reused, and the processing is done closer to the nodes (*i.e.*, vehicles/VRU), which means potentially lower latencies. However, it has a higher cost of deployment complexity since more equipment is required, and orchestration between the different instances is needed. In contrast, no orchestration between edge points is required in a centralized solution, but the latency can be more significant. Section VII-B compares the timing results for each approach.

V. SENSING INFORMATION

Several data sources can obtain information from vehicles and VRUs. Information about vehicles comes from vehicles OBUs, video cameras and radars dispersed throughout a smart city, while information about VRUs can come from cameras or their own devices containing several types of sensors.

Using several data sources improves reliability by eliminating the dependency on just one type of sensor. It also improves the system's overall accuracy since the aggregation of other sensor information can be used to improve overall data quality through sensor fusion processes, as described in Section III-B. Figure 4 provides an overview of each source of information and how it is used.

A. VEHICLE's OBUs AND RADAR

Figure 5 summarizes the information of the vehicle obtained through an OBU. The OBUs are connected to a set of sensors within the vehicle - inertial sensors and GPS - allowing to obtain information such as position, speed, heading, direction and yaw rate. Additional information, such as a more precise location and the vehicle's class, can be obtained from Radars.

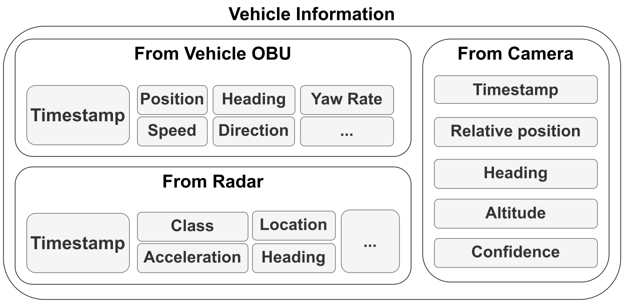

FIGURE 5. **Main awareness information that can be obtained about the vehicle.**

Algorithm 1 provides an overview of how information from the Radar is used: new information from the Radar is fused with vehicle information from an OBU if it exists. With both information, the *"Information processing and fusion"* module is responsible for joining the data from both data sources by using the size of the vehicle obtained by the Radar and its class in the computation of specific parameters, such as the maximum deceleration value of the vehicle (a parameter used in the collision detection module). The location provided by the Radar and the location provided by the vehicle OBU is fused using, for example, a Kalman Filter, ideal for adjusting the weight given to the positional measurement from both sources based on the measurement errors. Since the object location is given in relative coordinates, a conversion process needs to happen. The work in [41] designed and integrated this conversion within the ATCLL by applying a set of mathematical operations to the original coordinates - rotating the coordinate system and applying a transformational matrix.

Algorithm 1 Processing of Information From Radars

```
Input: New message from information aggregator
Parameters: Frequency_VehicleMessage,
  Frequency_VRUMessage
Result: New/Updated VRU or Vehicle Message
switch message source do
    case Radar do
        oldVehicleInfo = database.get
          (radarMessage.vehicleID);
        ▷ Radar detection corresponds
          to vehicle with OBU
        if oldVehicleInfo exists and
          radarMessage.timestamp ⩾
          oldVehicleInfo.timestamp) then
            ▷ Use width, length, vehicle
              class Information,
              location from Radar
            vehicleInfo = fuseInformation
              (oldVehicleInfo, radarMesssage);
            database.addOrReplace
              (key=radarMessage.vehicleID,
              value=vehicleInfo,
              TTL=Frequency_VehicleMessage);
        ▷ Radar detection does not
          correspond to vehicle with
          OBU - create new Vehicle
          Information
        else
            vehicleInfo = createVehicleInfo
              (radarMessage);
            database.addOrReplace
              (key=radaMessage.vehicleID,
              value=vehicleInfo,
              TTL=Frequency_VehicleMessage);
end
```

B. VRUs

Figure 6 summarizes the information of the VRUs, such as position, heading, speed, profile (pedestrian, cyclist, motorcyclist). The information is obtained through the sensors - GNSS sensors to accelerometer, gyroscope, magnetometer, orientation sensors and activity recognition sensors - in a VRUs ITS-Ss, an Android-based smartphone. The choice of the smartphone is motivated by its ubiquity (since most VRUs already possess one), its high programmability, its reduced cost compared to other solutions, and the fact that it possesses several sensors. However, alternatives, such as a custom-designed Application-Specific Integrated Circuit (ASIC) could be more powerful and cost-effective while keeping the same set of functionalities as a smartphone.

In order to obtain the location of the VRU, the initial approach was the joining of the data from the GNSS sensor with data from the other sensors using a Kalman Filter, improving the overall quality of the information about the VRU. The errors from each sensor were given by the Google Sensors API.[4] An alternative is using the Fused Sensor Provider API from Google, described in Section III.

[4]By defining the *onAccuracyChanged* callback as described in hbttps://developer.android.com/guide/topics/sensors/sensors_position

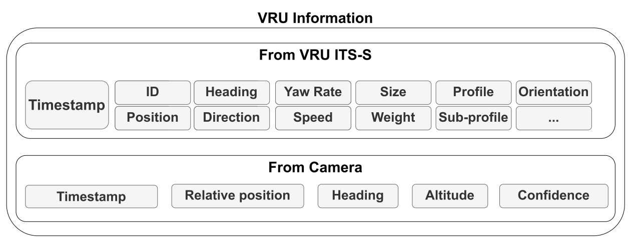

FIGURE 6. **Main awareness information obtained about the VRU.**

The obtained information is then used to create a standard VAM, which is exchanged with the infrastructure through Wi-Fi or cellular - LTE or 5G. Cellular usage is preferred due to its lower latency and higher availability compared to Wi-Fi. However, Wi-Fi is a fallback solution if cellular is unavailable.

C. VIDEO CAMERAS

Algorithm 2 provides an overview of how information from the video cameras is used. New information from cameras is

Algorithm 2 Processing of Information From Video Cameras

```
Input: New message from information aggregator
Parameters: Frequency_VehicleMessage,
Frequency_VRUMessage
Result: New/Updated VRU or Vehicle Message
switch message source do
    case Camera do
        for Detection in CameraMessage do
            ▷ Warn VRUs about close
              vehicles
            if Detection.Label == Vehicle then
                vrus = database.get (vrus);
                for VRUInfo in vrus do
                    distance = haversineDistance
                      (VRUInfo.location,
                      Camera.Location) if distance <
                      threshold then
                        warn (VRUInfo);
                end
            ▷ Use camera to detect VRUs
              without ITS-S
            else
                vruInfo = createVRUInfo(detection);
                database.addOrReplace(key=camera.ID
                  + ":" + detection.ID, value=vruInfo,
                  Time to live
                  (TTL)=Frequency_VRUMessage);
                runDetectionAlgorithm(vruInfo,
                  database.get(vehicles));
        end
    end
end
```

processed by dividing a frame into a set of squares - that effectively are Region of Interests (ROIs) - each one with a known fixed global position; an object with a determined bounding box will have a global position corresponding to the square that is within. Since a bounding box of an object may overlap more than 1 square, the square to be considered is the one in which the Intersection over Union (IoU) with the bounding box is greater. With this algorithm, an approximation of the location of objects can be obtained by defining the object's location with the coordinates of the center of the associated bounding box. This information can then be used to detect vehicles and VRUs that any other source could not detect. While the camera, with this algorithm, can only provide an approximated position and not much more information about the VRU or vehicle (such as speed and heading), it can be used as a fall-through sensor to detect more error potential dangerous situations. Moreover, it can differentiate people from bicycles or motorcycles, which is something not distinguishable with radars.

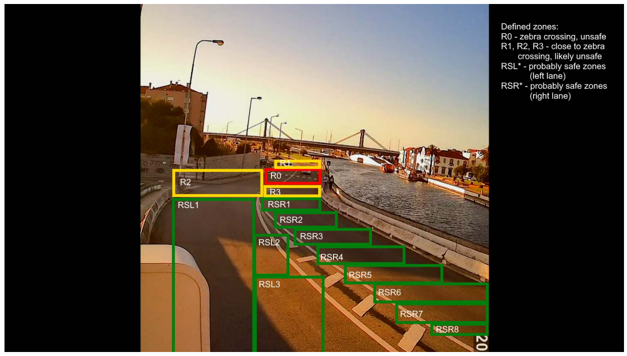

FIGURE 7. Example of the manual division of the original frame by a set of squares/ROIs.

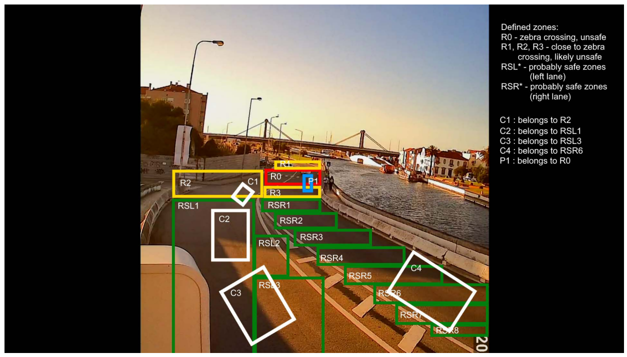

FIGURE 8. Association of bounding boxes with squares/ROIs.

A division of the frames into ROIs was considered to estimate the position based on the camera information. Figure 7 presents an example of such a division into ROIs. Considering the topology of the roads three types of zones can be distinguished: far away from the zebra crossing (green potentially safe zones), at the zebra crossing (unsafe red zones), and close to the zebra crossing (yellow, potentially unsafe zone). Based on this division, detected objects (vehicle C1 to C4 and person P1) were then associated with the ROIs, which overlaps the most with (with the highest IoU), as presented in Figure 8.

VI. SAFETY ALGORITHM

The VRU Safety Application considers the development of services and applications that interact with users to warn them about potentially dangerous and harmful situations on a road involving vulnerable users. The system considers a multi-stage algorithm based on computing the length of risk zones and collision points, re-evaluating the situation every 100 ms ($f = 10\,Hz$). The service notifies vehicles and VRUs about a potential collision. After receiving the relevant information from the subscribed topics of the information aggregator, the VRU Safety Application performs a set of operations to decide if a dangerous situation is likely or not. Figure 9 presents the overall algorithm.

The algorithm computes the Haversine distance between the VRU and each vehicle available in the database and computes the length of three zones: a zone where, if the

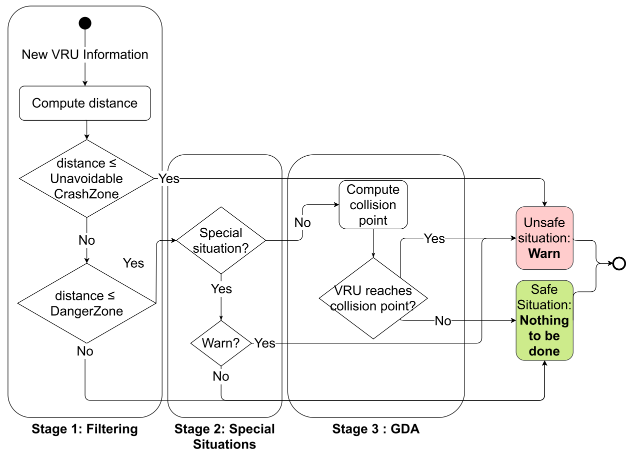

FIGURE 9. Overview of the potential collision detector algorithm.

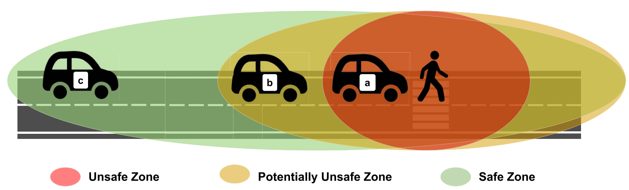

FIGURE 10. Example of collision risk zones (centered in the VRU).

vehicle and VRU are both within that zone, it means that an accident is inevitable; a zone where an accident might happen or not if the vehicle and VRU are both within the zone; and a safe zone if none of the previous options occurs.

Figure 10 depicts an example of such a situation with the zone center defined in the VRU. Vehicle *a* is within the unsafe zone (in red), so a collision is deemed unavoidable. Vehicle *b* is within the potentially unsafe zone (in orange), where it is not sure an accident might happen with the current situation. Vehicle *c* is within the safe zone (in green), where it is sure an accident will not happen with the current situation (however, it is always possible that in a subsequent evaluation of the situation, this changes if, for example, the vehicle suddenly accelerates significantly). This division between zones presents another advantage, allowing the filtering of vehicles and VRUs very far away in an easy approach (all nodes that are very far away will belong, by definition, to a safe zone).

As represented, the zones consider vehicles in front or behind the VRU. Such behavior might or might not be wanted in a potential collision system. Supposing the system wants only to consider typical forward-collision situations. In that case, the represented zones are only valid for vehicles before (left to) the VRU, with vehicles after (right to) the VRU not being deemed a collision since the vehicle is going forward. However, in situations where the vehicle is reversing, this analysis would not be correct. The best option is to consider the zone length only if the VRU and vehicle are in the same direction.

The zone lengths have in mind the vehicle's dynamics, such as acceleration, speed, and position, but also its characteristics and the driver characteristics [24]. The length of the unavoidable crash zone, $d_{UnavoidableCrash}$ can be given by

$$d_{UnavoidableCrash} = d_{reaction} + \left(-\frac{{v_{brake}}^2}{2 \times d_{deceleration}}\right). \quad (1)$$

This distance considers the vehicle characteristics through its $d_{deceleration}$, which corresponds to the maximum braking deceleration. The greater the value of this parameter, the better the vehicle can brake. This value depends on the state of the braking system of the vehicle (the better, the stronger the maximum deceleration), the weight of the vehicle (the larger, the lower the maximum deceleration), or the road conditions (the more slippery, the lower is the maximum deceleration).

The driver characteristics, like age, visibility conditions, and tiredness, that influence a $t_{reaction}$ are also taken into consideration in the computation of the $d_{reaction}$, the distance covered by the vehicle before the driver reacts, which is given by

$$d_{reaction} = \frac{1}{2} \times a_{vehicle} \times {t_{reaction}}^2 + v_{vehicle} \times t_{reaction}. \quad (2)$$

Finally, v_{brake}, the speed of the vehicle after driver reaction delay, is given by

$$v_{brake} = a_{vehicle} \times t_{reaction} + v_{vehicle}. \quad (3)$$

The length of the potential unsafe zone, d_{Danger}, is then given by:

$$d_{Danger} = d_{UnavoidableCrash} + v_{vehicle} \times t_{guard}, \quad (4)$$

where the vehicle is considered to cover an additional distance during a $t = t_{guard}$, with t_{guard} guard time defining the level of the conservatism of the length of the potential unsafe zone.

The second stage is the phase of the exceptional situations. In this stage, specific situations that can be extremely dangerous - if a vehicle is going too fast or if the VRU is a child - are immediately considered potential accidents. In opposition, some situations are ignored to avoid false positives. Examples of these situations include when the driver is already braking or where there is a considerable difference in altitude (e.g. a VRU on top of a bridge) or heading (e.g. VRU and the vehicle cannot collide because they are moving in opposite directions).

If no situation from stage 2 is verifiable, stage 3 is executed. In this stage, the goal is to predict the future trajectory of the vehicle and VRU based on the current dynamic. By predicting the trajectory, it is possible to analyze if it is likely that the vehicle and VRU are going to crash in the near future. The prediction follows a kinematic approach described in Section II. In this approach, the vehicle is represented with a bicycle kinematics model (*i.e.* only considering two wheels). The goal is to compute a point of collision ($x_{collision}, y_{collision}$) considering a vehicle of velocity v, width W, length L and yaw rate ω and a VRU in the x, y (position relative to the vehicle) and maximum velocity v_{pMax}:

$$\begin{aligned} x_{collision} &= r_S \times \cos\left(\theta + \frac{\epsilon_r}{2} - \frac{\pi}{2}\right) + x_S \\ y_{collision} &= r_S \times \sin\left(\theta + \frac{\epsilon_r}{2} - \frac{\pi}{2}\right) + y_S, \end{aligned} \tag{5}$$

where r_S is the radius of the gravity center, given by

$$r_S = \frac{v}{\omega}, \tag{6}$$

θ is the angle between the vehicle and VRU, given by

$$\theta = atan2\left(\frac{y - y_S}{r_S}, \frac{x - x_S}{r_S}\right), \tag{7}$$

ϵ_r is the vehicle's Ackerman angle, given by

$$\epsilon_r = \frac{L}{r_S}, \tag{8}$$

and (x_S, y_S) is the vehicle's instantaneous center of rotation, given by

$$\begin{aligned} x_S &= 0 \\ y_S &= r_S \times \cos(\epsilon_r/2). \end{aligned} \tag{9}$$

A potential accident is detected if the VRU (or the vehicle) reaches/is very close to the point of collision after a time to collision, $t_{collision}$, *i.e.* if $d_{VRU} < v_{pMax} \times t_{collision}$, where d_{VRU} is the distance between the VRU and potential collision

$$d_{VRU} = \sqrt{(x - x_{collision})^2 + (y - y_{collision})^2}, \tag{10}$$

and $t_{collision}$ the time to collision, which is given by

$$t_{collision} = \frac{\theta - (\epsilon_r/2) + (\pi/2)}{\omega}. \tag{11}$$

If a collision is detected, the relevant nodes are notified using a predetermined message format, in this case, ETSI DENM, and it is expected that either the vehicle or the VRU act to avoid a dangerous situation.

VII. EVALUATION

This section presents the setup and results for evaluating the overall system performance.

A. EVALUATION SETUP

All the presented evaluation results used real hardware from the ATCLL infrastructure [27]. Table 3 lists the equipment and software used for all the evaluations of the system.

This equipment was used for a set of real tests at two crossroads in Aveiro (Figure 11). The first test represents a proof of concept test to understand the system operation.

The technologies used for the communication between the VRU ITS-Ss and the infrastructure are LTE-A and 5G-NR using a pre-commercial Non-Standalone (NSA) 5G network in the n77 band (3.6 GHz), with base stations in two places in the city of Aveiro.[6] In an ideal location — location with

TABLE 3. Equipment characteristics.

Node	Equipment	Model	Characteristics
VRU	LTE ITS-S	Samsung Galaxy A50	LTE-A, Android 11
VRU	5G ITS-S	Xiaomi Mi MIX 3 5G	5G, Android 9
Vehicle	OBU	PC Engines APU3C4	AMD Embedded G series GX-412TC, 1 GHz quad-core, 4GB RAM, 30GB SSD, WLE200NX miniPCI express card WAVE module, GPS Module and 3 Gigabit Ethernet channels
Vehicle	RSU	PC Engines APU2E4	Same as APU3C4 but with 2 WLE200NX miniPCI express card Wi-Fi and WAVE module
Radar		Smartmicro UMRR-11 Type 4 Traffic Management Sensor	24GHz Radar sensor with multi-lane and multi-object tracking with 4D Doppler based radial motion detection. [42]
Video Camera	Camera	Reolink RLC-423	CMOS 5MP Sensor, day/night mode, pan and tilt capability, 2560x1920@30 fps
Video Camera	Computer	NVIDIA Jetson Nano	Developer Kit Version Jetpack 4.4.1, Tegra 210
Software	Information aggregator	Fiware Orion Context Broker	Broker appropriated for managing the entire lifecycle of context information including updates, queries, registrations and subscriptions[5].
Software	Safety Service	Dockerized Web Server Gateway Interface (WSGI) Python application	Usage of Python to leverage the Machine Learning libraries, of WSGI to improve performance while replying to several requests from several VRUs and vehicles, Docker to allow easy replication of the application in other contexts.
Software	Database	MongoDB document-based database	Allows flexible structure (non-relational) while keeping high performance and a JSON-like schema.

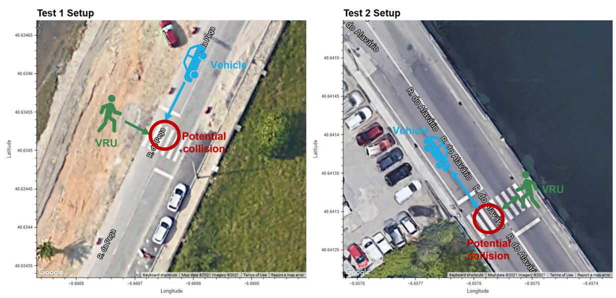

FIGURE 11. Evaluation tests. From left to right, tests 1 and 2.

direct line of sight to a 5G antenna close to Cais da Fonte Nova, in the city of Aveiro, Portugal — the bandwidth results are within the expected by the operator in terms of bandwidth (upload of 100 Mbps, download of 1200 Mbps). The vehicle communicates through ITS-G5 with a smaller data rate of around 8 Mbps.

Figure 12 presents the application that depicts test 1, showing the overall end-to-end operation of the system and that the system is capable of detecting potential collisions. The system warns both the VRU and vehicle through the VRU ITS-S smartphone application and a City Manager dashboard, respectively.[7]

The second test was performed on the road of *Ponte Dobadoura*, a place where a RSU, a Radar and a video camera are installed. During the execution of the test, the vehicle and VRU potentially collided twice while the VRU was crossing the road.

Unless otherwise specified, all results present the mean of 10 runs and a confidence interval of 95%.

B. CENTRALIZED VS EDGE COMPUTING

The proposed architecture follows a hybrid solution, with both edge and centralized cloud solutions. An edge solution,

[6]By October 1st 2021, the Autoridade Nacional de Comunicações (ANACOM) auction for allocation of 5G related frequency was not finished and therefore, the usage of 5G commercial network was not possible.

[7]Part of the ATCLL infrastructure was not developed by the author.

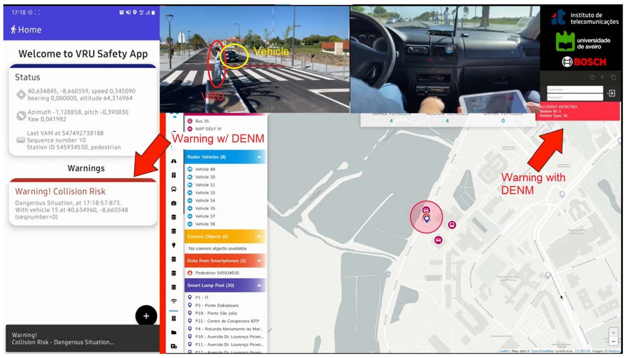

FIGURE 12. **Test 1 results**[8].

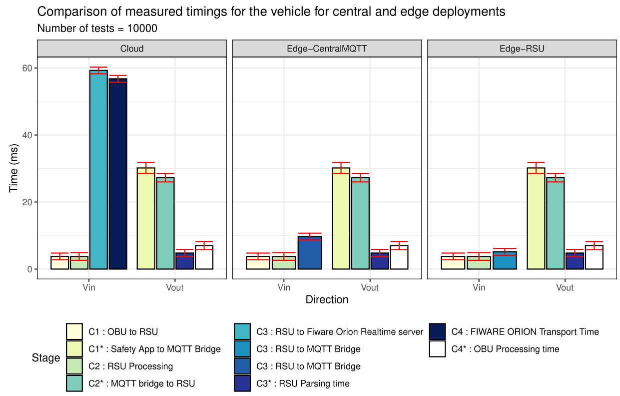

FIGURE 13. **Centralized vs edge computing approaches for vehicles and their impact on the timing of the information subscription.**

by deploying the safety application as closely as possible to the source of information, tends to decrease data transport times. However, edge solutions require orchestration between the different instantiations, and the processing capacity of the edge equipment is usually lower than in cloud solutions. Scalability is also an issue - horizontal (adding more machines is time-consuming, and the space in the city renders the solution unfeasible) and vertical (the equipment is not easily upgraded). In opposition, cloud infrastructure tends to be easier to scale, either by adding more machines or upgrading the existing ones to a central data center.

An intermediate solution is integrating the safety application in the cloud - entirely using the cloud resources - such as receiving information both from the centralized cloud and from edge points, with the edge points receiving and providing the information faster. This solution is also considered, and Figure 13 presents the results of the message transport times in a cloud solution and two edge solutions. The first edge solution considers that the data is obtained from the information aggregators in each edge point (*Edge-RSU*), while in the second approach, the data is obtained from a bridge information aggregator unifying all edge points (*Edge-CentralMQTT*).

An analysis of the results shows that, in the Cloud solution, the most significant points of delay are the two information aggregators required for the information (C_3 and C_4) to reach the public endpoint for the Safety App service. Therefore, the logical conclusion is to remove one of the information aggregators, decreasing the total time associated with vehicles by 50-60 *ms*.

When removing the cloud information aggregator, as in the *Edge-CentralMQTT*, results further improve. This optimization means that the C_4 time was eliminated, meaning that 56.77 *ms* could be saved. The temporal improvement is further increased because the time between the bridge information aggregator and the cloud (corresponding to the parsing done by a real-time server) is also eliminated. This optimization means that C_3 time - now time between the RSU and the bridge information aggregator - decreased to just 9.69 *ms* (against 59.27 *ms* observed before).

If the information is even closer to its generation sources, as in the *Edge-RSU* solution, results are further improved since the C_3 time decreases from 9.69 *ms* to 5.14 *ms*. These results stem from the fact that waiting for the synchronization of information between the edge information aggregator and the bridge information aggregator is no longer required. However, this is possible at the expense of adding complexity to the implementation of the safety application since all the RSUs have to be manually subscribed - instead of just one central information aggregator.

Both edge solutions make it possible to conclude that edge computing is not only essential to decrease the overall end-to-end latencies but also critical to the safety ITS applications. However, it also requires more complexity in the edge equipment - the RSUs needed a message information aggregator to support the solution, which might not always be possible.

C. LTE VS 5G PERFORMANCE

Vehicles, infrastructure, and VRU ITS-S can communicate using several network access technologies, such as cellular and ITS-G5. While VRU ITS-S, such as smartphones, can use ITS-G5, this support is still experimental. Cellular technologies, such as LTE and 5G, are more common. Figure 14 presents, for VRU ITS-Ss, the transport times computed of data from/to a VRU ITS-S. Results include measurements both for a Long Term Evolution Advanced (LTE-A) smartphone and 5G smartphone using a pre-commercial 5G network. All measurements were done with the smartphones in the same place, at the same time.

Results show a clear advantage of 5G over LTE-A, both in uplink (V_{in} times) and downlink/notification time (V_{out} times), with the difference between LTE-A and 5G being very significant - 120 *ms* and 100 *ms*, for uplink and downlink, respectively. The times are prohibitively high in LTE-A; only 5G can fully support latencies compatible with an emergency service such as the one of VRU safety - 300 *ms* for an average precision (1.0 *m*) as described in Section II. 5G would be an

[8]Full video version available at https://www.youtube.com/watch?v=m9PBEtlsQeA

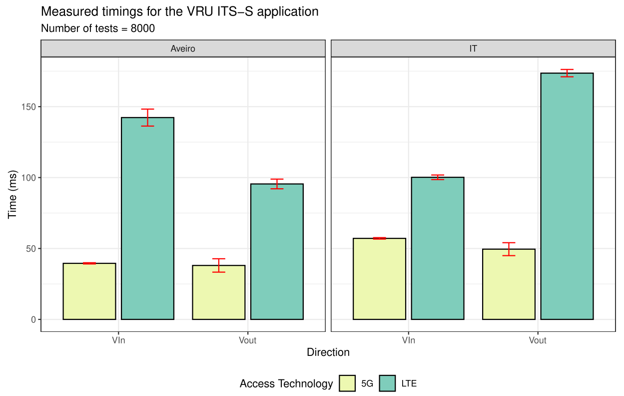

FIGURE 14. Stages evaluated for the VRU ITS-S application (set of tests 1, next to a 5G cell tower in Aveiro and in IT-Aveiro).

even clearer advantage for migrating to an edge computing approach with more processing in the VRU ITS-Ss nodes.

D. OVERALL TIMING RESULTS

Considering a worst case scenario defined in Figure 15, where a new VRU information is sent after the vehicle information (instead of simultaneously), and considering the bridge information aggregator approach and 5G VRU ITS-S (since the central approach for vehicle info and LTE for VRU presented greater latencies), the end-to-end time for vehicle and VRU is given by

$$\begin{aligned} t_{Vehicle} &= C_1 + C_2 + C_3 + V_{in}^{5G} + S_1 + S_2 \\ &\quad + C_1^* + C_2^* + C_3^* + C_4^* \\ &= 3.77 + 3.75 + 9.69 + 57.14 + 3.12 \\ &\quad + 0.0548 + 30.17 + 27.26 + 4.78 + 6.99 \\ &= 146.72\ ms \leq 300\ ms, \end{aligned} \tag{12}$$

for the vehicle, and

$$\begin{aligned} t_{VRU} &= C_1 + C_2 + C_3 + V_{in}^{5}G + S_1 + S_2 + V_{out}^{5G} \\ &= 3.77 + 3.75 + 9.69 + 57.14 \\ &\quad + 3.12 + 0.0548 + 49.52 \\ &= 127.04\ ms \leq 300\ ms, \end{aligned} \tag{13}$$

for the VRU, where S_1 and S_2 are parsing and algorithm times within the Safety Application. The results show that the timing requirements are fulfilled, with both end-to-end times below the 300 *ms* ceiling value.

E. THE IMPORTANCE OF SENSOR FUSION

Several types of information are required to detect potentially dangerous situations between road elements. Accurate awareness of their position is required from all the information that might be used.

As summarized in Table 2, all these sources present different characteristics and accuracies. The distance between each perceived location and the real position was computed

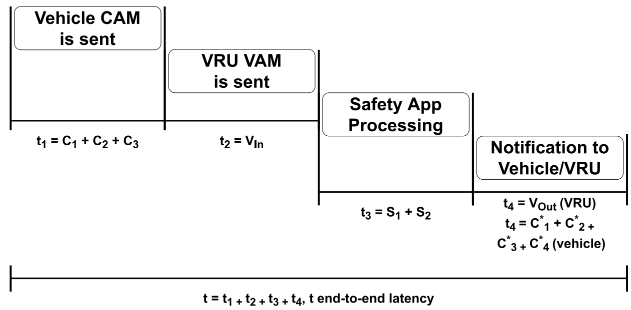

FIGURE 15. Worst case situation considered.

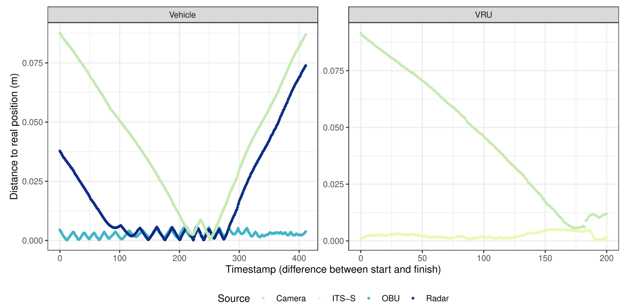

FIGURE 16. Comparison of the difference between perceived and real location (distance) over time, for vehicle and VRU.

TABLE 4. Accuracy for all location providers of the vehicle and VRU.

Node	Data source	Average distance to real path
Vehicle	OBU GPS	0.00271 m
Vehicle	Radar	0.01885 m
Vehicle	Camera	0.04309 m
OBU GPS is 7.7 times more precise than radar		
Vehicle (*)	OBU GPS	0.00314 m
Vehicle (*)	Radar	0.00278 m
Vehicle (*)	Camera	0.01264 m
Radar is 88.6 times more precise than OBU GPS		
VRU	ITS-S	0.00250 m
VRU	Camera	0.04544 m
ITS-S is 5.5 times more precise		

to study the accuracy differences between the different location providers. Figure 16 provides the variation of this distance over the time of the test, while Table 4 provides the average distance and introduces information on the number of different locations each provider detected. The accuracy parameter - distance between the real location and the location perceived by each source - is computed for each possible location source. In the case of the vehicle, further analysis is done to understand the difference in the precision when the vehicle is within the field of view of the radar.

An initial view of the overall results shows that the video camera information is not yet precise enough but can detect and give an approximation of the position - of VRUs and vehicles - and if they are or not in the zebra crossing. Therefore, the camera sensor can be considered a support for a fall-through situation when no other sensors are available. In addition, results seem to indicate that, for a vehicle, both the OBU and Radar have similar accuracy.

While OBU location tends to be more precise, the Radar can show a very close approximation with a much higher frequency (the OBU GPS can only measure one time per second). However, the higher precision of the Radar is also only possible within the range of detection of the Radar, while the OBU can be used in any place where the GPS is available.

For the vehicle, the results show that for the overall situation (*Vehicle*), the OBU location tends to be more precise than the Radar - approximately 7.7 times. However, the Radar is greatly affected by the vehicle being out of its line of sight. In these situations, the position given by the radar is a bad estimation. This bad estimation is even more pronounced in the video camera information, but a better precision on the object type is provided.

Situation *Vehicle (*)* describes the overall accuracy without considering the location detections provided by the Radar when the vehicle is out of the direct line of sight. In this situation, it is possible to observe that the radar is significantly - approximately 88 times - more accurate than the OBU GPS.

This means that the higher precision of the Radar is also only possible within the range of detection of the Radar. In opposition, the OBU can be used anywhere the GPS is available. A solution for this issue is the fusion of data - in the case of the vehicle, between the OBU GPS position and the Radar given position can improve the precision and number of points (more locations per second).

For the VRU, results show that the VRU perceived location is very close to reality, thanks to the usage of the fusion of data - the Fused Location Provider API from Google. This API showcases the potential of sensor fusion by fusing the information from several smartphone sensors, GPS, Wi-Fi, and Bluetooth signal information, improving the accuracy from a simple GPS reading. By opposition, and as expected, the video camera detection is wildly inaccurate.

F. SCALABILITY OF THE SAFETY ALGORITHM AND APPLICATION

The temporal analysis performed in Section VII-D considered that the network and vehicular equipment are under normal conditions and usage, *i.e.* they were performed during the day, with typical traffic from Aveiro. To fully show that the system can perform under stress, scalability tests were executed on the main points of the system - OBUs, RSUs, the VRU ITS-S application and the safety application.

1) VEHICLE RSUs AND OBUs

Figure 17 presents the results of a mean of 10000[9] tests and confidence interval of 95% for the time a CAM takes from the OBU to the Safety Application. This test was executed by injecting CAMs into the infrastructure by a threaded program, simulating several vehicles.

[9]A value considered reasonable for RSU coverage in an urban environment, in a road with two lanes for each direction, considering the coverage of a RSU of around 300 *m*.

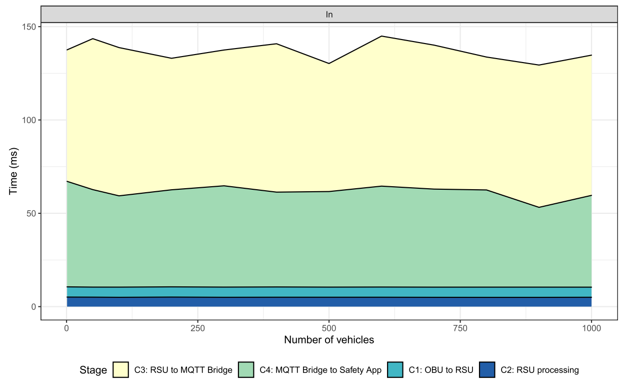

FIGURE 17. Results of the scalability evaluation for the vehicle.

Results do not show any increasing trend with up to 1000 vehicles. Values C_1 to C_2 (times from the OBU to the RSU and the RSU processing time) tend to be stable and within the system specifications. On the other hand, values related to the information aggregators (C_3 and C_4) do not relate to the variation in the number of vehicles. This conclusion can be explained by the fact that both brokers are a shared infrastructure, with load differences during the execution of the several tests that stem from the normal variations of information within a city.

2) VRU ITS-S APPLICATION

Figure 18 presents the results of a scalability test, representing a mean of 50000 tests and a confidence interval of 95%. In these tests, DENMs were injected into the infrastructure to simulate the VRU being notified about multiple potential collisions.[10]

Results show that the VRU ITS-S application is susceptible to receiving more DENMs per second, with the notification time varying proportionally with the number of DENMs. In addition, the notification times - that measure the time between DENM generation and the VRU being visually and audibly notified - will, naturally, tend to be infinite since the application itself can only process a finite number of UI operations per second. Therefore, in a situation where thousands of DENMs are sent to the application, the application will naturally start to queue the UI operations, making the notification times cumulatively higher (as it was verified for a number of DENMs superior to 2500).

It should be noted that understanding the impact of sending more VAMs per second is not critical since it is not supposed to have that scalability issue: the VRU ITS application is supposed to be exclusive to 1 VRU. Even in a situation of a VRU ITS application representing more than 1 VRU or a

[10]Since in this system, the VRU ITS-S is a smartphone communicating to the rest of the system through cellular (either LTE-A or 5G), thoroughly analyzing the scalability would include considering the impact in the network core, which could not be realistically be tested since the cellular network (Vodafone for LTE-A and pre-commercial Altice Meo for 5G) is used in production.

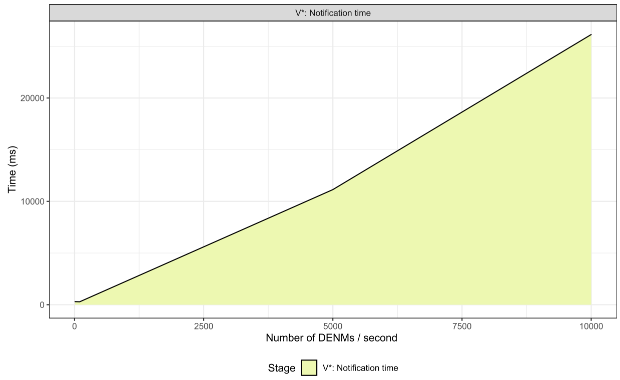

FIGURE 18. Results for scalability tests of VRU ITS-S.

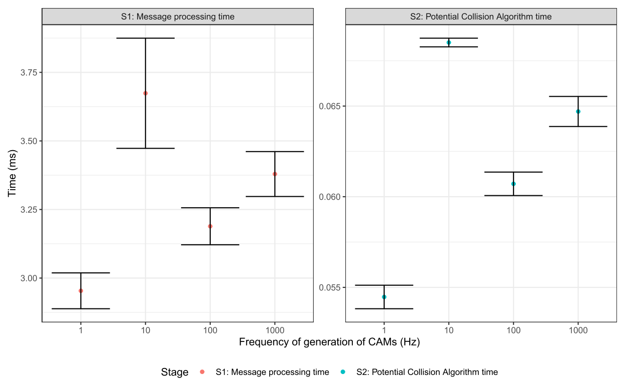

FIGURE 19. Results for scalability tests of safety app.

cluster of VRUs, just 1 VAM would be sent representing the whole cluster.

3) SAFETY APPLICATION

Figure 19 presents the results of a mean of 50000 scalability tests for the safety application tests and a confidence interval of 95%. These tests were executed in a testbed with 3 OBUs, 1 RSU and 6 VRU ITS-Ss smartphones.[11]

Results show no visible trend with increasing values of vehicles (simulated by different frequencies of generation of CAMs). However, results also show that the upper bound of the value of both times S_1 and S_2 is within the values presented in Section VII-D, which indicates that the safety application scales for a number of vehicles expected for one or a few RSUs. However, it is impossible to conclude that one instance of the Safety App can scale enough to process information about the whole city. Therefore, an edge approach, with several nodes deployed in each RSU, is a more scalable solution, with the correct operation of the App for that situation, as shown in this test.

[11] 1 Xiaomi Redmi Note 9T, 2 Motorola Moto G 5G, 1 OPPO Reno 4Z 5G, 1 Samsung Galaxy A50, 1 Xiaomi Mi MIX 3 5G - all Android smartphones with different hardware to simulate different VRUs.

VIII. CONCLUSION

This article proposed an approach with sensing, communication and processing capabilities to predict potentially dangerous situations - such as collisions - between vehicles and VRUs. This solution is crucial, considering the current number of fatal crashes involving VRUs. The amount of previous work exploring potential solutions to mitigate these exact problems corroborates that.

The proposed solution distinguishes itself from others by the fact that: (1) it uses aggregated data fusion from real sensors, such as video cameras, radars and data from communication vehicular and VRU messages; (2) it extends vehicular and VRU messages to integrate the required sensing data; (3) it proposes an algorithm for data fusion and collision prediction; (4) it studies both edge and cloud-based approaches; and (5) it uses both ITS-G5, 4G and 5G technologies.

This approach has been tested in a real environment with real infrastructure and aggregated and processed real data from the Aveiro Tech City Living Lab. The results showed that the system could detect dangerous situations with small latencies, high accuracy and scalability. The comparison of edge and cloud solutions, as well as 4G and 5G technologies, has also been provided, showcasing both the need for hybrid (cloud and edge) architectures and the need for next-generation network technologies.

Future work includes the improvement of the accuracy by supporting more sensors and an extension of the system to consider characteristics and use cases of other types of VRU (e.g. bicycles and motorcycles).

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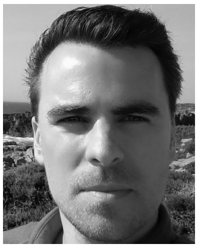

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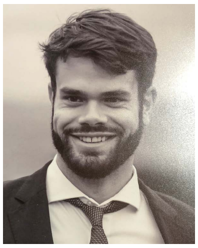

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