A Mobile Application to Secure Pedestrians Interacting with Automated Vehicles

Romain Tessier, Pierre Merdrignac(✉), Thomas Jacquet, and Natacha Métayer

VEDECOM Institute, 78000 Versailles, France
{romain.tessier,pierre.merdrignac,thomas.jacquet,
natacha.metayer}@vedecom.fr

Abstract. With the increasing deployments of automated vehicles (AVs) in shared environments, many questions arise concerning the safety of interactions between these vehicles and other road users, especially for the most vulnerable. This paper presents 1) a mobile application designed to provide real-time collision risk alerts to pedestrians, leveraging cellular network communication and edge computing for low-latency warnings, and 2) the evaluation of this application by end users after road tests. The system was evaluated through controlled experiments, demonstrating average delays of less than 100 ms for alert notifications. User feedback indicated strong support for such safety technologies, with most participants highlighting the importance of receiving notifications in poor visibility conditions. While some localization challenges led to occasional false positives, the overall user experience and system performance were promising, suggesting this approach as a viable solution to improve VRU safety in smart cities.

Keywords: VRU · Road Safety · automated driving · smartphone application · user assessment

1 Introduction

Cooperative, connected and automated mobility (CCAM) provides innovative technologies for safer, more efficient and more comfortable transportation. CCAM contributes to transform urban transport in smart cities, especially, by relying on automated vehicles (AV) and digital solutions [1]. While AVs offer new alternative for the mobility of persons and goods, ensuring safety is crucial for promoting their adoption [2], in particular when considering interactions with other road users such as pedestrians and cyclists, oftentimes referred as vulnerable road users (VRU). Deb et al. [3] have shown that safety is one of the key factors influencing the willingness of pedestrians to cross in front of an AV. Moreover, with the large adoption of smart devices and the cellular communication, people are always connected to the internet. In addition, recent advancement on the internet of things (IoT) technology enable seamless communication between multiple devices using data brokers. Recent works have investigated alert road users of danger either with direct communications [4, 5] or centralized approaches

© ICST Institute for Computer Sciences, Social Informatics and Telecommunications Engineering 2025
Published by Springer Nature Switzerland AG 2025. All Rights Reserved
A. Kocian et al. (Eds.): INTSYS 2024, LNICST 608, pp. 227–243, 2025.
https://doi.org/10.1007/978-3-031-86370-7_14

[6]. While the direct communication has raised a high interest to ensure low latency communication for warning dissemination, they are limited due to low penetration rate of the technology. Complementary, centralized approach relying on cellular networks are becoming more and more appealing since their performances have been improved with the new generation of mobile networks (5G and beyond). Remaining challenges are to design the communication architecture supporting the vehicular communication in these centralized environments, i.e. developing efficient network services for real time sharing of road hazard and assessing how the solution is understood and accepted by the final users, hence, ensuring technology adoption. Considering the specifications of an automated public shuttle, we have developed an application which can be deployed on top of cellular network to assess collision risks between AVs and VRUs and alert pedestrians through a dedicated application installed in their phone. Our application has been evaluated in an experiment with real participants. The contribution of this work are as follows:

- Design the communication architecture for securing automated driving system and implement VRU protection service for low latency risk warning
- Develop and experiment an application alerting VRUs in the presence of automated vehicles
- Evaluate the technical performance in two separate scenarios
- Assess the solution with external participants in terms of user needs and user acceptance

The rest of the paper is organized as follows. Section 2 addresses the related works and Sect. 3 introduced the proposed system model for VRU warning services. Section 4 presents the methodology for field experimentation and Sect. 5 provides the results. Finally, Sect. 6 concludes the paper.

2 Related Work

Pedestrian decision-making in urban environments relies on infrastructure such as crosswalks, sidewalks, and traffic lights. However, pedestrians also heavily depend on observing vehicle drivers' intentions [7]. Habibovic et al. found that a visual interface could help pedestrians feel safer around automated vehicles [8]. Advances in high-computation hardware improve the detection of VRUs, allowing AVs to respond preemptively before a situation becomes critical [9, 10]. Despite these improvements, current methods do not fully leverage the high density of sensors available in urban environments.

Teixeira et al. developed a method to aggregate data from various sources and alert pedestrians through a smartphone application [11]. External hardware solutions, such as internal audio sensors [12] or radar sensors [13], also aim to protect VRUs. However, these solutions do not consider that predicting an AV's decision-making is generally easier than that of a human driver. Consequently, studies have explored establishing a connection between vehicles and pedestrians to share decision-making processes [4, 14, 15]. These methods, however, often require additional hardware [14, 15] and have limited range and deployment [4].

A centralized solution using cellular connectivity can reduce the need for extensive infrastructure, hardware, and, with the development of new cellular technologies, offer relatively low latency [11]. Our approach focuses solely on AV, which, being connected and operating on predetermined routes, can facilitate edge computing and minimize the required data.

Furthermore, our methodology includes a user-centered approach to include the end user in the design loop as early as possible. Indeed, a user-centric approach is essential when developing a new technological solution. If the proposed solution is accessible and usable but ultimately not useful and does not achieve the user's goals, it will not be adopted [16]. Regarding the use of smartphone applications, Krebs et Duncan [17] the importance of addressing technical features during the requirements gathering phase to ensure that the functionality meets user expectations. By incorporating user insights throughout the development process, developers can create solutions that not only meet technical standards but also deliver real value, increasing overall user satisfaction and adoption.

Although, multiple works studied the requirement and communication architecture for vehicle-to-pedestrian communication during the last decade, most of these studies remain either theoretical or simulation based and few of them have proposed proof-of-concepts. It remains a challenge to deploy such solutions to real world due to environment complexity and diversity of scenarios. By focusing on interactions between automated shuttles and pedestrians in urban condition, our work extends the current state of the art. We propose an architecture relying on edge computing to host VRU protection service where multiple situations, namely hazardous area and collision avoidance, are assessed in parallel to send warnings and messages on a user application. This application has been evaluated with external participants, thus, involving final users in the design and testing to facilitate further adoption.

3 System Modeling and Service Development

3.1 General Architecture

Our work focuses on enhancing communication between an automated shuttle and VRUs. Relying on vehicle-to-everything (V2X) communications protocols, VRUs and AVs share their respective location through cooperative awareness message (CAM) [18].

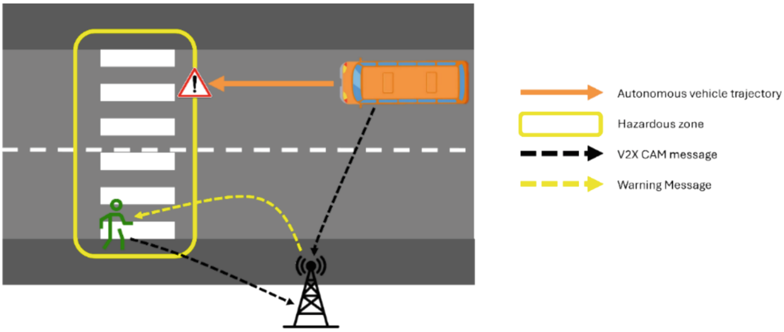


Fig. 1. VRU protection in hazardous zones use case

Unlike conventional vehicles, automated shuttles operate on a predetermined route. This allows the shuttle operator to identify zones with a high risk of interaction between VRUs and the vehicle. By leveraging the shuttle's trajectory, the system can warn VRUs within these high-risk zones when the vehicle is approaching. This constitutes the first use case that the system must address as shown in Fig. 1.

However, VRUs, particularly pedestrians, often exhibit unpredictable behavior in urban environments. Consequently, the system is also equipped with collision detection using the trajectory of both vehicle and VRU. This constitutes the second use case, shown in Fig. 2.

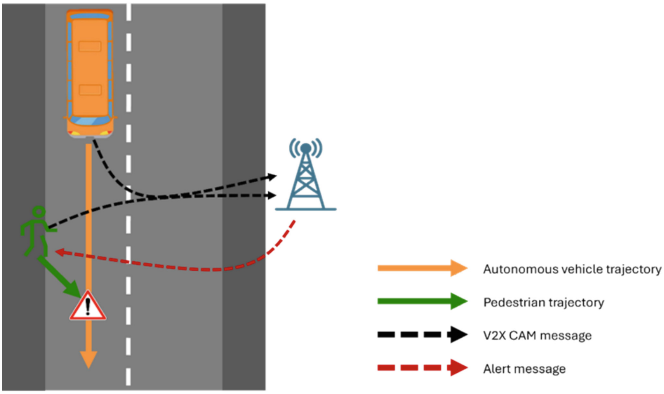


Fig. 2. VRU protection in non-signalised crossing use case

It is crucial to note that both use cases can occur simultaneously. For example, if a pedestrian crosses a sidewalk identified as a hazardous zone, they will first receive a warning for entering a high-risk area as the vehicle approaches. If the pedestrian does not stop, they will also receive a collision detection alert.

3.2 VRU Safety Service

The solution is built around a server that collects data from AVs and VRUs by relying on the Message Queuing Telemetry Transport-(MQTT) protocol, a lightweight messaging protocol ideally suited for IoT applications, as shown in Fig. 3. Periodically, VRUs and vehicles send their location using CAM messages [18] to an MQTT server. The two use cases are handled by two sub-services. One sub-service manages the state of the hazardous zone and triggers warnings if the situation is deemed dangerous, while the collision detection sub-service handles potential intersections between the trajectories of vehicles and VRUs and triggers alerts.

The algorithm, illustrated in Fig. 4 is designed to enhance road safety by processing vehicle and pedestrian messages individually in real time. By updating the dynamic data—such as position and trajectory—of each vehicle and vulnerable road user (VRU), the algorithm proactively assesses risks within hazardous zones. Its primary objective is to provide timely alerts and warnings. The algorithm is divided into two parts: Vehicle

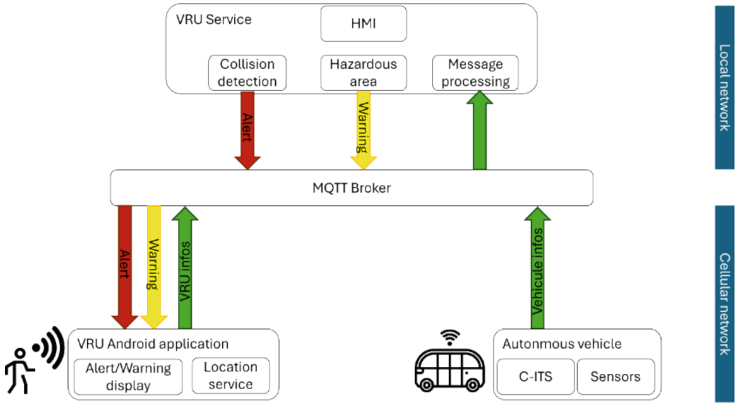


Fig. 3. Architecture of the solution

Message Processing and Pedestrian Message Processing, each responsible for handling interactions within hazardous zones and collision detection from the perspective of either the vehicle or the pedestrian.

Vehicle messages are processed as follows:

1. **Start**: When a vehicle message is received, the server updates the vehicle's last known position and trajectory based on the incoming data.
2. **Update Vehicle Dynamics**: The server processes the message to update the vehicle's dynamic properties, such as speed and direction, ensuring the most current trajectory is used for safety calculations.
3. **Hazardous zone area** – Triggered after vehicle message (case 1):

- The algorithm verifies if the hazardous zone is already marked as dangerous.
  - **Yes**: If the zone is already classified as dangerous, the process ends for this message, as no further action is needed.
  - **No**: If the zone is not yet dangerous, the algorithm proceeds to evaluate potential risks.
- To evaluate the potential risk, the system determines if the vehicle will intersect with a hazardous zone within a certain time threshold.
  - **Yes**: If an intersection is predicted, the system marks the zone as dangerous and sends a first-level warning to any VRU already inside the zone.
  - **No**: If no intersection is expected, the process ends.

VRU message are processed as follows:

1. **Start**: Upon receiving a VRU message, the server updates the pedestrian's last known position and trajectory.

2. **Update VRU Dynamics**: The message data is processed to reflect the VRU's updated dynamics, ensuring accurate tracking within potentially hazardous areas and collision with the vehicle.
3. **Collision Detection** – Triggered after VRU message (case 2):
   - This is the first step after the dynamic update. The system estimates all collision between this VRU and thevehicles based on their last position and trajectory.
     - **Yes**: If an intersection is detected, the system checks if the VRU has already been alerted.

       ○ **Yes**: If already alerted, no further action is required, and the process ends.
       ○ **No**: If not yet alerted, an alert is generated and sent to the VRU

     - **No**: If no intersection is found, the process continues.
4. **Hazardous area** – Triggered after VRU message (case 3).
   - This is the second step, the server checks if the VRU is inside a zone which is marked as dangerous.
     - **Yes**: The system verifies if the VRU has already been warned.

       ○ **Yes**: If they have, no further action is needed, and the process ends.
       ○ **No**: If they have not, a warning is issued

     - **No**: If the zone is not dangerous, the algorithm ends the process.

3.3 End-To-End Delay Minimization

The proposed approach aims to optimize two parameters: latency for VRUs (i.e., alerting the VRU as quickly as possible) and precision (i.e., alerting the VRU only when the situation is genuinely dangerous). Since messages from vehicles and VRUs are not synchronized, making decisions based on a message from a single source may be unreliable. Indeed, as one decision is taken, information from other users may be outdated, thus, affecting precision, or users may be alerted too late, thus affecting latency.

For the collision detection alert case, latency is critical as the situation is immediately dangerous. So, the system concentrates on timely alerting VRUs immediately after the server receives a message from their device. This approach can create false positive as the information of vehicle can be outdated. To minimize such effects, our implementation of hazardous area warning case exploit knowledge on the AV trajectory to anticipate when a situation becomes dangerous and issue a warning to the VRUs. This allows the VRU to be alerted before the situation becomes immediately dangerous, focusing on precision. Consequently, the situation is evaluated after receiving vehicle messages, which may cause a longer latency for the VRU, particularly when they are inside dangerous zone before the AV.

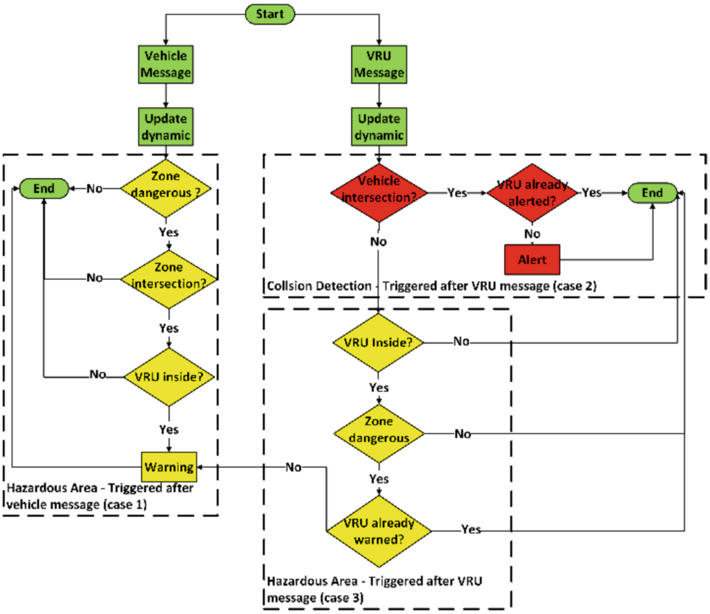


Fig. 4. Algorithm implemented in server for VRU warning and alerting

The analysis of the overall delay to alert pedestrians has been cut out based on the following time instants:

- Ttx_vru: Time of the message transmission from a VRU
- Trx_vru: Time of the message reception from a VRU at the server
- Ttx_av: Time of the message transmission from an AV
- Trx_av: Time of the message reception from an AV at the server
- Tp_start: Time at which processing from the server starts
- Tp_stop: Time at which processing from the server terminates and alert is sent
- Trx_alert: Time at which the alert is received by the VRU

For the pedestrian perspective, the total delay expressed Trx_alert- Ttx_vru and illustrated by the sequence diagram of Fig. 5, comprises several components:

- The communication delay for the last message sent by the VRU
- The computation time for generating the warning/alert at the server
- The communication delay for receiving the incoming alert/warning

In the hazardous area warning case, processing is triggered either at the reception of a message from a VRU or an AV and an alert is triggered when the conditions are met for one of these cases. In the worst case, end-to-end delay is the highest when the pedestrian is already in the alert zone and has send its message before the vehicle, i.e. Trx_vru < Trx_av. In this case, the waiting before processing the VRU message is not null and can be large (0 < Tp_start- Trx_vru < Refresh Rate).

In the collision detection alert, the end-to-end delay between the message issued by the VRU and the reception of an alert is minimized as the processing is necessary triggered at Trx_vru, so that Tp_start- Trx_vru = 0. In this case, the system triggers alert on the fly in the most critical situation where very low latency is required.

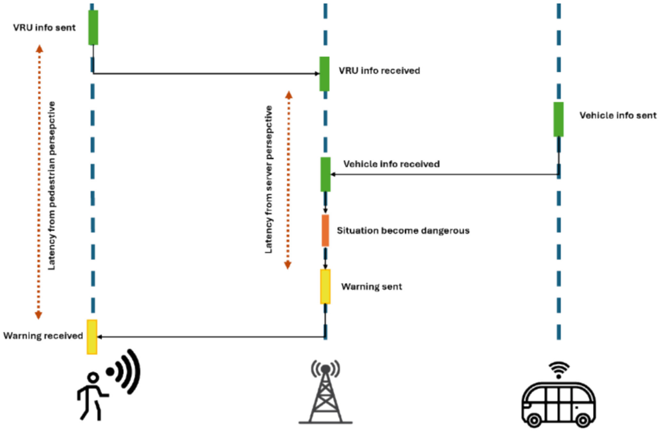


Fig. 5. Sequence diagram including delay for the VRU service

4 Field Experimentation Methodology

4.1 Scenarios

The solution has been tested on relevant scenarios aiming to evaluate the interaction between a user of the smartphone application and one or more automated shuttles. For the experiment, external users are invited to travel along a predefined route and interact with the automated shuttles. Each user is equipped with a smartphone on which the mobile application is installed and experiment the system in two parts:

- Scenario 1: The shuttle runs parallel to the pedestrian, approaching from behind. In this situation, there is no danger to the pedestrian, so they should not receive an alert, but they may be surprised by the sudden presence of a vehicle nearby. This scenario is assessing false positive alerts.
- Scenario 2: The shuttle arrives perpendicular to the pedestrian who is about to cross at a crosswalk. A building obstructs the direct view between the pedestrian and the vehicle. In this scenario, the pedestrian should be alerted to the potential danger. The crosswalk is identified as a hazardous zone and should triggers a warning. Moreover, in certain instances, the system may also emit an alert if the vehicle fails to come to a complete stop while the pedestrian is crossing.

These two scenarios illustrated in Fig. 6 are used to evaluate the benefits of our mobile application compared to a baseline situation where users do not have the application and may be unaware of potential dangers.

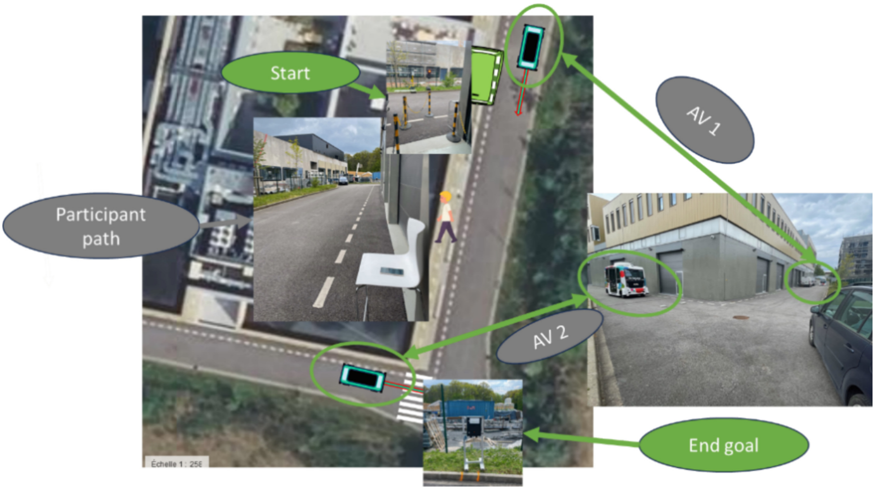
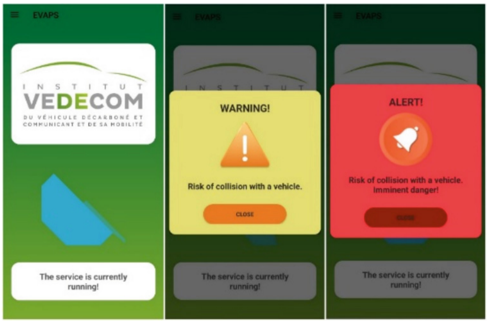


Fig. 6. Experimentation environment

4.2 Mobile Application for Pedestrian Alerting

A mobile application depicted in Fig. 7 was provided to the participants serving two primary functions: transmitting the position and status of the user to the server and alerting the user by displaying alerts or warnings emitted by the server. To closely simulate the V2X environment, the mobile application emits Cooperative Awareness Messages (CAM) at fixed intervals generated using Google's location service, which combines GPS, Wi-Fi positioning, and cell tower triangulation to determine the device's precise location. The alerts and warnings are disseminated using Decentralized Environmental Notification Messages (DENM) [19].



WARNING!

Risk of collision with a vehicle.

ALERT!

Risk of collision with a vehicle. Imminent danger!

The service is currently running!

Fig. 7. Snapshot of Android application for VRU warning and alert

Upon receiving DENMs, the application converts them into alerts or warnings based on the cause code and sub-cause code of the event. It also triggers auditory, tactile (vibration), and visual alerts based on whether it's an alert or warning. Additionally, the application includes a database to store both alerts and warnings.

4.3 User Assessment

Participants

44 participants were recruited for the experiment. Experiments took place during the day in good weather conditions (i.e., no rain) and lasted about 15 min. Before the experiment, each participant read the information notes and gave their written informed consent. The experiment was conducted in accordance with the most recent version of the Declaration of Helsinki (1964).

Procedure

Participants were greeted by the experimenter, who first explained that the purpose of the study was to investigate the interaction between pedestrians and AVs. They had to complete a multi-part course with or without the assistance of the mobile application that warned them of the risk of collision with a visual, auditory, and haptic (i.e., vibrating) signal. The course shown in Fig. 6 consisted of exiting a hangar through a door when a light turned green to press a button located approximately 30 m away. To do this, after retrieving a smartphone, they had to walk alongside a building and finally cross a street. The participants were warned about possible encounters with automated vehicles along the way. Before starting, each participant was informed that they would receive a smartphone alert warning them of the risk of a collision with an automated vehicle. Participants completed two rounds and completed several computerized questionnaires at the end of the session. These questionnaires included a rating scale, questions about the importance of receiving warnings about nearby automated vehicles, the timing and intensity of the warnings, and sociodemographic information.

To control order effects, 22 participants used the application first and then did a second round without it, while the other 22 participants did the first round without the application and the second run with it.

Questionnaires

First, participants rated the importance of receiving warnings about AVs operating nearby under three specific conditions: lack of visibility due to obstacles, lack of visibility due to poor weather conditions, and lack of visibility at specific locations (e.g., unsignalized intersections). Ratings were provided on a 4-point scale: 1 (Not at all important), 2 (Somewhat important), 3 (Very important), and 4 (Extremely important). The lack of visibility due to poor weather conditions or at specific locations were not tested directly by the participants, they had to project themselves and indicate their perceptions after testing the application in a situation of lack of visibility due to an obstacle.

Next, they assessed the timing and intensity of the warning signals received through the application. Evaluations were conducted for three modalities: auditory, visual, and haptic. Timing was rated on a scale of 0 (Not perceived), 1 (Much too early), 2 (A little too early), 3 (Ideal), 4 (A little too late), and 5 (Much too late). Intensity was rated on a scale of 0 (Not perceived), 1 (Much too weak), 2 (A little too weak), 3 (Ideal), 4 (A little too strong), and 5 (Much too strong).

Finally, a visual analog scale (0 to 100) was used to measure ease of understanding (0: Difficult to understand, 100: Easy to understand), reliability (0: Not reliable, 100: Reliable), meeting user needs (0: Does not meet my needs, 100: Meets my needs), and future desirability (0: Something I would not want in the future, 100: Something I would want in the future). Participants responded by moving a cursor between the two markers on each scale.

5 Results

5.1 Involved Users

The data collected during our study, involving 44 participants (26 men and 18 women) have published online[1]. The mean age was 33.45 years old (±11.14). Among the participants, 1 had a baccalaureate degree, 32 had a high level of education, and 11 had a doctorate. Additionally, 13 participants had already interacted with automated vehicles before participating in this experiment (i.e., 29.5% of participants).

5.2 System Performances

Time-to-Collision (TTC), representing the time instant at which a warning or an alert is triggered is presented in Table 1. The results show that the warning is triggered earlier (indicating a larger TTC) because it is easier to determine the intersection of the vehicle's trajectory with an attention zone over longer distances than to compute the intersection between the vehicle's and the pedestrian's trajectories.

Table 1. Time-to-Collision for the different services

	Average	Max	Min	Var	Median
Time-to-Collision for VRU Warning (s)	3,15	4,92	0,97	1,29	2,98
Time-to-Collision for VRU Alert (s)	1,68	2,50	0,87	0,50	1,67

Since there is a timestamp within the message from the android application, computing the delay seems to be straightforward. However, it is important to note that the clocks between the server and the smartphone may not be perfectly synchronized. Therefore, the delay is calculated from the server's perspective, which involves summing the processing delays. To pedestrian latency is then estimated by summing the communication latency to the server's perspective latency.

Table 2 introduces the processing delay on the server side, without the communication delay. It depicts a higher processing time for the VRU warning due to higher variability in the different scenarios:

5. After receiving a pedestrian message when the pedestrian enters an already dangerous attention zone, resulting in a delay similar to the alert.

---

[1] https://zenodo.org/records/14098488.

Table 2. Processing time at the server

	Average	Max	Min	Median
Processing delay for VRU Warning (ms)	33,36	171,2	0,86	5,10
Processing delay for VRU Alert (ms)	1,50	2,50	0,69	1,47

6. After receiving a vehicle message when the pedestrian is inside the attention zone, and the zone transitions from safe to dangerous upon receiving the vehicle message. Thus, the delay between the reception of the last message from the pedestrian and the reception of the vehicle message which generate the warning increase the global delay.

Tests to measure the latency of messages sent and received have been conducted. The results revealed an average round-trip latency of 36.2 ms, with a standard deviation of 17.2 ms, indicating moderate variability in latency. While the majority of messages experienced relatively low latencies, with a minimum of 0.2 ms, outliers were observed, with the maximum latency recorded at 274.1 ms. Notably, the median latency of 32.1 ms suggests a central tendency towards lower latencies. Further analysis revealed that 95% of messages experienced latencies below 59.1 ms, while only 1% of messages encountered latencies exceeding 89.7 ms. Importantly, no packets were lost during the tests, resulting in a packet loss rate of 0.00%, underscoring the reliability of the MQTT protocol.

To summarize, our findings suggest that, from a pedestrian's perspective, the average delays typically range between 70 ms to 100 ms for the warning and approximately 60 ms for the alert notifications. It is noteworthy that the primary contributing factor to latency appears to be the MQTT protocol, which accounts for the majority of the observed delays. TTC and delay metrics tend to correlate, for a warning, the delay may be longer, but the pedestrian is warned earlier (larger TTC). In contrast, for an alert, the pedestrian is alerted later, but the delay is shorter.

Table 3. Succes rate during the scenarios

	Warning Message	Alert Message
Scenario 1	0% (0/44)	14/44 (32%)
Scenario 2	71% (31/44)	14/44 (32%)

Table 3 presents the success rate during the two experiment scenarios. In scenario 1, false positives, i.e. alert messages, are generated by the first vehicle due to inaccuracies in GPS positioning, either of the vehicle or the pedestrian. The fundamental problem lies in the precision of the localization service. In these experiments, the environment resembled an urban setting, situated between two tall buildings, which blocked the direct line of sight to satellites. Consequently, as the pedestrian walked, their position was often inaccurately recorded, sometimes significantly off, until a satellite came into direct view. The inaccuracies also affected the success of the first-level warning in the second scenario. In some cases, the geographical location of the pedestrian was recorded as being outside the hazardous zone, even when their true position was inside it.

The second-level alert was impacted by both inaccuracies of the satellite position system (e.g. GPS) and the experimental setup. For safety reasons, the second vehicle had to stop at a safe distance. As a result, depending on the pedestrian's walking speed, the vehicle might already be stopped or braking sharply when the pedestrian comes in the line of sight of the vehicle, preventing any intersection between the pedestrian's and the vehicle's trajectories.

5.3 User Needs

Participants highlighted the importance of receiving collision risk notifications when visibility is poor. For low visibility due to obstacles, 34% of respondents found warnings extremely important and 39% found them very important, with only two participants finding them unimportant. Similarly, for poor visibility due to bad weather, 41% found warnings extremely important and 32% found them very important, with only three participants finding them unimportant. At specific locations, such as unsignalized intersections, 50% of participants found warnings important and 20% extremely important, with only two participants finding them unimportant (Fig. 8). Notably, women placed greater value on these notifications compared to men, particularly when visibility was limited at specific locations ($p < .001$) or due to weather conditions ($p = .023$).

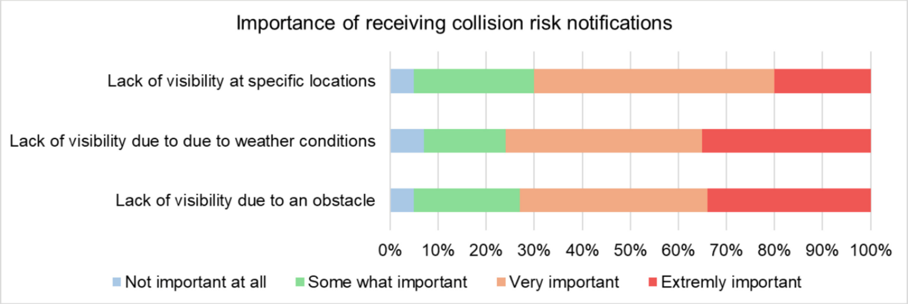


Fig. 8. Evaluation of the important of receiving collision risk notifications

5.4 User Feedback

Participants rated the timing and intensity of alerts from the smartphone application at the end of the experiment. For the auditory modality, 41% of participants found the timing ideal, while 11 participants felt the warning was a little late and three thought it was much too late. Conversely, five participants found the warning a little early, and two found it much too early. Regarding intensity, 43% of participants deemed it a little too weak, 14% found it much too weak, nine participants found it ideal, and six found it a little too strong (Fig. 9 and Fig. 10).

For the visual modality, about half of the participants did not perceive the message. Among those who did, 13 rated the timing as ideal, six as a little too late, one as a little too early, and one as much too early. The intensity was rated a little too low by 14 participants and much too low by seven, with only one finding it ideal. There was a negative correlation between age and intensity perception; older participants found the visual signal less noticeable. Additionally, those who had prior interactions with AVs perceived the visual signal as less intense than those who had never interacted with AVs (Fig. 9 and Fig. 10).

For the haptic modality, 59% of participants perceived the warning as too early, and an additional seven found it much too early. Only four participants found the timing ideal, and one found it a little too late. In terms of intensity, 19 participants rated it as ideal, nine as a little too strong, three as much too strong, five as a little too weak, and one as much too weak (Figs. 9 and 10).

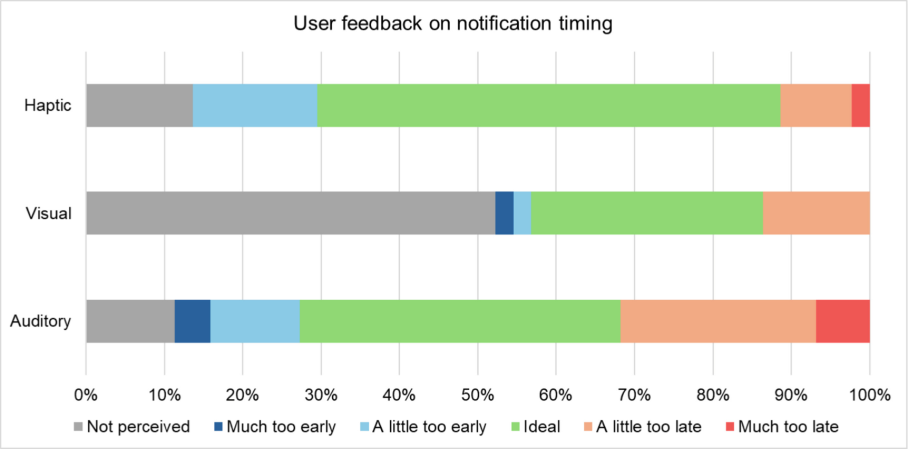


Fig. 9. User feedback on notification timing

5.5 User Acceptance

The application was well understood by most participants, averaging a score of 91/100 ($SD = 13.75$), with 19 participants scoring a perfect 100. However, two participants reported below average understanding. Reliability had a lower average score of 68/100 ($SD = 29.52$), with significant variability; two participants rated it zero, while six found it perfectly reliable. The perceived need for the application scored an average of 58/100 ($SD = 32.84$), showing divergent opinions, and desirability averaged 68/100 ($SD = 29.39$), with nine participants giving a perfect score. There was no significant difference in understanding, need, reliability, or desirability between those for whom the application worked correctly and those for whom it did not (all $p > .10$). Furthermore, no difference appears between men and women ($p > .05$).

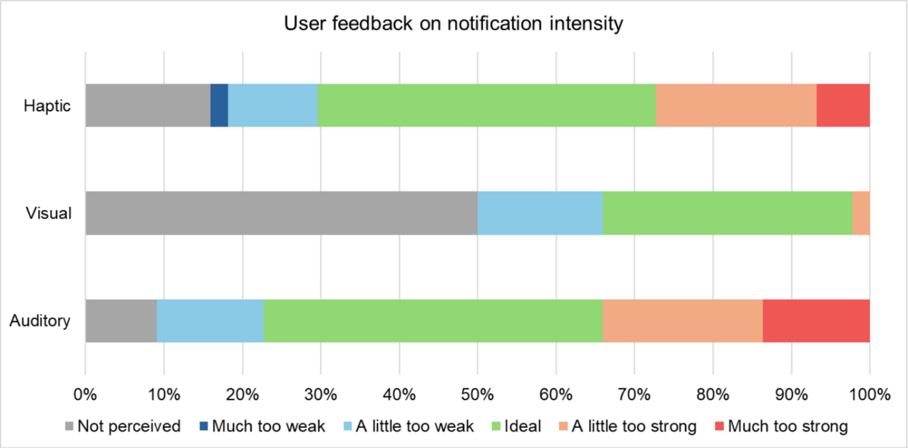


Fig. 10. User feedback on notification intensity

6 Conclusion and Perspectives

In this paper, we demonstrate the technical soundness and user willingness to rely on mobile application combined with cellular communication networks to provide VRU safety alerts in the presence of connected vehicles. The experimental study shows that by running the VRU protection service in an edge environment, the system can provide communication latency below 90 ms in more the 99% with processing time on average of 1.5 ms for alert triggering and 33 ms for hazardous area warning. The main limitation comes from the accuracy of the google localization service resulting in a high false positive rate of the alert (about 32%). To cover such limitations, the use of predefined zones leads to higher detection rates. Thus, increasing location accuracy in urban deployment represents a major challenge which could be solved using infrastructure around hazardous zone and using fusion could be a solution as it has been described in [11]. Participants highlighted the importance of being notified in case of risk of collision with an AV. Interestingly, for women, receiving notifications in this kind of situation was of even greater importance. Although our study did not test this aspect, it could be linked to the fact that women perceive AVs as riskier than men [20] where this higher perception of risk among women is observed in many areas [21]. Moreover, pedestrians' assessments of the application indicated that the messages were delivered at the right time and with appropriate intensity. However, visual messages were often poorly perceived, which may be due to the application's design, as it failed to display visual alerts when users were engaged with other applications on their phones. Although the proposed mobile application solution has been well understood, improvements are still needed to better meet user needs and make it more attractive. This study thus highlighted that the proposed application could be a way to secure interactions between AVs and pedestrians, particularly by using sound and haptic systems, well evaluated in this study, but that further studies are needed to propose a system that meets the needs of users, and it could be interesting to evaluate this kind of application in more challenging situations.

This work has focused on providing information to VRU via their smartphone, however, it is crucial for the VRU to know if the automated vehicle is aware of the dangerous situation. Therefore, it could be beneficial for the safety and reassurance of the VRUs to also transmit the information to the automated shuttle, enabling the shuttle to send a visual or auditory notification, hence, increase the trust and cooperation. Further work can also consider other aspects for large scale deployment such as legal and regulatory challenges.

Acknowledgements. The authors would like to thank the experimental team of VEDECOM, Alexis, Benoit and Émile for their involvement during the experimentation.

The results included in this paper are part of SHOW, a project which received funding from the European Union's Horizon 2020 research and innovation program under Grant Agreement No. 875530.

References

1. Yaqoob, I., Khan, L.U., Kazmi, S.M.A., Imran, M., Guizani, N., Hong, C.S.: Autonomous driving cars in smart cities: recent advances, requirements, and challenges. IEEE Network **34**(1), 174–181 (2020)
2. Prasetio, E.A., Nurliyana, C.: Evaluating perceived safety of autonomous vehicle: the influence of privacy and cybersecurity to cognitive and emotional safety. IATSS Res. **47**(2), 160–170 (2023)
3. Deb, S., Strawderman, L., Carruth, D.W., DuBien, J., Smith, B., Garrison, T.M.: Development and validation of a questionnaire to assess pedestrian receptivity toward fully autonomous vehicles. Transp. Res. Part C: Emerg. Technol. **84**, 178–195 (2017)
4. Anaya, J.J., Merdrignac, P., Shagdar, O., Nashashibi, F., Naranjo, J.E.: Vehicle to pedestrian communications for protection of vulnerable road users. In: IEEE Intelligent Vehicles Symposium Proceedings, Dearborn, MI, USA (2014)
5. American Honda Motor Co., Inc., https://www.prnewswire.com/news-releases/honda-demonstrates-advanced-vehicle-to-pedestrian-and-vehicle-to-motorcycle-safety-technologies-221495031.html. Accessed 30 Sep 2024
6. Nguyen, Q.H., Morold, M., David, K., Dressler, F.: Car-to-Pedestrian communication with MEC-support for adaptive safety of vulnerable road users. Comput. Commun. **150**, 83–93 (2020)
7. Risto, M., Emmenegger, C., Vinkhuyzen, E., Cefkin, M., Hollan, J.: Human-vehicle interfaces: the power of vehicle movement gestures in human road user coordination. In: Driving Assessment Conference, University of Lowa, USA (2017)
8. Habibovic, A., et al.: Communicating intent of automated vehicles to pedestrians. Front. Psychol. **9** (2018)
9. Islam, M.M., Newaz, A.A.R., Karimoddini, A.: A pedestrian detection and tracking framework for autonomous cars: efficient fusion of camera and LiDAR data. In: IEEE International Conference on Systems, Man, and Cybernetics (SMC), Melbourne, Australia (2021)
10. Alfred Daniel, J., Chandru Vignesh, C., Muthu, B.A., Senthil Kumar, R., Sivaparthipan, C.B., Montenegro Marin, C.E.: Fully convolutional neural networks for LIDAR–camera fusion for pedestrian detection in autonomous vehicle. Multimedia Tools Appl. **82**, 25107–25130 (2023)
11. Teixeira, P., Sargento, S., Rito, P., Luís, M., Castro, F.: A sensing, communication and computing approach for vulnerable road users safety. IEEE Access **11**, 4914–4930 (2023)

12. Xia, S., De Godoy Peixoto, D., Islam, B., Islam, M.T., Nirjon, S., Kinget, P.R.: Improving pedestrian safety in cities using intelligent wearable systems. IEEE Internet Things J. **6**(5), 7497–7514 (2019)
13. Wang, Z., Wan, Q., Qin, Y., Fan, S., Xiao, Z.: Intelligent algorithm in a smart wearable device for predicting and alerting in the danger of vehicle collision. J. Ambient. Intell. Humaniz. Comput. **11**, 3841–3852 (2020)
14. Lewandowski, A., Bocker, S., Koster, V., Wietfeld, C.: Design and performance analysis of an IEEE 802.15.4 V2P pedestrian protection system. In: IEEE 5th International Symposium on Wireless Vehicular Communications (WiVeC), Dresden, Germany (2013)
15. Zhang, C., Wei, J., Qu, S., Huang, C., Dai, J., Fu, P.: Implementation of a V2P-Based VRU warning system with C-V2X Ttchnology. IEEE Access **11**, 69903–69915 (2023)
16. Loup-Escande, E., Burkhardt, J.M., Richir, S.: Anticipating and evaluating the usefulness of emerging technologies in ergonomic design: a review of usefulness in design. Le Travail Humain **76**, 27–55 (2013)
17. Krebs, P., Duncan, D.T.: Health app use among US mobile phone owners: a national survey. JMIR mHealth uHealth **3**(4) (2015)
18. ETSI EN 302 637–2: Intelligent Transport Systems (ITS); Vehicular Communications; Basic set of Applications; Part 2: Specification of Cooperative Awareness Basic Service. v1.4.1 (2019)
19. ETSI EN 302 637–3: Intelligent Transport Systems (ITS); Vehicular Communications; Basic set of Applications; Part 3: Specification of Decentralized Event Notification Service. v1.3.1 (2019)
20. Hulse, L.M., Xie, H., Galea, E.R.: Perceptions of autonomous vehicles: relationships with road users, risk, gender and age. Saf. Sci. **102**, 1–13 (2018)
21. Gustafson, P.E.: Gender differences in risk perception: theoretical and methodological perspectives. Risk Anal. **18**, 805–811 (1998)