Accelerate the understanding and adoption of VRU protection services enabled by C-V2X

5GAA Automotive Association
Technical Report

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VERSION:	Version 1.8
DATE OF PUBLICATION:	23 February, 2023
DOCUMENT TYPE:	Technical Report
EXTERNAL PUBLICATION:	Yes
DATE OF APPROVAL BY 5GAA BOARD:	31 October, 2022

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Executive summary

5GAA is a strong promoter of the mass deployment of Vulnerable Road User (VRU) protection services using Vehicle-to-Everything (V2X) technologies.

Through a set of activities in 2020-2021, six groups of 5GAA members have committed to make progress in V2X-based VRU protection. The groups widely targeted proof-of-concepts (PoC), demos and deployment activities to show how diverse approaches using V2X can increase safety for pedestrian, roadworkers, cyclists, e-bikes, mopeds, e-scooters and other powered two-wheelers (PTW) Each of these experiments are described in details:

- A set of very pragmatic and low-hanging warning use cases in school zones or at bus stops targeting children in Alpharetta, Georgia, US;
- A cloud- and app-based approach to monitor and learn from intersection movements and warn about conflicting trajectories between VRUs in Hamburg, Germany;
- An infrastructure-based sensor detecting and reporting pedestrian movement at intersections in Arizona, US;
- An electric bike-vehicle interaction method exchanging newly standardised VRU awareness messages including path prediction in Hildesheim, Germany;
- A fast app-based pedestrian and bicycle presence awareness information tool with wide deployment potential in Seoul, the Republic of Korea;
- A more advanced in-vehicle-sensor VRU detection and presence-sharing system in Aldenhoven, Germany.

These six experiments as well as a few others running in parallel among the 5GAA members led to a debate on a dozen recommendations written in 2020 by the first 5GAA VRU Work Item (WI). For each recommendation, the groups gave their perspectives on what are necessary steps to address the described barriers, and the best way to progress towards market introduction of these life-saving solutions.

This is all described in the opening chapters of this Technical Report. In Chapter 4, we then look at recent standards used throughout the WI and identify potential improvements based on the learnings.

By no means are these experiments meant to compete or be corralled into a single solution for adoption. It is clear that VRU protection can only be solved via step-by-step innovations and approaches using all technologies and capabilities at hand. As one low-hanging opportunity, many group members focused more on ways to better exploit the capabilities of smartphones carried ubiquitously by most road users. This should come as a complement to sensor-based VRU protection being evaluated by the likes of EuroNCAP.

A combination of these solutions is therefore the most likely scenario for market introduction, whether it is based on short range, mobile network, mobile apps, edge computing, sensors, etc.; as long as it has potential to save lives.

5GAA is committed to pursuing the efforts emerging from the different initiatives. Learnings from the experiments are already feeding concrete plans to scale up deployment in different parts of the world. More work is needed on more large-scale demonstrations and in-depth studies on VRU Awareness Messaging (VAM) and Personal Safety Messaging (PSM) standardisation.

1 Introduction

1.1 5GAA VRU recommendations

5GAA's White Paper *Vulnerable Road User Protection*[1] examined the significant safety benefits some V2X-enabled use cases had for Vulnerable Road Users.

Published in September 2020, the paper identified a series of areas as well as further work to achieve progress in V2X-based VRU protection. These areas are the following:

- Define minimum triggering conditions for delivery of VRU warnings;
- Provide guidelines for common presentation of VRU warnings, i.e. haptics, audio, visual;
- Define minimum triggering conditions for transmitting VAM/PSM;
- Set requirements for efficient use of spectrum, e.g. reduction of VAMs/PSMs in clusters;
- Identification of high-risk situations regarding pedestrians and places;
- Research into pedestrian path prediction;
- Minimise power consumption in smartphones operating a VRU protection service;
- Sensor fusion;
- Identify containers for sensor fusion data in each VRU category;
- VRU profile;
- Integration with existing systems.

1.2 Work Item approach

5GAA is a strong promoter of the mass deployment of VRU protection services using V2X technologies. In order to meet the 5GAA's proposed roadmap for VRU use cases[2], this Technical Report (TR) details a series of activities (demonstrations, tests, trials, evaluations, PoC, validations) in various locations and by different 5GAA members to showcase the potential of C-V2X-enabled use cases addressing VRU protection. Moreover, by means of practical experience, the WI also addresses the challenges and gaps to be closed in relation to the technology enablers, standards and requirements.

VRU is defined by the UNECE as follows: "Road users may be defined as vulnerable with regard to their degrees of protection in traffic, such as pedestrians, cyclists, non-motorised road users and motorcyclists, or their degree of mobility, such as the young, the elderly, and people with disabilities or special needs." In the context of the report, VRU includes pedestrians, roadworkers, cyclists, e-bikes, mopeds, e-scooters, other powered two-wheelers (PTW), as well as persons with reduced mobility, e.g. on a wheelchair and any other road users for whom a traffic collision may lead to severe consequences.

During the execution of the work, 5GAA left a high level of autonomy across the activities, which were carried out by different groups of 5GAA members addressing different kinds of VRUs, at various locations. Activities varied in form, duration, technology scope, audience and impact. Eventually, six groups of 5GAA members were identified with different approaches:

- Applied Information in Atlanta, Georgia, deployed and evaluated a set of very pragmatic and low-hanging warning use cases in school zones or at bus stops, targeting children with the help of their TravelSafely app;
- Deutsche Telekom and Continental demonstrated in Hamburg a cloud- and app-based approach to monitor and learn from intersection movements, including exchange of Cooperative Awareness Messages (CAMs) over the

[1] https://5gaa.org/news/vulnerable-road-user-protection/

[2] https://5gaa.org/news/5gaa-releases-new-2030-roadmap-for-advanced-driving-use-cases-connectivity-technologies-and-radio-spectrum-needs/

mobile network and traffic light information. It reduced false warnings when conflicting trajectories between vehicles, pedestrians and bicycles were observed;

- Intel made a proof of concept of Cooperative Perception Message (CPM) using an infrastructure-based sensor detecting and reporting pedestrian movement at intersections in Arizona;
- Bosch developed an electric bike interacting with other short-range equipped vehicles using the newly standardised VAM including path prediction in Hildesheim;
- LG Electronics introduced a widely deployed and fast app-based pedestrian and bicycle presence-awareness information exchange for PSM messages over the mobile network in Korea;
- Vodafone, Here and Porsche opted for more advanced in-vehicle-sensor VRU detection and presence-sharing in Aldenhoven.

A common methodology for the preparation and collection of conclusions was developed to eventually consolidate the results around the series of recommendations listed in the previous section.

2 Review of VRU-PRO activities

In total, six different groups of 5GAA members were identified during the VRU-PRO WI activities. Each of them described and executed their own activities, showcasing the potential of VRU protection using V2X technologies. This chapter describes the activities performed by each group, including the approach, the methodology, and the research questions. Each group concludes with its own lessons learned before addressing together the VRU recommendations in Chapter 3.

The variety of approaches shows that the VRU protection topic is still very much open for innovations, but offers room for low-hanging fruit contributing to a potential impact on VRU safety. Beyond the use of on-board vehicle sensors, there is a need to include the pedestrians in the safety ecosystem and, in some cases, complementary sharing of the roadside or in-vehicle sensors helps to pick up undetected dangers. The group experiments ranged from demonstrations, tests and trials, to evaluations, proof of concept (PoC), and/or validations, and they investigated the potential of various network enablers, ITS messages, devices, sensors and radio interfaces. Table 1 gives an overview of the groups' technological choices to address VRU protection.

Table 1: Overview of technologies, features and/or functionalities included in each of the VRU-PRO activities

	Network enablers		ITS Messages				Devices/Sensors			Radio Interface	
	5G SA	MEC	CPM	PSM/ VAM	CAM/ DENM	SPAT/ MAP	Vehicle sensor	Roadside sensor	Mobile devices	Uu	PC5
Group A							X		X	X	X
Group B		X	X		X	X		X	X	X	
Group C			X					X			X
Group D				X			X				X
Group E				X					X	X	
Group F	X	X			X		(X)		X	X	

It should be noted that while 5G Stand Alone and Multi-access Edge Computing (MEC) was required for the last group, none of the other groups required the presence of a fully operational 5G Stand Alone network. However, many of the groups used the readily available 4G/LTE mobile network.

A variety of standardised messages was used to address VRU protection: CAM/BSM/DENM* are the best known, as well as the newly standardised VAM/PSM and the exploratory CPM. In the future, a combination of these messages from different sources could help correlate or reinforce efficiently the presence of a dangerous situation involving a VRU.

* Cooperative Awareness Message, Basic Safety Message, Decentralised Environment Notification Message

Groups used different sensor sources of information from vehicle, infrastructure, and mobile phones. The inclusion of mobile phones in the use cases usually implied the presence of an app running in the background.

Finally, both mobile network-based and/or short range-based communication channels were used; sometimes both of them in a complementary way.

2.1 Group A: VRU protection evaluation in Alpharetta – Applied Information

2.1.1 Description

The objective of this VRU-PRO Group A activity was to implement two different use cases to help protect vulnerable school children. The use cases were intentionally very basic or simple in order to prove that VRU protection solutions can start today rather than waiting for standards and technology to answer complex situations. The VRU evaluation in Alpharetta asked the theoretical question: Would these use cases be accepted by the local governments and would they be willing to pay for these systems?

Motivation: According to the latest data from the National Highway Traffic Safety Administration, 2018 saw nearly 6,300 pedestrian fatalities[3] in the US – the highest rate since 1990. Additional data shows, on average, more than 100 children are killed and approximately 25,000 injured each year walking to or from school[4].

A number of studies[5] have also reported that 'stop-arm' violations continue to be one of the greatest dangers to school children; that is, a driver speeding up or failing to stop when a school bus is flashing its yellow or red signal lights and its stop sign. Over 50,000 stop-arm violations happen daily in the USA.

The first application, using C-V2X direct technology, is designed to warn drivers when they are approaching an **active school safety zone** and exceeding the speed limit when children are present. When active, Roadside Units (RSU) installed in school-zone safety beacons flashing signs to slow drivers down as they pass by a school. These broadcast messages to vehicles indicating the location of the school and the reduced speed limit. This initial deployment will also help to alert drivers to the changes in speed limit as school times change due to circumstances, such as half school days and early dismissals for the weather.

Figure 1: Active school safety zone use case helps drivers to adapt their speed

The second application is designed to warn drivers when they are approaching a **school bus stopped to pick up or drop off students**. In the second deployment application, Onboard Units (OBU) broadcast C-V2X safety messages from school buses to C-V2X-equipped vehicles when the bus stop arm is extended to indicate no passing is allowed.

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[3] https://www.nhtsa.gov/road-safety/pedestrian-safety
[4] https://www.prnewswire.com/news-releases/curb-back-to-school-tragedies-with-aaas-tips-166721046.html
[5] https://www.nhtsa.gov/school-bus-safety/reducing-illegal-passing-school-buses

Figure 2: School bus stopped alert warns drivers approaching a bus picking up or dropping off students

Following a short development cycle, the VRU-PRO Group A activity has tested and validated the two use cases: **school-zone warnings** and **school-bus warnings** transmitted directly to vehicles. Once validated, further steps are being planned towards real-life deployment of the technology in a fleet of school buses and different school zones.

2.1.2 Research questions studied

The research focused on whether public authorities would be willing to fund the deployment of roadside equipment for school zones and vehicle equipment for the school buses.

This activity focused essentially on two specific research questions:

- How do drivers react to school-zone or school-bus warnings displayed in the vehicle?
- How can these use cases be quickly expanded to all school zones and school buses?

Previous research has been made on the time it takes to warn drivers and the type of warnings that are best.

2.1.3 Methodology

The setup of the experiment consisted of driving a PC5-equipped car along different routes on which school-zone warnings were activated. Similarly, the car was driving behind a school bus in operation.

School zone: The alerts for these messages are automatically provided when a vehicle enters an active school-zone area. This is defined by the roadway markings and, in turn, by the MAP file. Once the school beacons are active, the Traffic Information Message (TIM) is broadcast and received by the vehicle. This is then provided to the user. The user will then be able to see the speed limit of the active school zone and receive alerts if they are speeding.

School bus: The alerts when a school bus is active ahead are defined by the BSM message. Once the stop-arm is active on the school bus, the vehicle will calculate a time to collision alert approximately 2-5 seconds away from the collision point.

2.1.4 Data collected and studies available

The experiment was focused on quickly deploying simple use cases for improving safety and on better understanding driver reactions to the different warnings. No systematic data collection was planned at this stage. However, once more vehicles get deployed on the roadway, more data can be collected. That said, previous studies have been made by the University of Florida on when and how a warning should be displayed to the drivers.

The main purpose of the Florida University study[6] was to evaluate the smartphone-based app called 'TravelSafely' developed by Temple/AI. This app has the capability to alert drivers if they exceed a given speed threshold in an active school zone or when they are approaching a cyclist, and a collision is possible. We collected trajectory and eye tracking data from 50 participants. Each participant drove a circuit twice and, in each circuit, drove through four school zones and one staged cyclist. The driving subjects were randomised across three conditions: (1) Stealth/OFF condition (drivers did not receive any alerts), (2) Audio ON (drivers received audio alerts), and (3) Audio/Visual ON (drivers received both audio and visual alerts).

Overall, the experiment suggests that the availability of an app decreased the probability of speeding in school zones and increased visual scanning behaviour. This could translate into improved situational awareness and safety in school zones. The results showed a significant increase in the probability of seeing the cyclist thanks to the app, even when the cyclist was not expected. It is useful to acknowledge that these results are based on a relatively small sample of valid data points. Therefore, future studies with larger samples are warranted.

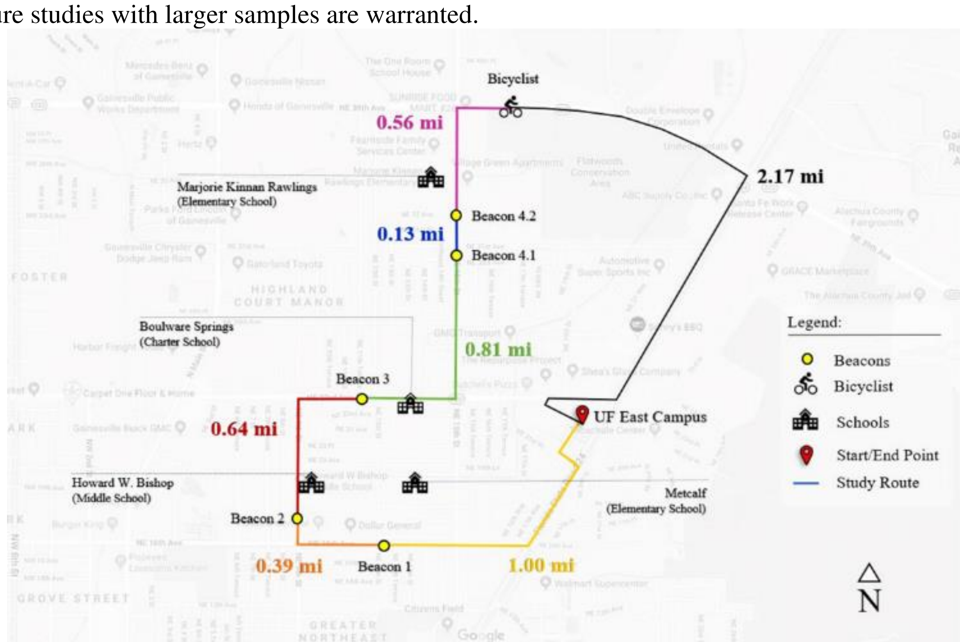


Figure 3: Route used to collect driver behaviour data in the Florida University study

2.1.5 Conclusions

The technology works well, and all the participants found that the alerts were meaningful and that it would add to the safety of school children. Providing alerts to drivers that they were speeding in school zones slowed them down, and drivers were more likely to stop when alerted that a school bus had stopped ahead.

Audio and visual alerts represent the best way of ensuring drivers slow down. However, the difference between audio only and audio and visual is relatively small, according to the study conducted by the University of Florida.

6 For more information on the Florida study see link: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv31-977-103-rpt.pdf

The most important outcome concerning this deployment is the willingness of local authorities to deploy this safety technology for school safety. All stakeholders – parents, agencies/authorities, governments – backed this use case. Once deployment of PC5 vehicles becomes more prevalent further studies will be done.

A summary video[7] shows how the technology was perceived by multiple actors.

2.2 Group B: VRU protection enabled by 5G demonstrated at ITS World Congress – Deutsche Telekom and Continental

2.2.1 Description

The Digital Guardian Angel was a concept demonstrated at the ITS World Congress in Hamburg, 2021. To reach the destination safely and efficiently, different road users were networked with each other via a high-performing, low-latency telecoms infrastructure, based on MEC.

In addition to the four-wheeled vehicles (cars, public transportation, trucks, etc.), VRUs such as pedestrians, cyclists, e-bike and scooter riders, are warned of dangerous situations via their digital devices (i.e. smartphones, smart watches). Standardised interfaces and highly accurate localisation were crucial for this.

In the context of developing new mobility services (automated vehicles, potentially noiseless electric vehicles, increased mixing of individual mobility modes), it is important to counter the associated risks of injury to VRUs through targeted measures, and to promote the attractiveness and safety of the modes of transport chosen by VRUs. Networking between VRUs and other road users (vehicles, buses, etc.) is an important tool for this. The project applied the now available edge-based mobility infrastructure towards increased VRU safety, in particular through targeted collision warning services. Also, by providing information from the traffic infrastructure (lights, intelligent detection, tracking stations) to VRUs, they can optimise their behaviour and reach their destination safely and efficiently.

To demonstrate the networking between VRUs, vehicles and other transport elements at a realistically reproducible level, but also with a broad and extensive target group – and to be able to derive scalable solutions or approaches – Group B targeted a broad set of different thematic aspects (road users and means of transport, traffic infrastructure elements) while allowing for 'quantitative resilience' (high quantities of traffic infrastructure elements, many real users, especially VRUs) to be factored in.

The outcome would be an app on a consumer device intended to protect VRUs by providing collision warnings and traffic light phase assistance, and to increase the flow of traffic in general and of bicycles and scooters in particular. The project partners have tested these features in Hamburg during summer 2021.

[7] https://youtu.be/SM1Gq7zWohQ

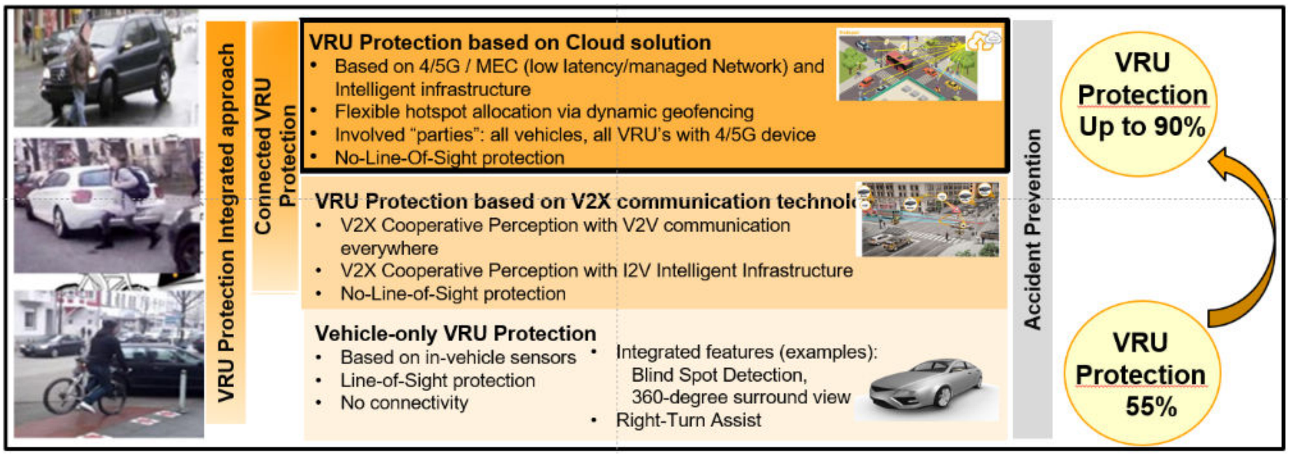


Figure 4: VRU protection – a taxonomy

2.2.2 Research questions studied

- How do connected road users, especially VRUs such as pedestrians, cyclists and scooter riders, move more safely and efficiently along roads as well as sidewalks and bicycle lanes?
- Is the 4G/5G telecommunications network with MEC applicable for the VRU safety protection application?
- What are the most critical sensor data for preventing crash and near-crash situations in the majority of traffic conditions (how to reduce/avoid false warnings)?
- How to set up a system architecture considering:
  - Usage of only commercially-off-the-shelf hardware (COTS HW)
  - Lean and open API specifications between a (centralised) cloud algorithm and the (decentralised) multitude of clients/road users
  - Feature and service extensions keeping the client API unchanged
  - Lean client software (SW) applicable to most devices today (smartphones, IOT devices, smart watches etc.)
  - Minimum set of standardised C-ITS messages to achieve a robust collision warning algorithm

2.2.3 Methodology

A PoC was defined and implemented in the City of Hamburg. The system has been connected with a traffic simulation tool in order to mitigate the risks associated with limited live testing.

The project operated based on CAM/DENM messaging in the base versions. Further message types were integrated in a second phase: MAP/SPAT messages. The third phase utilised information received via CPM messages as well.

The cloud-based collision warning solution operates on a ‘hotspot’ basis characterised by a geofenced area (e.g. an intersection, an area along a road, a larger region of the city, etc.). The system supports multiple hotspots (several thousands). During the PoC, the system was applied to three dedicated hotspots.

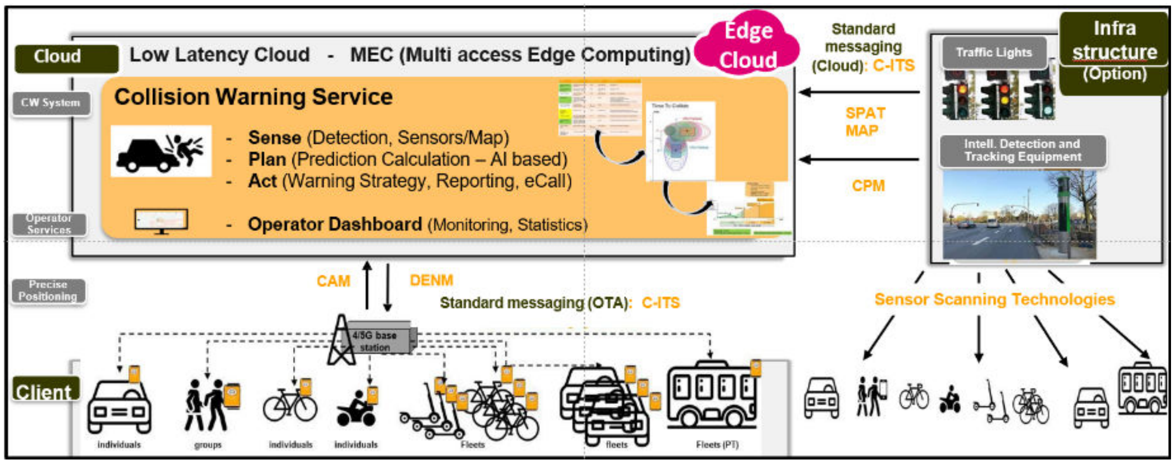


Figure 5: VRU protection, 5G-enabled cloud approach extension, integrated digitised city infrastructure

2.2.4 Conclusions

The system provides evidence of a reliable service setup for VRU protection. The solution is scalable and covers the majority of critical road traffic situations involving VRU injuries and fatalities. The demonstrated solution can be considered as a superset of the EC and UNECE regulated Turn Assist solution.

Regulation/Incentivisation

- VRU deployment depends on the successful penetration rate
- Contractual framework-setting by cities (e.g. part of licence agreements for fleets – taxi, ride hailing, car sharing, bike sharing, …) as well as logistics companies – needs to be combined with enforcement measures
- Beyond UNECE151: it does not consider use cases based on connected solutions
- Incentivisation: integration into NCAP (EURO, China, North America) – technology neutral
- Acceptance of smartphone solutions, aftermarket solutions, embedded solutions

Technology

- VRU protection solution should be promoted as technology neutral – focus on dedicated use cases
- Technology should support fast and cost-efficient deployment strategies – SW-based solutions should be the focus, stepwise HW-based enhancements (e.g. at intersections and vehicle-based) for potential performance (and quality) improvements
- Consider operational/scalable system architectures to manage crowded settings (e.g. traffic jams at intersections, large events like soccer games, cyclist groups on roads)
- Avoid too many – unimportant – warnings

Minimum set of data: positioning, speed, heading; enhanced set of data: environmental data (camera, radar, etc.), HD map, infrastructure data (traffic light, etc.), historical data/machine learning, vehicle specific data – intention data (turn signal, etc.), and dynamic data. All above mentioned topics have been partially considered in the joint project of Deutsche Telekom and Continental.

How do connected road users, especially vulnerable road users such as pedestrians, cyclist and scooter riders, move more safely and efficiently along roads as well as sidewalks and bicycle lanes?

- Main means of VRU involvement: smartphones; to achieve the integration of majority of VRU devices, the client solution of an VRU protection system should be very lean, based on COTS hardware, and easy to use
- In-time audio-visual information about approaching traffic participants, considering certain exclusion criteria: no pedestrian-to-pedestrian warning, no low-speed warning, all traffic participants follow the traffic rules (e.g. no red-light jumping)

- Furthermore, the VRU protection system design should easily integrate a VRU client into further value-added services (i.e. time-to-green, cyclist navigation, fleet management client systems, etc.)

Is the 4G/5G telecommunications network with MEC applicable for the VRU protection safety application?

- The results of system test and evaluation validated the initial assumption to apply MEC technology within 4G/5G networking

What are the most critical sensor data for preventing crash and near-crash situations in the majority of traffic conditions (how to reduce/avoid false warnings)?

- Positioning, heading, speed in conjunction with HD map and historical data (machine-learning approach)

How to setup a system architecture considering COTS HW usage only?

- o The centralised solution approach demonstrated all capabilities to interconnect COTS clients (like smartphones) with a very lean Application Programming Interface (API) and SW integration only (e.g. via an AppStore)

How to set up a system architecture considering lean and open API specifications between a (centralised) cloud algorithm and the (decentralised) multitude of clients/road users.

- o See above
- o Furthermore, the approach does allow to integrate further traffic information (i.e. traffic light information via SPAT/MAP) and intersection monitoring information (i.e. CPM) without any impact on the client (smartphone) API

How to set up a system architecture considering feature and service extensions, keeping the client API unchanged.

- See above
- Further services can be combined with the VRU protection service with a limited impact on the client (smartphone) API; examples are real-time traffic information (RTTI), data service, speed advice service, traffic rule violation service, etc.

2.3 Group C: Smart-RSU Demonstration – Intel and Cohda Wireless

2.3.1 Description

Intel, Cohda Wireless and partners have tested and showcased VRU safety use cases at the City of Anthem, Arizona (AZ). The use cases were enabled by smart RSU technology, which combines computer vision, analytics, edge computing, and C-V2X communications for VRU protection. The objective of this demo was to show and test the capability of the smart RSU technology, to provide effective VRU protection by means of computer vision and edge analytics using AI/machine-learning algorithms and C-V2X communications.

With this setup, both, VRU awareness and VRU protection can be achieved using dedicated warning messages. For example, by broadcasting VRU awareness-related information using the pre-standard version of the CPM. Such awareness information can eventually be utilised to protect VRUs by, say, appropriate manoeuvring, braking (full or partial), or stopping the vehicle – thus avoiding any imminent collision with a VRU. Alternatively, or in addition, any V2X-equipped road users with a VRU protection application may be able to receive such messages, learn about such imminent collision situations, and take self-protective actions such as manoeuvring away or stopping. Nevertheless, this demo focuses on the former method of raising awareness about the VRU (and not the latter).

The setup is as follows: several IP cameras on the roadside feed the smart RSU with their video streams; the smart RSU hardware and software perform the ‘vision analytics’ for detecting pedestrians (VRUs), vehicles, etc. That information is conveyed to the V2X-equipped road users via the C-V2X hardware and software stack. At the V2X-equipped road user end, the information is received and interpreted using human-machine interfacing (HMI) or other means.

In the first phase, the focus was on smart RSU-to-vehicle wireless communications only. On the vehicle side, that means a similar C-V2X hardware and software setup is used to receive the CPM messages. The CPM decoding and HMI processing are running on the on-board edge computing module. Meanwhile, the tablet or HMI display device in the vehicles renders the surroundings and the presence of the VRUs visually.

As Group C was focusing on the CPM messaging rather than HMI, no specific tests were conducted on how the message was displayed to the driver.

2.3.2 Research questions studied

The main research question addressed was:

- What is the impact of smart RSU with C-V2X capability on VRU safety? For example, with smart RSU-based VRU awareness and safety mechanisms, what is the increase in reaction time on the vehicle side (or VRU) to avoid any potential collision (thus reducing the collision risk) when the VRUs are in a dangerous collision-prone situation?

2.3.3 Methodology

The setup: the smart RSU is deployed at the four-way intersection with live traffic. Four cameras are facing each direction. A few vehicles will be equipped with OBUs for testing and data collection.

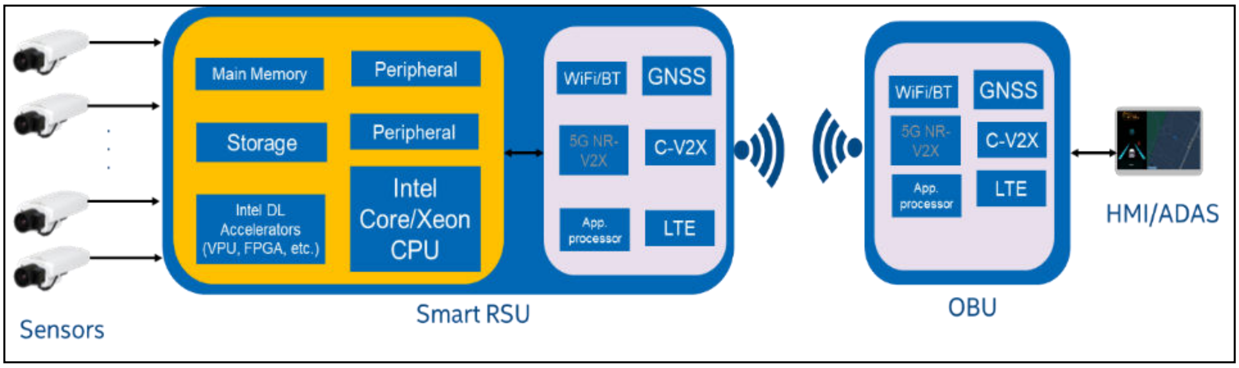


Figure 6: Functional architecture of the smart RSU demo

<u>Test Scenario 1: VRU crossing the road</u>

For this test scenario, the following two cases – Test Case A and Test Case B – are considered. Note that the cases also cover the jaywalking scenario when the pedestrian is not crossing at an intersection.

Test Case A – Pedestrian crossing direction 'UP'

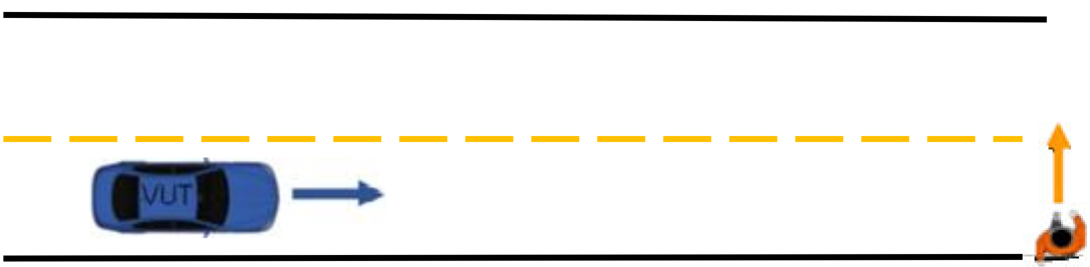


Figure 7: Test Case A – Pedestrian crossing in the 'UP' direction

Test Case B – Pedestrian crossing direction 'DOWN'

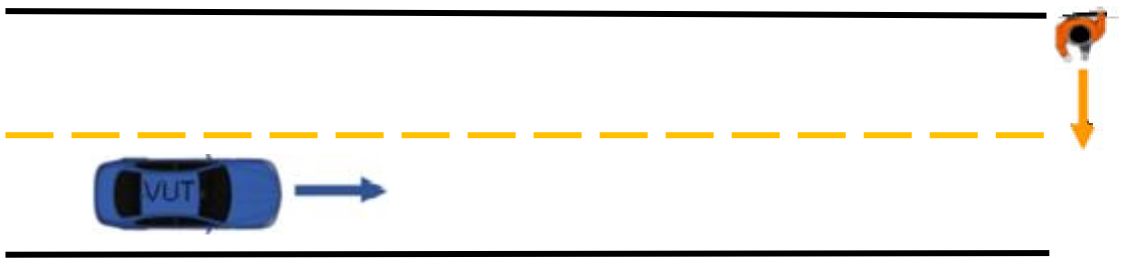


Figure 8: Test Case B – Pedestrian crossing in the 'DOWN' direction

Tests conducted for passive VRU under the following test conditions (it includes jaywalking):

- Test vehicle moves at a constant speed towards an intersection/pedestrian crossing zone
- VRU crosses the road at the designated pedestrian crossing zone from either direction
- Care to be taken so the pedestrian is in the camera's field of view (FoV)
- The roadside camera detects the VRU and communicates the information to the MEC

Table 2: Test parameters

Vehicle speed (MPH)	10-40
VRU category	Adult
VRU walking speed (MPH)	3
Message duty cycle (ms)	200, 500

Test methodology (steps) are as follows:

a) Test vehicle increases to the speed (10 to 40 MPH) – according to the speed limit: at least three rounds of tests to be conducted at each test speed

b) Test vehicle reaches stable speed, cruise control can be used (if possible/available) at higher speed; for lower speed (<25 MPH), cruise control option may not be available

c) Test vehicle approaches the pedestrian crossing zone with stable speed

d) Test vehicle enters the performance evaluation and test data collection phase

e) Test vehicle stops for a pedestrian/VRU (safety warning message displayed)

f) VRU crosses the road

g) Test vehicles crosses the zone, stops, U-turns and prepares for the next test

h) At the end of all rounds, test data is collected and checked for accuracy before moving to the next test case

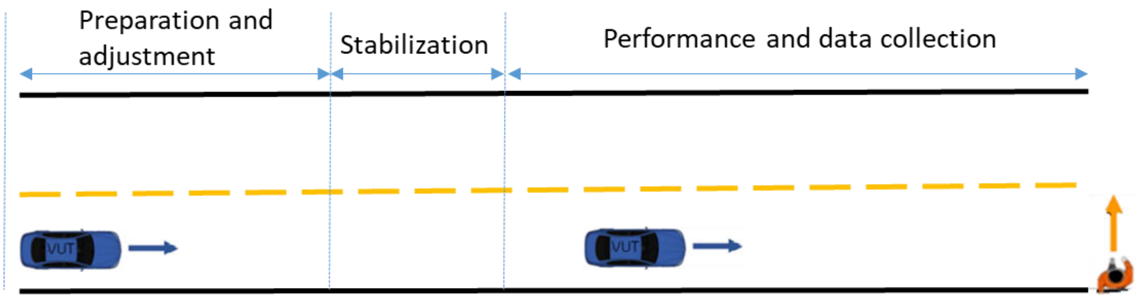


Figure 9: Test Case A – with zoning demarcation

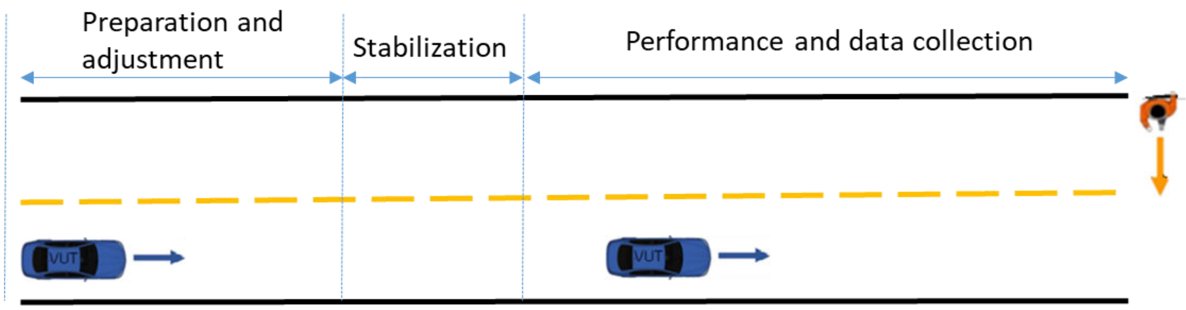


Figure 10: Test Case B – with zoning demarcation

Table 3: Test parameters with pass condition

Test No.	Test parameter			Pass conditions			
	Vehicle speed MPH	VRU style	VRU speed MPH	Min warning distance (m)	Min warning time TTC (s)	Max warning distance (m)	Max warning time TTC (s)
1	30	Adult	3	~30	~2.5	~60	4.0
2	40	Adult	3				

We assumed is that the provided TTC (2.5-4 seconds) includes driver reaction time; though we recommend considering 1.5-2 seconds as driver reaction time

All tests were documented with the following information:

- Number of false alarms/messages: Does not receive alerts when the direction of the pedestrian does not result in a collision course.
- Minimum and average time-to-collision (TTC): The alerts are received between the maximum warning distance and minimum warning distance.

Additional metadata were added:

- Weather condition
- Road condition and surrounding
- Placement of RSU/camera etc., camera FoV

<u>Test Scenario 2: VRU crosses the road while test vehicle driver's view is blocked by a large standing vehicle</u>

The same test procedure as in Test Scenario 1 while a large vehicle (truck) is parked on the side of the road blocking the view of the driver and may also cause poor line of sight between the vehicle-under-test (VUT) driver FoV and the VRU as shown in the illustration below.

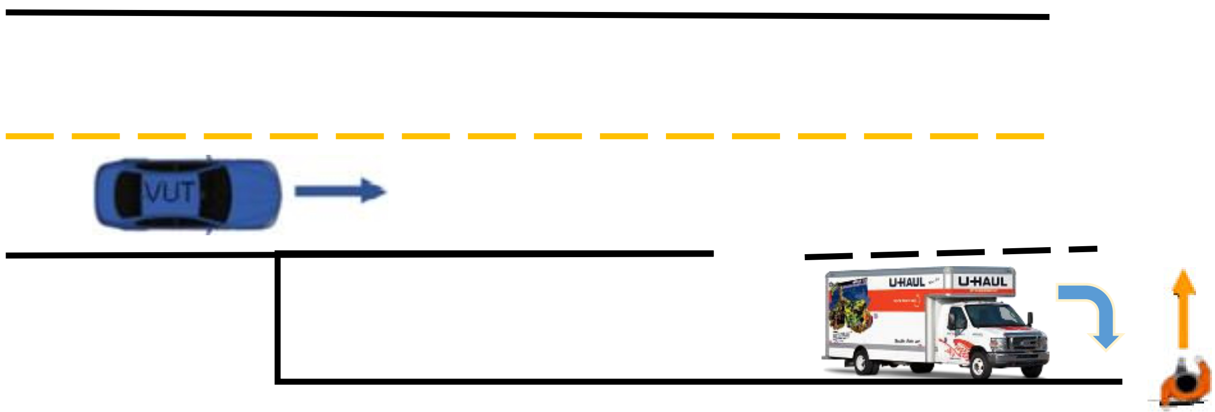


Figure 11: Test Scenario 2 with VRU obstructed from vehicle driver's view and travelling in the 'UP' direction

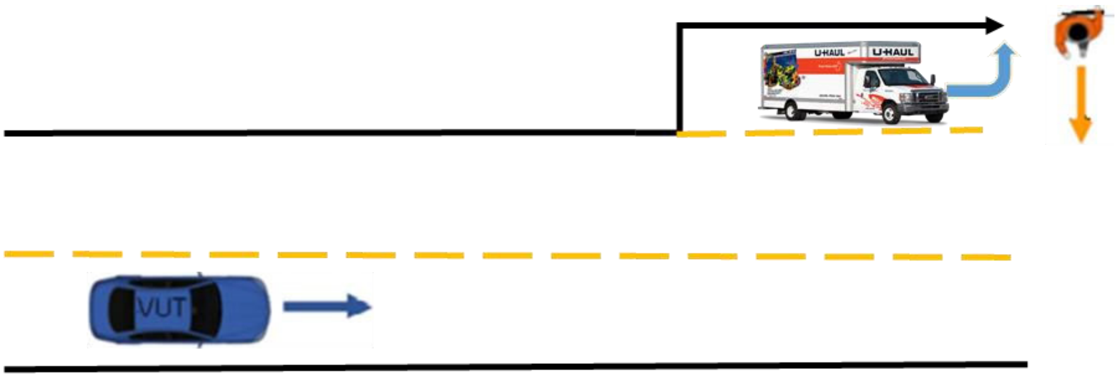


Figure 12: Test Scenario 2 with VRU obstructed from vehicle driver's view and travelling in the 'DOWN' direction

The methodology for conducting Test Scenario 2 for passive VRU was as follows:

a) The test vehicle moves at a constant speed towards an intersection/pedestrian crossing zone
b) There is a large truck standing at the intersection waiting to take a right/left turn
c) The large truck has blocked the view of the driver and is causing poor line of sight between the VUT driver and the VRU
d) The VRU crosses the road at the designated pedestrian crossing zone from either direction
    a. Care to be taken so the pedestrian is in the camera FoV
e) The roadside camera detects the VRU and communicates the information to the MEC

Table 4: Test parameters

Vehicle speed (MPH)	10-40
VRU category	Adult
VRU walking speed (MPH)	3

Message duty cycle (ms)	200, 500

Further testing area: Anthem smart intersection layout

More measurements are planned on the Anthem smart intersection layout, Intersection of W Daisy Mountain drive and N. Gavilan Peak parkway, Anthem, AZ, where smart RSUs have been installed.

Figure 7: Anthem smart intersection layout (Imagery @2023 Google, Imagery 02023 Maxar Technologies, U.S. Geological Survey, USDA/FPAC/GEO, Map data @2023)

2.3.4 Conclusions

Improving VRU safety using a roadside infrastructure with cameras, edge computing and C-V2X communications was demonstrated. The edge-computing module performs the AI analytics and computation required for the V2X software stack. The CPM (pre standard SAE SDSM) message was used to inform the road users about the presence of VRUs in the field of view. The duty cycle of the messages was 200 ms and it is found to be reasonable for the tested scenario considering the compute latency and real- time situational awareness. In the breakdown of the end-to-end latency, the AI compute latency consumed the significant part. The larger intersections with multiple cameras and other sensors may require additional hardware (scalability) to support the computation needed to meet the requirements (key performance indicators). Thus, providing sufficient computing capability (CPU and accelerators) is key for reducing the cost while meeting the performance requirements to protect VRUs. More measurement data from the AZ IAM (City of Anthem) testbed will be collected and shared in future work.

2.4 Group D: E-bike V2X demonstration – Bosch

2.4.1 Description

Cars and e-bikes were equipped with V2X technology, enabling bidirectional 'direct' communication between e-bikes and cars with the car sending CAMs and the e-bike sending VAMs. The message content was fed from sensor information from e-bike and car, respectively.

The project set out to validate the VAM for use between e-bikes and cars, including bicycle path prediction and aspects of precise position, via direct (or/and network) communication.

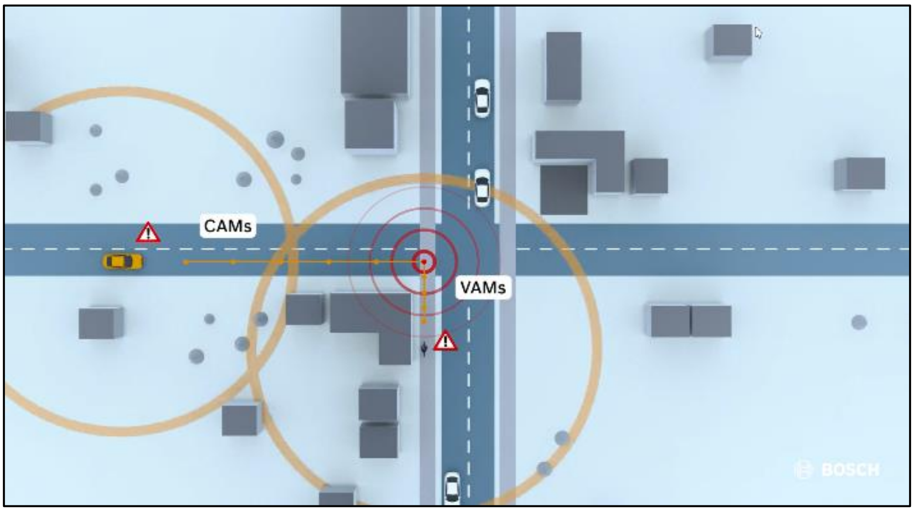


Figure 8: E-bike protection demonstration scenario

Based on the predicted path, the collision probability is calculated in both the car and the e-bike. The car driver is warned visually and acoustically, the e-bike rider visually, acoustically and by vibrating handlebars.

In the next figures, the setup is explained in more detail:

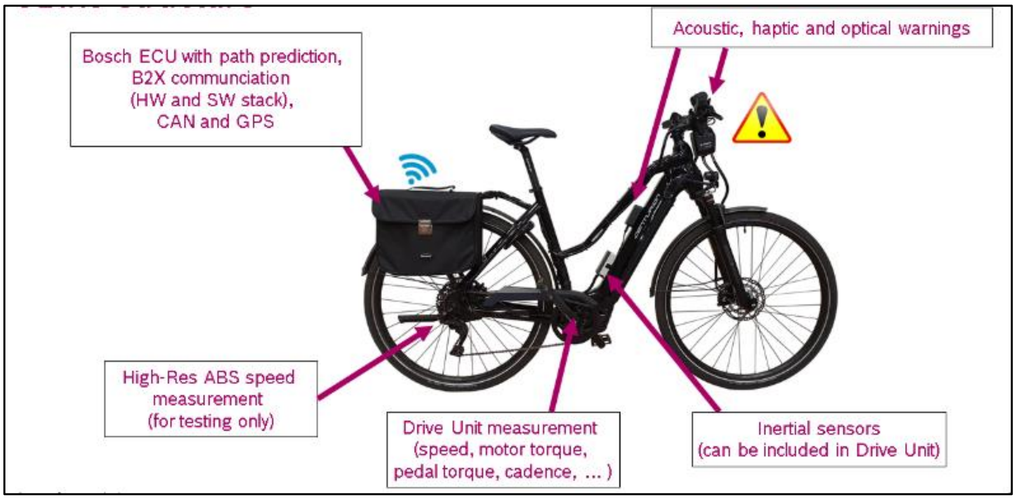


Figure 9: E-bike structure

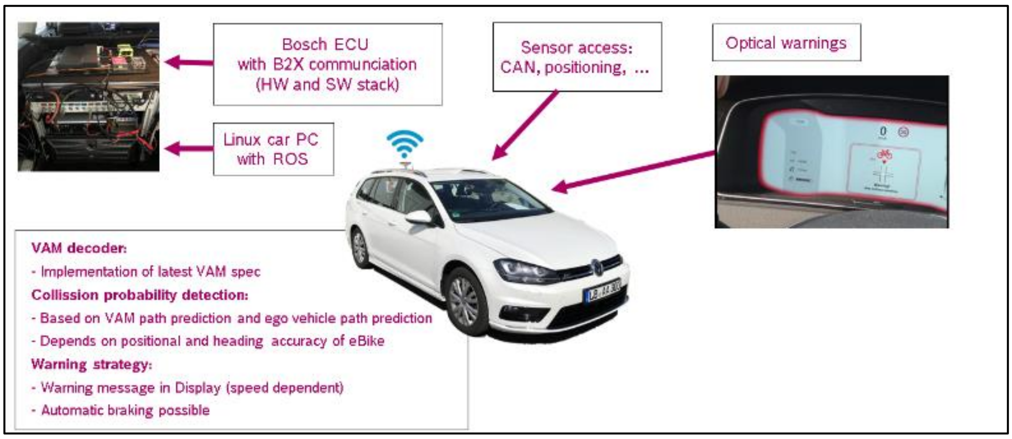


Figure 10: Vehicle setup

Focus 1: VAM validation

Special focus was put on the e-bike's path prediction. For now, the path prediction is based on inertial sensor data (6D) and a simple bike model, but more sensor data as well as more elaborate prediction models can be included.

The first step is to estimate the current state of the-e-bike (pitch and roll angle, heading and yaw rate in street coordinates, position and speed). Then, the future path can be calculated.

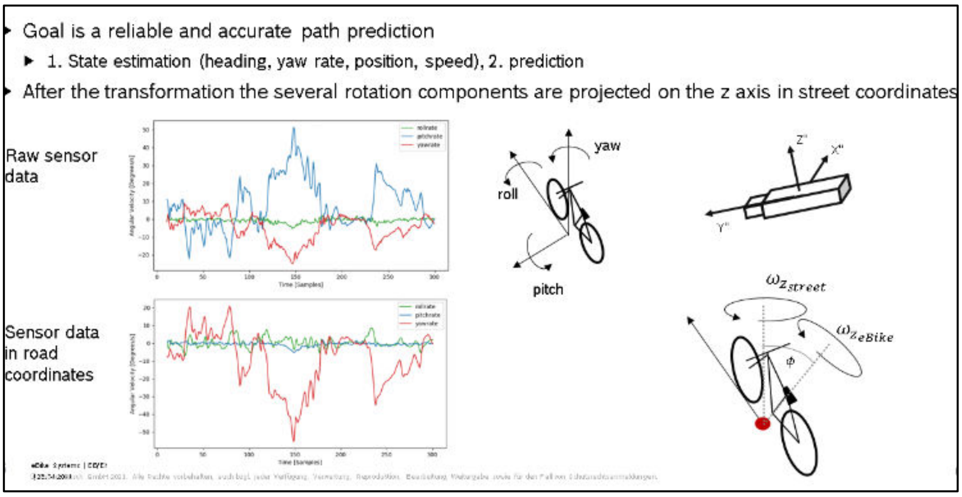


Figure 11: Recording of sensor data

Already with those simple models, the cyclist's path can be predicted pretty well for 1-2 seconds; of course, a longer time horizon is possible, but the prediction will be less accurate. Based on the preliminary results, we consider the path prediction an important means to reduce the number of false positive warnings or interventions.

When navigating a curve, quite a lot of time is spent 'going into the curve' and 'coming out of the curve', and only a small amount is focused on the trajectory, which has a constant radius. This can be seen in the following picture.

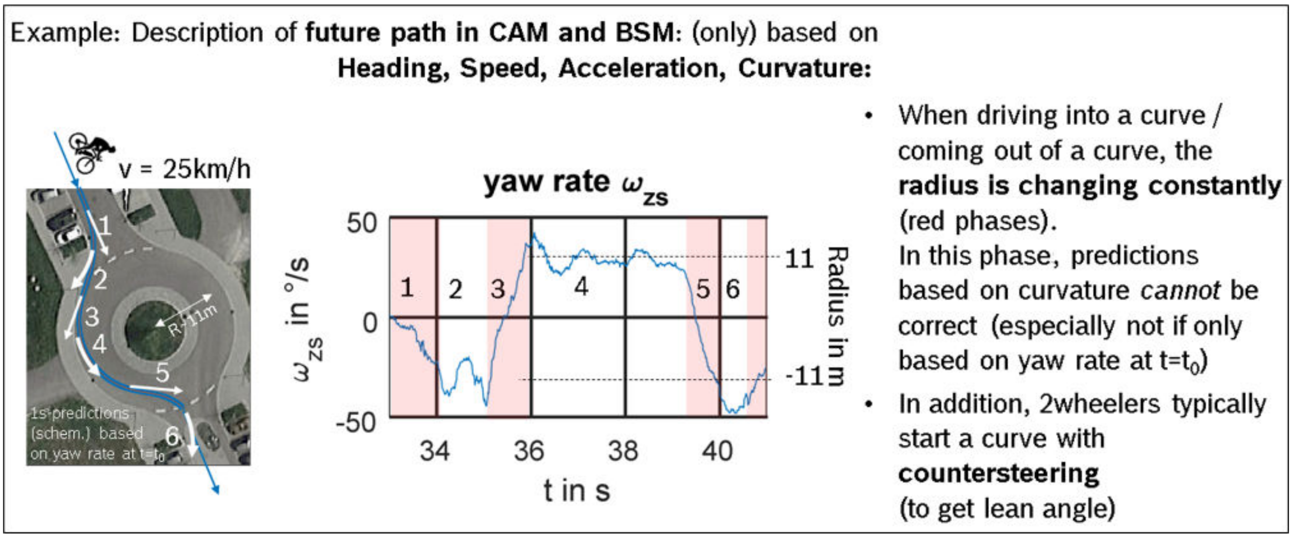


Figure 12: Example of path prediction based on heading, speed, acceleration and curvature

Only in this short period (white areas), the future path can correctly be predicted with a radius, whereas in the red shaded areas (especially when starting the curve), a constant radius cannot adequately describe the future path. Therefore, we consider the new path prediction mechanism in the VAM (based on individual future path points instead of a radius) to be important to describe the dynamics of a vehicle, especially of a two-wheeler where effects like counter-steering also come into play.

Using individual path points has an additional advantage: it can not only be used to describe a changing radius, but also changing acceleration. Thus, it can be used to describe scenarios like 'the cyclist will start braking in about x milliseconds', based on increased brake pressure (not yet resulting in deceleration) or other sensor information.

Focus 2: Guidelines for VRU warnings

Several studies were carried out to evaluate optimum warning concepts for cyclists. In one of the studies [e-bike1], haptic, audio and visual warnings were compared with n=52 individuals on a pre-defined track with environmental conditions affecting the different warning types, e.g. a rough road on which the haptic feedback was harder to recognise, or a section parallel to a highway where acoustic warnings were more difficult to perceive. Having perceived a warning, the individuals were requested to press a button. Then, the measured perception rate was evaluated.

As a result, it turned out that the acoustic and haptic warnings were best perceived in all environmental conditions, except that haptic warnings were less well perceived on rough surfaces like dirt roads – which is probably not that relevant for B2X warnings, since they are expected to be necessary rather in urban environments. After the ride, the individuals were asked to fill out a questionnaire [e-bike2]. Interestingly, when being asked how well the different signals were perceived, the answers revealed an even larger difference between the warning types. The participants chose the auditory and vibro-tactile signal clearly over the visual signal. When asked, they significantly preferred an auditory warning to the other two signal types. The participants rated the auditory signal as the most urgent and frequently associated it with warnings. Participants reported the visual signal as distracting from the cycling task and the vibro-tactile signals as difficult to distinguish from surface-related vibrations.

2.4.2 Background information

Accident statistics show that the fatalities trend for cyclists is not decreasing at the same rate as for all road fatalities. The major share of two-wheeler users killed in traffic accidents results from a collision with a motorised vehicle. B2X communication between all types of bikes and other vehicles has the potential to lower the Bike-to-Vehicle (B2V) accident rate thanks to greater awareness and/or collision warnings, smooth reactions (e.g. speed adaption), or adding B2V sensor to car's automated systems such as AEB for braking.

2.4.3 Research questions studied

- Research into pedestrian, two-wheeler and other vulnerable road user path prediction
- Evaluate the impact VRU localisation and path prediction accuracy has on false positive and false negative rates
- Define optimal warning and escalation strategies for different user groups and derive requirements for path prediction: accuracy and time horizon of the prediction

2.4.4 Studies available

[e-bike1] Erdei, E.-H., Steinmann, J., & Hagemeister, C. (2020). Comparing perception of signals in different modalities during the cycling task: a field study. *Transportation research part F: traffic psychology and behaviour, 73*, 259-270.doi:https://doi.org/10.1016/j.trf.2020.06.011

[e-bike2] Elke-Henriette Erdei, Jochen Steinmann & Carmen Hagemeister (2021) Which signal modalities do cyclists prefer based on experiences in road traffic?, Traffic Injury Prevention, 22:8, 640-645, DOI: 10.1080/15389588.2021.1985113

2.4.5 Conclusions

Based on accident research in Germany, it turned out that crossing and turning scenarios in urban environments are the most dangerous scenarios for cyclists. In those crossing scenarios, warning the car driver as well as warning the bike rider is considered helpful, because depending on relative speed, driver and/or rider reactions can help to prevent the accident. For those warnings, B2X methods are considered to play an important role.

A demonstrator car and e-bike were built in order to test the different scenarios and validate the VAM.

In order to avoid false positive warnings, an accurate path prediction including, as far as possible, the rider's intention is necessary, together with adequate positioning accuracy. Based on sensor data, a two-wheeler can provide important data on its predicted path as well as its status (like bicycle stability, light status, pedaling status, etc). The VAM path prediction using individual data points is well suited to describing a rider's future trajectory but should be based on relative positions (instead of absolute GNSS positions for each path point, as currently foreseen in the VAM) in order to save bandwidth.

With regard to rider alerts, acoustic and haptic warnings turned out to be most suitable in the majority of environments, whereas optical warnings alone cannot be used (especially close to a crossing, a rider should be encouraged to focus on the road and traffic conditions, not forced to look at a display).

There is a significant potential to reduce accidents via V2X, because our analysis revealed that there are sight obstructions at least 24% of the B2C accidents at the point of time when the accident could have been prevented by an action like braking.

The communication needs to be bidirectional, thus able to warn the car driver and the rider, and enabling him or her play a more active role in preventing the collision).

2.5 Group E: Demonstration of connecting VRU to ITS via Uu – LG

2.5.1 Description

LG is testing and showcasing various VRU protection services (e.g. VRU collision warning, school-zone/bus notification and real-time information sharing) in the Republic of Korea. In LGE showcase, the VRU protection services are enabled by 4G/5G mobile network communication, also incorporating direct communication and smart RSU technology. A software application is installed in the smart phones of VRUs and enables information exchange with the ITS application server via 4G/5G mobile network communication. The ITS application server connects various ITS players (vehicles, RSUs, VRUs) not only via mobile network communication but also using direct communication with translation via smart RSUs. A smart RSU also detects VRUs, with its AI-based smart camera and help from the ITS application server, and transmits messages for the VRU protection system.

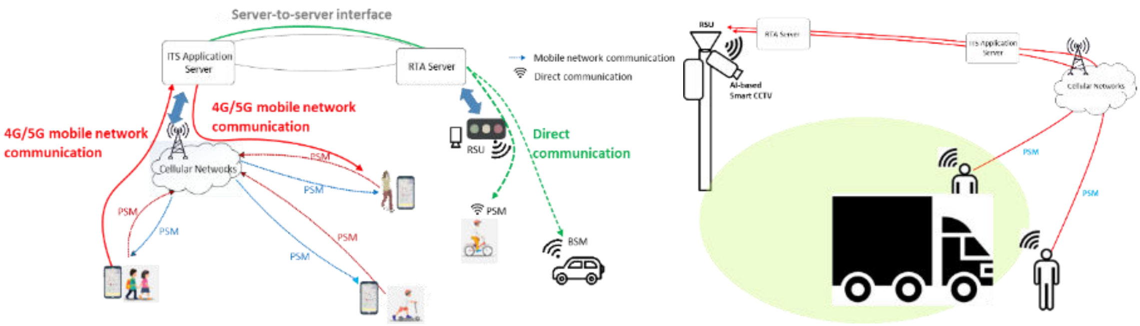
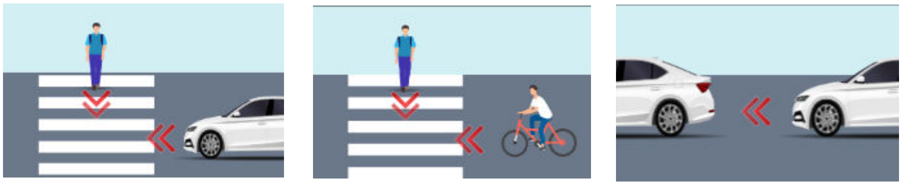


Figure 13: Scenarios for demonstrations

Specifically, LGE participated in Seoul Smart Mobility Expo (SSME) 2021 in June and showcased its VRU protection services based on Uu communication. In this showcase, various VRU protection use cases were demonstrated, such as collision warning, hazard warning, notification of school zone, and emergency vehicle.

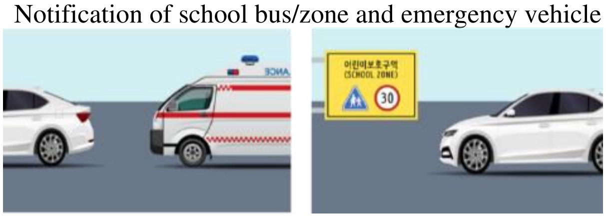
Target use cases

- Collision warning in various scenarios



- Hazard warning

- Notification of school bus/zone and emergency vehicle



- Real-time information sharing

Figure 14: Use cases tested in LGE showcase

To support the above use cases, VRUs who installed the VRU protection service app transmit PSMs to the server using Uu interface, and the server delivers information received from the surrounding VRUs to other nearby VRUs connected to the server. Also, based on UE detection/positioning, path prediction and high precision map/positioning technologies, collision risk is then assessed at the server or VRU device side (VRU protection service app installed on the devices) depending on the capability of the VRU devices and real-time workload of the server. Visual, audio, vibration warnings can be provided using the VRU devices, and the VRU can decide how to represent VRU warning messages using the app.

2.5.2 Research questions studied

Is LTE/NR Uu communication applicable for VRU protection services?

- E2E latency
- Verification of PSM (J2945/9, J2735) which was designed for short-range communication

How to integrate a Uu communication-based V2X system and legacy short-range V2X system?

How to use spectrum more efficiently in Uu-based V2X communication (e.g. message clustering/aggregation, message filtering on a server)?

2.5.3 Methodology

Aspect 1: Reduction of data traffic in Uu-based V2X communication (including UL/DL/server-to-server communication)

Collision assessment and message filtering on the server side

As can be seen in the figures below [REF 1], 5GAA WG2 discussed two types of collision assessment model. In Alt 1, collision assessment can be done in the cloud, while the assessment is performed on the VRU device based on the information received from the cloud in Alt 2.

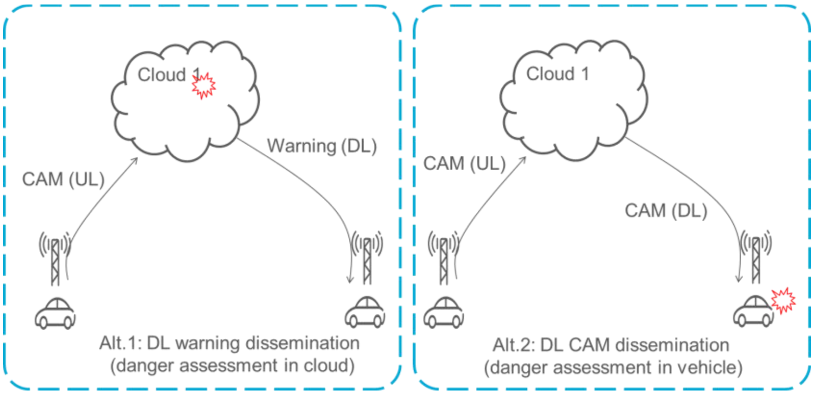


Figure 15: Two different types of collision assessment model [REF1]

For the initial demo/showcase, the Alt 2 model was implemented in the LGE demo platform and collision assessment could be performed on VRU devices.

As the next step, Group E is planning to implement risk-assessment and path-prediction algorithms in the server as well as the app installed on VRU devices. Also, a 'hybrid solution' of these two types of collision assessment models will be implemented in the platform, and signalling between the server and VRUs could be necessary to determine who will perform the risk assessment in this hybrid solution.

Again, with the hybrid solution the collision assessment can be performed on the VRU devices or at the server side, adapting according to the capability or status of the VRU devices (i.e. computing power and battery level). For instance, when the battery of a VRU device is fully charged and the device has enough data processing/computing power, the collision assessment is performed at the VRU device side. As another example, if the phone battery is low or the VRU device does not have the capability for data processing, the server can assess the collision risk of the VRU and send the warning message to the VRU device. Therefore, the burden of risk assessment for VRU devices can be offloaded to the server if needed, and the solution enables efficient support of VRU protection services for power-sensitive UEs and those with lower capabilities. Also, depending on the server's collision assessment, it can transmit warning messages only to VRUs (or vehicles) in a high accident risk group. This can be interpreted as a kind of 'message filtering' by the server, and thus this results in downlink (DL) traffic reduction in Uu-based V2X communication.

<u>Message clustering and aggregation</u>

To reduce the data traffic in Uu-based V2X communication, Group E is considering implementing the message aggregation/clustering feature in the demo platform. To support the message clustering/aggregation, the server decodes messages received from individual VRUs (within a given time window) and generates clustered/aggregated messages. And then those messages can be sent by the server to other VRUs/vehicles.

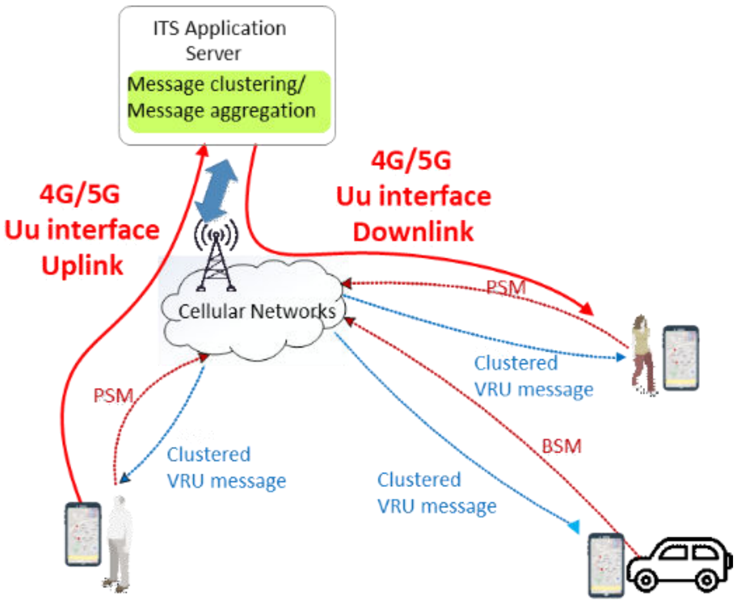


Figure 16: Concept of Transmission and reception of clustered/aggregated messages in Uu V2X

Before implementing this feature in the platform, it was important to investigate the feasibility of the message clustering/aggregation by calculating the traffic load reduction and weighing that against any delays incurred, which then gives a measure of the expected gain in using this method.

<u>Size of aggregated message</u>

Assumptions:

- VAM is considered in the message size calculation
- Messages received from VRUs in a given area (e.g. [2m]-by-[2m] square tile in the fixed position) are aggregated in a single message
- By limiting the size/position of the tile for the message aggregation, longitude/latitude information included in VAM for VRUs in that tile is expressed with VRU common information and VRU specific information (e.g. the size of the latitude field is 31bits. When we consider the message aggregation for VRUs located in 10m-by-10m square tile, 21bits out of 31bits can be common information for all VRUs located in that tile, and the rest of the 10bits can be UE-specific information. Therefore, in the aggregated message generated by the server, the latitude information of N VRUs can be expressed with
  *(21 (for UE common data) + N*10 (for UE specific data))) bits.)*

Table 5: Comparison of message size with and without message aggregation method

[Note 1] Size of individual VAM = 250bits; only mandatory fields are considered in this calculation.
[Note 2] Depending on the tile size, the size of 'UE common information' regarding latitude/longitude data fields is different.
Size of the UE common information:
10m-by-10m tile: 42bits (21bits for latitude, 21bits for longitude)
5m-by-5m tile: 44bits (22bits for latitude, 22bits for longitude)

2m-by-2m tile: 47bits (23bits for latitude, 24bits for longitude)				
Tile size	# of messages aggregated in a single message (N)	w/ aggregation (A)	w/o aggregation (B = N * 250 bits)	Reduction in message size ((A-B)/B * 100 [%])
10mx10m	2	458	500	-9.2
	3	666	750	-12.6
	4	874	1000	-14.4
	5	1082	1250	-15.5
	6	1290	1500	-16.3
	7	1498	1750	-16.8
	8	1706	2000	-17.2
	9	1914	2250	-17.6
	10	2122	2500	-17.8
5mx5m	2	456	500	-9.6
	3	662	750	-13.3
	4	868	1000	-15.2
	5	1074	1250	-16.4
	6	1280	1500	-17.2
	7	1486	1750	-17.8
	8	1692	2000	-18.2
	9	1898	2250	-18.5
	10	2104	2500	-18.8
2mx2m	2	453	500	-10.4
	3	656	750	-14.3
	4	859	1000	-16.4
	5	1062	1250	-17.7
	6	1265	1500	-18.6
	7	1468	1750	-19.2
	8	1671	2000	-19.7
	9	1874	2250	-20.1
	10	2077	2500	-20.4

Conclusion

With the above assumptions, when 10 messages are aggregated in a single message, the traffic load can be reduced by 18%~20%.

Analysis on delay due to the clustering/aggregation

As explained above, for the clustering/aggregation, the server decodes messages received from individual VRUs within a given time window and generates clustered/aggregated message using the information collected during that window. So, delay due to the gathering of individual VRU messages as well as data processing may occur in the server, and are considered 'additional' delays caused by message clustering and aggregation operation. Here, to reduce latency due to the gathering of individual VAMs at the server side, Tx timing of the individual VAMs can be adjusted. Additionally, the message timing alignment method can be applicable for reducing the delay in collision assessment, as presented in the table below.

Table 6: Latency due to the message aggregation

Scenario	Message latency	Increase of the latency (%)
Scenario A (Reference): Server send message to all VRU w/o message aggregation	54.1 msec	-
Scenario B: Aggregation w/o message timing alignment	93.3 msec	Compared to scenario A: +72.5% Compared to scenario C: +64.0%

Scenario C: Aggregation w/ message timing alignment	56.9 msec	Compared to scenario A: +5.2% Compared to scenario B: -64.0%

When we compare the latency of scenario A and C, we can observe the additional processing delay caused by message aggregation is negligible (2.8msec, +5.2%).

When we compare the latency of scenario B and C, the delay due to the message aggregation can be much reduced by aligning the timing of individual messages.

Additionally, in our showcase in SSME 2021, we demonstrated various VRU protection use cases (e.g., school zone warning, collision warning) and measured the message related and non-message related (e.g., delay in application and HMI) latency in those use cases. In the measurement, the average message and non-message related latency were 43.59 msec and 53.35msec, respectively. We can see the message related latency measured in this showcase is almost identical to the latency of scenario A in the above table. Also, as the non-message related latency measured in the showcase is 53.35 msec, when we consider the message aggregation/clustering with message timing alignment (scenario C in the above table), it is expected the total (service-level) latency could be 100msec, which could be an acceptable level for the support of basic safety services. To further reduce the latency, however, the optimisation of the demo platform and development of technical solutions are ongoing.

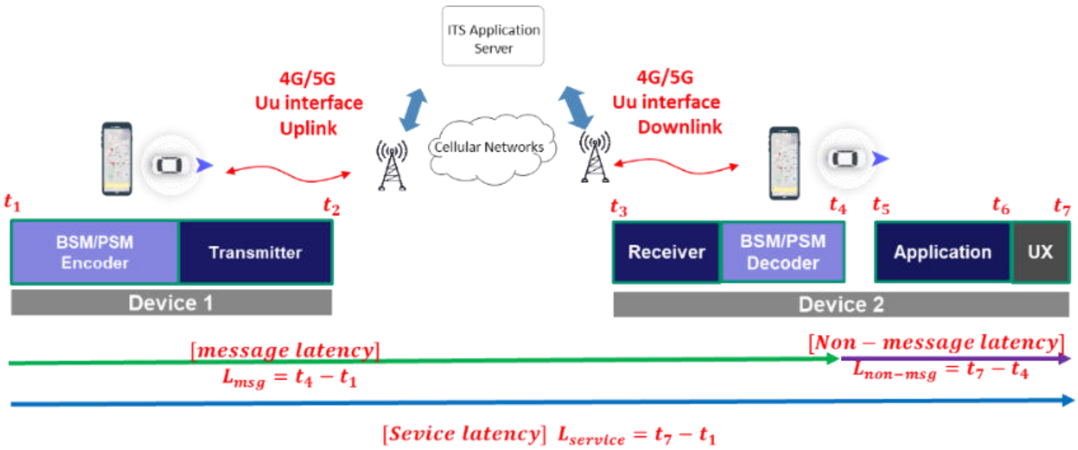


Figure 17: Latency measurement in connecting VRU to ITS via Uu (LG)

Table 7: E2E latency measurement in Uu V2X

Service latency	Message-related latency	Non-message-related latency
96.94 msec	43.59 msec	53.35 msec

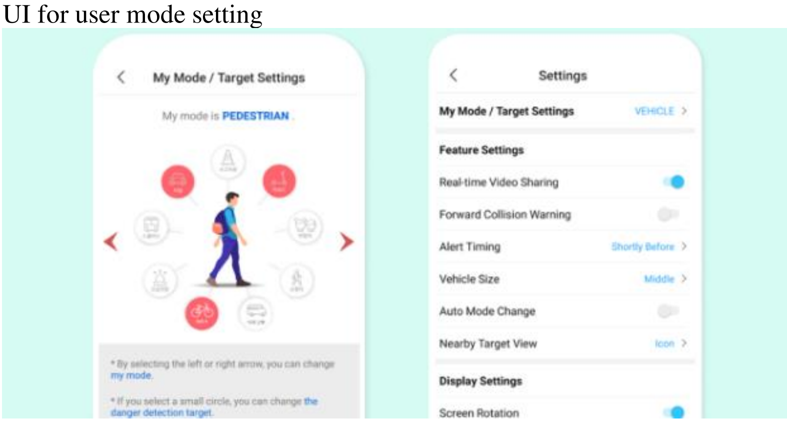
Adjustment of periodicity of PSM transmission

Frequency of VRU messages can be adjusted depending on the level of risk in geographical areas (e.g. transmit VRU messages more frequently in a school zone), and the VRU can stop transmitting the messages in zero-risk areas (e.g. inside a building or public transport).

Aspect 2: User mode management (including VRU profile management)

Using LGE's VRU protection service app, users can select/change user mode (e.g. pedestrian, e-scooter, cyclist, emergency vehicle, children), types of warning messages the users want to receive, and notification method of the warning message (e.g. audio, vibration warning) 'manually' to suit their preference.

- UI for user mode setting



- E.g. user modes supported in the app

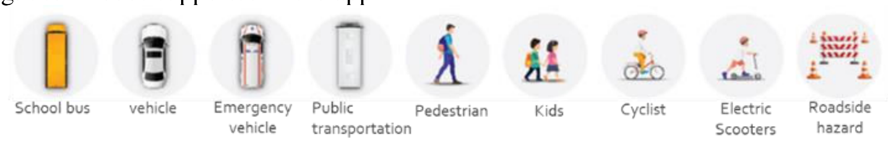


Figure 21: User mode (VRU profile) management in LGE's VRU protection map

Alternatively, the user mode can be selected/switched automatically via an 'AI-based automatic user mode selection scheme' performed on the VRU device side. The user mode can be detected by the VRU protection app thanks to sensor data collected by the VRU device and learning algorithms.

Based on the above schemes enabling accurate detection of user mode, VRUs can efficiently determine the type of messages they should transmit to the server (or other VRUs) and adjust message transmission frequency according to the user mode. In addition, the user mode information obtained by these methods can be used for risk assessment and message filtering at the server end (e.g. if pedestrian-to-pedestrian message exchange is not necessary, the message can be filtered out by the server using the user mode information acquired by these schemes).

Aspect 3: Integration with legacy ITS system

Combination/fusion of information obtained by sensors and V2X messages

AI-based smart cameras and sensors deployed through RSUs are used for VRU detection and positioning in current smart RSU implementations. However, if we use V2X messages received by the smart RSU for the detection/positioning, in addition to the object information obtained by the cameras/sensors, the detection/positioning performance of the RSU can be further improved because information obtained from the V2X messages and sensor/camera data can complement each other. For example, when the RSU detection/positioning performance is degraded due to the environment or time varying situations (e.g. occlusion, blurring, low light, bad weather such as rain or fog), VRU information included in V2X messages can be helpful for the RSU because the information can be related to the VRU detection and positioning adjustment. Also, the RSU can acquire additional (and/or more accurate) information about VRUs by receiving messages from them, and the accuracy of VRU detection/positioning via the RSU could be increased with that information. To enhance VRU detection/positioning performance through the fusion of data obtained from sensors/cameras and V2X messages, a matching process between VRUs who transmitted the V2X messages and the detected objects should be carried out by the smart RSU – before the data fusion – based on the similarity in position and trajectory of the VRUs and detected objects. And, if accurate the matching algorithm is supported by the RSU, it can further adjust the positioning of the VRU (or detected object) using his or her own information (e.g. VRU profile, location/speed/direction obtained from appropriate V2X messages).

The figure below shows the VRU positioning performance through the RSU when the fusion of position data obtained from cameras and V2X messages is used. In this figure, we compared the root-mean-square (RMS) position error of the following two positioning schemes according to VRU occlusion duration:

- (Conventional) V2X message-based VRU positioning (GPS + IMU)
- (Proposed) V2X message- and camera-based VRU positioning (GPS + IMU + Camera)

Note: In scheme B, positioning offset information obtained from the camera and V2X message just before the occlusion (e.g. difference between the position obtained from V2X messages and cameras) is used to compensate the VRU positioning error.

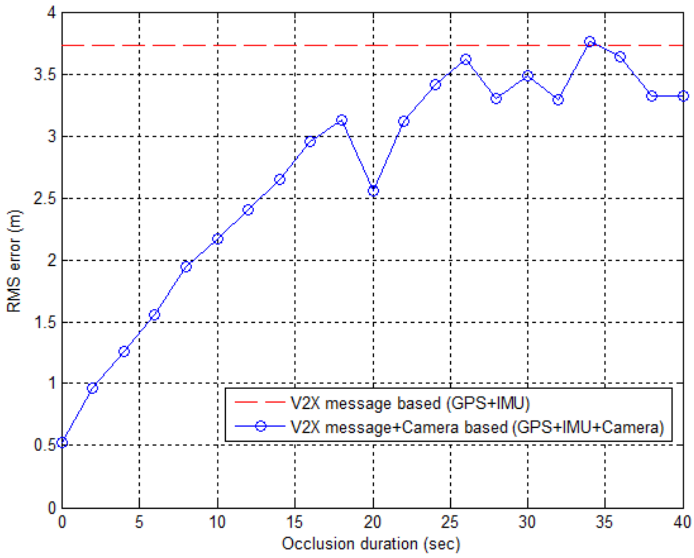


Figure 22: Comparison of positioning error

As can be seen in the above figure, the positioning error compensation using position data obtained from cameras and V2X messages can increase the accuracy of VRU positioning/detection (if the occlusion duration does not exceed 25 seconds). Also, even if a pedestrian is blocked from camera view by a big truck for about 8 seconds, the pedestrian can be tracked quite well in scheme B within up to 2 metres of RMS position error.

Integration between Uu communication-based V2X system and legacy short-range, communication-based V2X system

In the current ETSI ITS specification, such as the VAM specification, a VRU device that does not have short- range communication capability is called a ‘non-equipped VRU’. However, in the integrated ITS system proposed here, even the so-called ‘non-equipped VRUs’ can be efficiently protected based on information exchange between Uu V2X devices and short-range, communication-based V2X devices, thus further reducing VRU accidents. Additionally, compared to when VRU messages are distributed to multiple, nearby VRUs using Uu communication only, DL traffic load can be reduced by broadcasting VRU messages using short-range communication in this integrated system, especially when Multimedia Broadcast Multicast Services (MBMS) are not available.

To implement the integrated ITS system, the application server can connect various ITS players (vehicles, RSUs, VRUs) not only via mobile network communication but also using direct communication. Also, for instance, information exchange and translation between legacy C-ITS devices and Uu-based ITS devices can be performed by smart RSUs. Further study on who and how to translate information/messages exchanged between these two different systems/devices is needed.

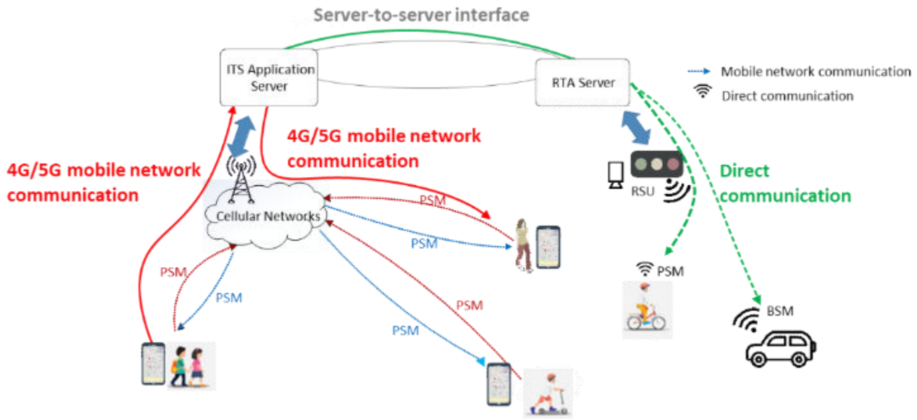


Figure 23: Integration of Uu V2X system and legacy short range communication based V2X system

2.5.4 Data collected and studies available

[REF 1] A-170134, ‘Discussion on CAM message transmission procedures for cellular transport’, Ericsson

2.5.5 Conclusions

LG showcased various VRU protection services based on LTE/NR Uu communication in the Republic of Korea. The demo was completed successfully and the following observations were made.

E2E latency:

The E2E latency measured by the demo was about 96msec, which was an acceptable level in this real-time demo for basic safety services. However, to further reduce latency, optimisation of the demo platform and development of technical solutions are ongoing.

Validation of PSM/BSM:

PSM and BSM were used for this Uu communication-based VRU protection services demo, and it was observed that those messages worked well in a Uu-based V2X system.

Entities for data processing/analysis in Uu-based VRU protection services

Different deployment scenarios can be considered depending on the amount of data processing/analysis performed by the MEC/cloud, i.e.

- Centralised approach: Data processing and analysis are performed by the cloud
- Decentralised approach: Data processing and analysis are performed on the device-side (i.e. VRUs and vehicles)
- Combination of above scenarios (e.g. selective/hybrid operation between those two scenarios)

The demo was mainly focused on the second scenario, and thus a VRU device with collision assessment capability can calculate its collision risk based on information obtained from MEC/cloud, sensors/cameras, etc. The platform/devices used in the demonstration worked well in this scenario. Tests for the first and third scenarios are ongoing in 2022.

Traffic efficiency in Uu-based VRU protection services

As explained above, in this demo it was assumed that the data processing and analysis could be performed by VRU devices. Therefore, it would be beneficial to transmit enough (or all relevant) information from the MEC/cloud to VRU devices to enhance the accuracy of the analysis (e.g. awareness of environments, assessment of collision/risk). However, such operations result in increased DL traffic in Uu-based VRU protection services, and thus solutions to reduce DL message size (e.g. message aggregation/clustering) would be necessary.

In this demo, message size reduction through VAM aggregation was tested. It was observed that DL traffic load can be reduced by 18~20% when 10 VAMs are integrated into a single message, compared to the case when 10 individual VAMs are transmitted (without message aggregation) from the cloud to VRUs using DL.

VRU detection/positioning based on fusion of information obtained from sensors/cameras and ITS messages

In this demo, V2X messages received by the smart RSU were used for VRU detection/positioning in addition to the object information obtained by the cameras/sensors. We observed that the detection/positioning performance of the RSU can be further improved through this data fusion, especially when the detection performance using sensors/cameras is degraded due to the environment or time-varying situations (e.g. occlusion, blurring, low light, bad weather).

LGE is planning to test more VRU-related services considering the following scenarios/technologies:

1. Integration of Uu-based V2X system with legacy short-range, communication-based V2X system
2. Support of other data processing/analytics deployment models
   a. Centralised approach: Data processing and analysis are performed by the MEC/cloud
   b. Combination of centralised and decentralised approaches
3. Positioning enhancement using sound wave signalling

2.6 Group F: Low-latency 5G C-V2X pedestrian detection and alert (HERE/Vodafone)

2.6.1 Description

This was a proof-of-concept focused on a low-latency 5G C-V2X use case for pedestrian detection and alerts. It is meant to test the integration of location technology, 5G network and distributed MEC cloud computing.

In this PoC, a vehicle with a forward-facing camera and local image detection capability (i.e. a smartphone with real-time video image processing app) detects a potential VRU in front of the vehicle. The image is transmitted to HERE's machine-learning models hosted by Vodafone's MEC site using a 5G connection. The edge-based intelligence verifies the presence of the VRU and attributes a precise position to the VRU. This information is transmitted to a trajectory modelling module, also on the MEC, to estimate whether a collision path is likely.

Potential collision alerts are then transmitted to other vehicles/UEs in the vicinity, particularly those whose 'vision' may be occluded by the image-originating vehicles (which may be a large van or heavy vehicle). HERE's 'relevancy filter' (tool) identifies specific vehicles/UEs with collision potential, to ensure that warnings are not sent to vehicles that do not need to receive them.

In addition to demonstrating the VRU detection and warning capability, this PoC aims to highlight further factors which can contribute to the protection of vulnerable road users in the context of V2X capabilities and services.

Firstly, the targeted alerting of adjacent vehicles (and drivers) of potential collisions, particularly when those vehicles and their drivers are not in a position to 'see' the VRU that has been detected by the device/system in a vehicle that is within sight of the VRU is shown.

Secondly, another important aspect is the use of the mobile network, specifically 5G aspects such as edge cloud computing to host service capabilities locally and thereby reduce latency between detection and alert (in this case), and to leverage the coverage of mobile networks to enable such a solution to operate wherever acceptable (good 4G, 5G) quality is provided.

2.6.2 Research questions addressed

Latency

- Can latency for road hazard warning alert distribution be significantly reduced by leveraging 5G communication in combination with edge computing?
- Is a GPU-accelerated ML model on the MEC a feasible architectural design for this type of C-V2X safety solution, assuming it will increase latency?
- What is the roundtrip latency for this system? Do we expect this to be sufficient?

Usability

- What throughput rate is sufficient?
- How far ahead in time should the alert be in order to prevent a collision?
- Can road hazard warning alerts be efficiently transmitted to relevant IoT devices in the near vicinity of an event by leveraging Message Queuing Telemetry Transport (MQTT) message-brokering deployed on the MEC?

2.6.3 Methodology

1. Cellular communication

In a first run in the Aldenhoven Testing Centre, a Vodafone 5G Non-Standalone test network was used to transfer data from HERE Live Sense to the Vodafone Multi-access Edge Computing site.

In a second run in the Porsche Weissach R&D Centre the public Vodafone 5G Standalone network was used to transfer data from HERE Live Sense to the Vodafone MEC site.

The difference between these is that in 5G Non-Standalone architecture, 4G and 5G network elements are combined to build the mobile network. An example for a 5G Non-Standalone architecture could be a radio network comprised of 5G gNBs and 4G eNBs connected to a 4G EPC (core network). In 5G Standalone architecture the radio network and core network are 5G.

A Hive MQ MQTT message broker, a server that receives messages from clients and then routes the messages to the appropriate destination clients, was deployed on the Vodafone site, to leverage efficient alert message distribution among involved vehicles.

2. Visual detection

A front-facing camera in a vehicle using HERE Live Sense vision detection registers objects of interest. Live Sense is a HERE product that turns devices with a front-facing camera into an intelligent vehicle sensor. In this PoC, Live Sense continuously scans the driver's environment in search of pedestrians. When a pedestrian is detected it triggers data transfer to MEC with information about his or her movement and position.

3. Analyse, position, estimate

HERE's lane-level map and HD GNSS – a cloud-based solution that enables mass market devices to achieve sub-meter accuracy – are used to estimate the position and trajectory of a pedestrian and nearby vehicles to see if a 'conflict path' exists. If so, the system creates an alert.

4. Relevancy filter and alert

This module filters the relevance of alert based on the vehicles' direction of travel and position, or road segment, to alert only relevant vehicles. A message is sent by a CV2X broker via Vodafone 5G network to relevant vehicles and an alert is displayed on a mobile app.

2.6.4 Architecture

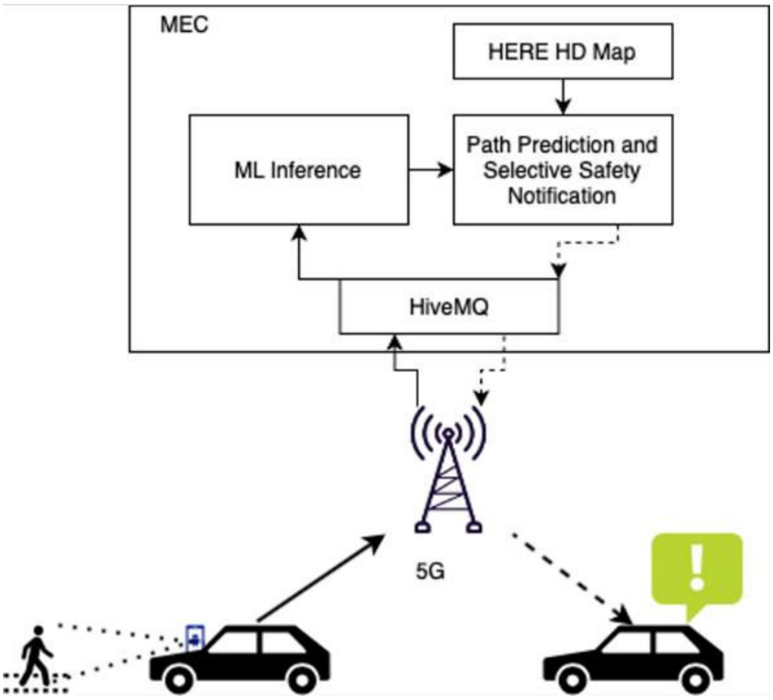


Figure 184: Architecture of the PoC for low-latency 5G C-V2X pedestrian detection and alert

2.6.5 Conclusions

Through this PoC, several criteria were successfully tested with the focus on warning a driver/car in relevant hazardous situations. The driver was warned via smartphone when a pedestrian was walking in front of the van/behind the bus towards the middle of a road (at a crosswalk). This helped the driver – while overtaking – to stop in advance even though the line of sight was blocked by larger vehicles. The PoC addressed the research questions in the following ways:

Latency

- Can latency for road hazard warning alert distribution be significantly reduced by leveraging 5G communication in combination with edge computing?
  Yes, 4G connectivity was 300ms more than 5G MEC configuration in the test site setup. With 5G MEC optimised design, the difference between the two types of connectivity can be as large as 750ms.

- Is a GPU-accelerated ML model on the MEC a feasible architectural design for this type of C-V2X safety solution, assuming it will increase latency?
  No, in this PoC design GPU-accelerated ML models in the critical loop added 200-500ms of latency, which is

too high for a real-time V2X use case. For use cases that demand low latency, having ML models on the device seems to be a more appropriate solution/design. Additionally, AI on the MEC does not scale to multiple users well. As the number of users increases, GPUs on the MEC would also need to increase proportionately.

- What is the roundtrip latency for this system? Do we expect this to be sufficient? In this case >500ms was observed; while the roundtrip latency was too high in this PoC on the test tracks, optimising the setup design can decrease latency to as little as 50ms, which is sufficient for real-world use cases.

Usability

- What throughput rate is sufficient?
  Around 5 messages per second was tested by Group F and deemed to be sufficient for real-time use cases. However, there could be uplink congestion if there are multiple users sending observations to the same radio. Further stress testing is required to understand this. Further testing can also be done to understand whether 1 message per second is sufficient, however more intelligence for the device and network application could be needed to make up for less user input.

- How far ahead in time should the alert be for it to be relevant in preventing a collision?
  Group F tested 5 seconds and deemed it to be sufficient for this use case.

- Can road hazard warning alerts be efficiently transmitted to relevant IoT devices in the near vicinity of an event by leveraging MQTT message-brokering deployed on the MEC?
  MQTT message-brokering was helpful in user privacy and multi-casting situations. Group F expects to leverage the MQTT message broker in future V2X concepts.

a) **Areas of improvement**

All tests were run with an application on a smartphone. The initially planned deployment to car-grade hardware could not be realised due to time constraints, which presents an opportunity for improvement in follow-up tests.

Also, given that the state of the application was PoC-grade and not production-grade, few areas of improvement have been identified. These were mainly related to the latency and stability.

- End-to-end round-trip performance in the PoC was a few hundred milliseconds, which Group F deems to be too high. However, it can be as low as 50ms with architectural design improvements, such as making the MEC pedestrian processing (ML inference on MEC) step independent of the critical loop
- 5G and the location of the MEC are critically important for performance; optimisation of the network could further reduce round-trip latency; with a partial 5G roll-out and limited numbers of data centres/cells (away from Weissach), the test saw a higher network latency (which will be lower once roll-out is completed)
  - <15ms network latency in Aldenhoven (5G NSA)
  - 25-30ms in live network (5G SA & NSA)
  - 5G: 5G-SA for lower latencies, when rolled out over Germany/Europe with distributed Core DCs

- Application improvement: Usage of native container services, using Nvidia low-latency codecs, use of Vodafone STEP (Safer Transport for Europe Platform), cloud-based platform built on open, industry standards that enables an ecosystem of participants to work together
  AWS WL improvements: Low-latency AWS WL internal communication across AWS accounts, more GPU models to choose from, IoT-SIM connectivity (GDSP), MEC data contracts/MEC Vodafone Pass for Enterprise, Roll-out of WL in EU

b) Future testing possibilities

Possibilities for further testing could include: 1) when in motion, cell handover will increase latency (it would be interesting to test that scenario and gather some latency measurements); 2) when visibility is low (poor lighting, rain/snow), camera detection of hazards would be affected (further testing would indicate the boundaries of the computer vision capability); 3) pedestrian trajectory modelling can be enhanced by testing variations in pedestrian movement (acceleration, sudden stop, etc); 4) test the ecosystem integration and scalability of the VRU concept with multiple MNOs and OEMs integrated.

2.7 Other VRU activities

2.7.1 5GAA's MEC4AUTO demonstrations

In the framework of the 5GAA WI MEC4AUTO there were two additional demos with two sets of partners that demonstrated two identical pedestrian protection use cases in each location. The use cases covered are active and passive pedestrian protection, i.e. the pedestrian carries handheld equipment such that both vehicle and pedestrian receive alerts, and in the second case the pedestrian does not carry equipment and only the vehicle receives alerts based on the data obtained by processing video signals from the cameras installed in the roadside infrastructure. In both demos, a 5G cellular network is used in addition to MEC infrastructure. The focus is on a multi-MNO roaming scenario where vehicle and/or pedestrian might be using a SIM card from a different MNO than the one offering the local radio access network (RAN) connectivity. In this case, the same pedestrian protection service should be enabled in both home and visiting network. Moreover, the same applications are employed in both demos, which use a very different setup as well as set of partners, meeting the requirements for global availability of the pedestrian protection service.

Regarding V2X awareness messages, the vehicles transmit BSMs and the pedestrian PSMs to the application running on the MEC via Uu interface. The roadside infrastructure transmits – also via Uu to the MEC – metadata about pedestrians detected by smart cameras or video-streaming. The MEC application, the so-called 'virtual RSU', analyses the data collected and in case of collision danger, it issues an RSA (RoadSide Alert) message to the vehicle and pedestrian concerned.

Other details about the two demonstrations can be found in the two following press releases:

https://5gaa.org/news/live-trial-of-5g-connected-car-concept-launches-in-blacksburg-virginia-va/

https://5gaa.org/news/live-trial-of-5g-connected-car-concept-to-launch-in-turin-italy/

It is worth mentioning that the US demo was repeated in Atlanta, GA during the 5GAA event at the beginning of May 2022 with an identical setup as in Blacksburg, VA.

5G Barcelona Anti-Collision

The 5G Anti Collision pilot project demonstrated in 2020 a warning system with different advanced communication and localisation technologies both to monitor two vehicles – in this case a forklift truck and a bicycle – on a collision course with each other, and also to issue a warning signal to prevent the crash. The use case addressed a specific safety issue regularly occurring in busy commercial and industrial zones like Mercabarna in Barcelona. The project used a live 5G mobile network operated Orange.

Both the forklift truck and bicycle were equipped with an OBU device connected to the 5G network allowing the constant issue and receipt of messages. They were also equipped with another device (hardware, HW) necessary for geolocating vehicles accurately, by merging positioning data provided via satellite, autonomous inertial navigation systems that measure the vehicle's acceleration and rotation, and distance measurements based on radio technology (which provides additional accuracy and reliability in challenging and complex environments).

When the system detects a hazard based on the cyclist's course, a signal is emitted in order to activate a warning (horn sound) and notify one of the two vehicles of the potential risk of collision.

A video of the demonstration is posted here: https://youtu.be/1TXqUDyWkZ4

5G technology offers the project extremely low latency guarantees (a very short delay between the issue and receipt of information), universal network availability (broad indoor and outdoor coverage) and scalability (increased capacity) with a view to providing service to a lot of devices at the same time. The pilot trial has also shown that it is feasible to integrate hybrid positioning solutions that increase the accuracy and robustness of GNSS in 5G services when used in combination with communication and UWB positioning systems, inertial navigation systems (INS), and communication between vehicles and infrastructure.

2.7.2 Qualcomm, Spoke and Commsignia

Qualcomm, Spoke and Commsignia have sought new ways to address the growing challenges that new forms of mobility and vehicles pose. Spoke Safety has announced plans to bring connected technology through a portable OBU to VRUs, including cyclists and scooter riders, using C-V2X solutions from Qualcomm Technologies. Additionally, Commsignia and Audi have joined a collaboration to explore technical solutions for C-V2X with connected car-to-bicycle technologies, to help reduce roadway accidents and fatalities involving motor vehicles and bicycles. For instance, a smart intersection enabled by a protective V2X system can detect and localise VRUs accurately via smart sensors. However, due to their unpredictable and dynamic behaviour, VRU-specific safety applications are needed to account for the different road interactions. Consequently, V2V and V2VRU collision detection algorithms differ.

The combined assessment efforts include studying the feasibility of SAE 2735 use cases such as:

- Intersection Movement Assist in the vehicle as well as on the bike
- Front Collision Warning in the vehicle when a bike is ahead of the car
- Left Turn Assist in the vehicle
- Right Turn Assist in the vehicle

In additional bike specific use cases not covered by the standard will be considered such as:

- Car approaching warning on bike with car behind
- Bike approaching warning in parked vehicle when a bike is approaching in the adjacent lane

Furthermore, the following figure highlights general challenges faced by VRUs.

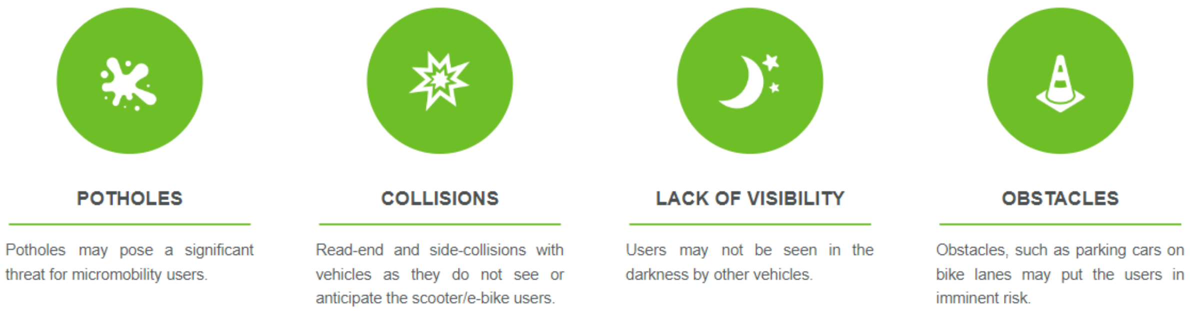


Figure 19: Challenges identified by the Qualcomm/Spoke project

While sensor equipped RSUs could increase intersection safety, their performance depends on the detection method used. As a preliminary step, a study by Commsignia has been done comparing the various sensor types deployed at intersections with respect to the ability to protect VRUs. Six important aspects were analysed, the following table highlights the aggregated results.

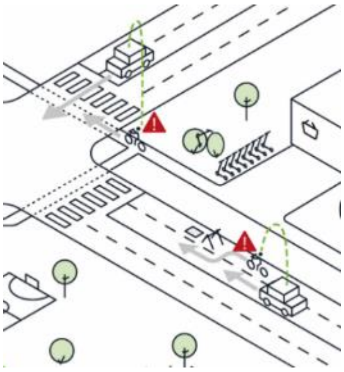
Table 2: comparison between different sensor types

Sensor type	Camera	Radar	Lidar
Mechanism	Optics and light	Radio waves	Laser and light
Detection space	Pixels	Radial motion	Point cloud
Range	25-50m	150-250m	150-250m
Localisation accuracy	50-100cm	25-50cm	3-5cm
Latency	50-150ms	75-125ms	75-125ms
Primary limitation	Requires light source	Side-moving objects are hard to detect	Inability to measure distance in harsh weather conditions
Deployment cost	Low	Medium	High

The study showed that sensor selection can be location and problem specific (e.g. radar-based roadside systems require a specific angle of deployment related to the protected zone), and that some locations and use cases require a combination of different types.

To assess the Vehicle-to-VRU specific challenges, Commsignia created micro-mobility-specific safety applications, including but not limited to Intersection Movement Assist (IMA), Right Turn Assist (RTA), and Blind Spot Warning (BSW).

This new protective ecosystem enabled by the safety applications shown above were tested in a pilot in which the supporting ITS equipment was a Lidar-based smart RSU. While the applications provide direct protection for VRUs, such sensor-enabled RSUs (in conjunction with V2P communication) serve a vital role in including the non-connected traffic participants, e.g. pedestrians without UE or dogs, in the V2X ecosystem via CPMs and SDSMs, thus lessening the strain of the generally low V2X penetration rate.



https://www.commsignia.com/news/commsignia-connects-bicycles-to-v2x-ecosystem-with-spoke/

https://www.spokesafety.com/news/audi-joins-spoke-safety

3 Analysis of the VRU White Paper recommendations

This chapter reviews each of the recommendations provided in the first 5GAA VRU WI. The recommendations are interpreted in more detail, then each participating Group provided its findings, and an overall conclusion is proposed.

Recommendations	Group A	Group B	Group C	Group D	Group E	Group F
Define minimum triggering conditions for delivery of VRU warnings	X	X	X	X	X	X
Provide guidelines for common presentation of VRU warnings, i.e. haptics, audio, visual	X		X	X		
Define minimum triggering conditions for transmitting VAM/PSM		X		X	X	
Set requirements for efficient use of spectrum, e.g. reduction of VAMs/PSMs in clusters		X			X	
Identification of high risk situations regarding pedestrians and places	X	X	X	X		
Research into pedestrian path prediction		X		X		X
Minimise power consumption in smartphone operating VRU protection service		X				
Sensor fusion		X	X			
VRU profile			X	X	X	
Integration with existing systems					X	

3.1 Define minimum triggering conditions for VRU warnings

3.1.1 Definition of the recommendation

The point of this section is to focus on the **triggering conditions** for a VRU warning, given that a potential danger or collision has been detected.

The focus of this recommendation is on 'delivery of VRU warnings' inside or outside a vehicle related to a potential conflict between road participants (e.g. a car and a bicycle). This may be enabled thanks to different C-ITS standard messages such as CPM, CAM/BSM, DENM, or/and VAM/PSM, but not exclusively those. In this section, we focus on the generation or the trigger of the VRU warning.

'VRU long-distance awareness', e.g. a pedestrian on a motorway which could be qualified as a 'hazard warning', is not part of the present discussion.

Warnings are in general used for driver notification. ETSI 103 300 mentions a possibility to activate AEB as a result of the VRU warning; this is yet to be considered in any of the implementations tested. In any case, an AEB will only be triggered based on a combination of information coming from diverse sensors.

Once detected, the way to deliver a VRU warning can differ depending on the approach adopted: suitable messages may be DENM or other similar (proprietary) message types. In some cases, the decentralisation relies only on CAM/PSM/VAMs so it leaves the warning trigger to the vehicle. In other cases, CPM is used to detect free space or object movements (see also Section 3.3.). In yet other cases, a DENM may be generated by a vehicle for a light client (a smartphone carried by a VRU).

ETSI TR 302 637-3 defines 'information quality' level (8), which may be linked to the probability of a crash. For this kind of trigger mechanism, all participants would need to have a common interpretation of the standardised information quality level in the DENM standard.

3.1.2 Findings

Two approaches were considered to trigger a VRU warning:

Cloud/edge generated (centralised)

Group B, E, as well as Group F used a novel approach to deliver cloud-generated VRU warnings. Collision warnings were generated more centrally, so that clients (vehicles, pedestrian) did not need to use additional computation power to receive and detect potential conflicts. Collision warnings were computed within the cloud and potential collisions were delivered by the cloud/edge to the relevant vehicles.

In Group B, first 'presence awareness' warnings with low 'information quality' could be computed and sent about 3-5 seconds before the conflict area (ETSI mentions 8 sec for first warning). The likelihood of collision increased significantly when time-to-collision decreased: up to 4 seconds before an accident, 30% likelihood of collision; less than 1.5 seconds, 90% likelihood of collision. Warnings were generated every second up to the conflict zone and interrupted as soon as the zone/moment disappeared. An AI-based approach using the history of the intersection allows more accurate VRU warnings to be triggered. Two warning distribution models were used: the VRU warning, in the form of a DENM, may be broadcasted to all participants in the vicinity or it may be directed to the right road participant; and a broadcasted message would still require enough logic at the client side to trigger the warning (challenge: false positive warnings).

Vehicle generated (decentralised)

Vehicle-generated warning triggers have been the most common approach among the tests in the past. Each individual vehicle or smartphone collects VAM/PSM/CAMs and computes the likelihood of a collision. In Group D, warnings were computed and generated by the vehicle (car, e-bike). In Group C (smart RSU), as per the ETSI standards, the CPMs were sent periodically with duty cycle between 100ms to 1sec in steps of 100ms.

3.1.3 Conclusions

The VRU-PRO activities helped to identify two fundamentally different approaches when it comes to triggering VRU warnings: the traditional vehicle-generated warnings and the edge/cloud-computed warnings. While most groups have used ITS standard messages, it is clear that edge/cloud-generated warnings could benefit from a change of message characteristics such as transmission rates.

In general, the warning level framework used in the experiments was in accordance with ETSI standards but the message transmission rates needed to be tuned. VRU presence-awareness warnings proved to be a good early notification. It is up to each implementation to decide when to first trigger an awareness message with low information quality. Repetition of the warnings as the information quality increases looked like a convincing approach. Warnings triggered under 3secs to the time coordinated computing (TCC) showed rapidly increasing likelihood of collision, thus reducing the potential false positives.

If a pedestrian is actively using a phone while walking, it is likely that he/she pays less attention to the surroundings. Inattention such as this could be a factor to take into account when triggering a VRU warning on the smartphone (e.g. ‘Look left!’).

To increase acceptance of such warnings and adapt to the type of users, the warning strategy should be configurable and offered via the user HMI settings – ‘early warning’, ‘short-notice warning’ – and it will depend on device types and differ for pedestrians, cyclists, and car drivers.

Additional consideration on timings of the VRU warning are described in below.

3.2 Provide guidelines for common presentation of VRU warnings, i.e. haptics, audio, visual (user groups, app supplier, OEMs)

3.2.1 Definition of the recommendation

This chapter includes basic principles on how VRU warnings should be provided but also summarises the learnings with respect to the look and feel of the warnings, based on the findings of Group A, Group C and Group D.

The following types of warnings were understood as ‘VRU warnings’:

- Warnings to car driver inside the car
- Warnings to the VRU on their smartphone or on wearables
- Warnings to the VRU vehicle, e.g. bicycle

The generic term ‘warning’ embraces the following more detailed types of notifications, indicating the urgency and the character of a warning:

- Information → increase awareness
- Warning → notify a danger
- Critical warning → danger confirmed

Target audience: smartphone vendors, wearables, app suppliers, and vehicle manufacturers.

3.2.2 Findings

In **Group A (Applied Information)**, the focus was on audible alerts in cars with visual alerts being secondary. Some studies[8] have found that audible alerts are best for keeping drivers eyes on the road therefore that is the focus here. The tests used different levels of warning: information with an audio chime, and a 'red warning' with an alarm when the driver did not react. Multiple levels of warning were based on a ‘miss level’, i.e. did the user react to the previous warning.

8 Florida study: https://fdotwww.blob.core.windows.net/sitefinity/docs/default-source/research/reports/fdot-bdv31-977-103-rpt.pdf

There was little difference between audio only vs. audio + visual. However, for audio + visual, integrated in-vehicle HMIs were more acceptable than a smartphone display.

The optimum time to warn a driver in urban setting was 3sec, as the driver could link the warning to the VRU.

The Manual on Uniform Traffic Control Devices (MUTCD) has provided standards on the physical signs along the roadway. The warnings displayed on the vehicle dashboard conform with those road signs, as defined by MUTCD. It was a good practice to replicate the same signs (or symbols) as found by the roadside. This can be tuned across countries.

For **Group C (Intel)**, the vehicle OBU was equipped with a HMI. The HMI would be able to display a rendered map of the vehicle's surrounding road environment along with the VRU's presence, and issue warnings as applicable.

VRU presence could be highlighted with eye-catching, display such as adding blinking caution/warning symbols corresponding to VRU locations in the map, and/or via audio warnings. The HMI screen can also show auxiliary data such as vehicle speed, VRU speed, the road speed limit, as well as any other advisory warnings for the road.

For **Group D (Bosch)**, user studies with n=52 individuals on bicycles were carried out[9], in which the perception of different types of warning signals (audio, haptic, acoustic) was evaluated in different environments (acoustically challenging, haptically challenging, visually challenging environments). When having perceived any of the signals, the individuals were requested to press a button, which was recorded. After the test ride, the individuals also filled out a questionnaire[10]. The main results were as follows:

- Visual notifications alone are not suitable for warnings because they are often overlooked
- Audio and/or haptic were preferred for quick warnings, and perceived best in all environments except for haptic signals on haptically challenging environment
- The questionnaire confirmed the acoustic signals to be the most preferred signal type for warnings

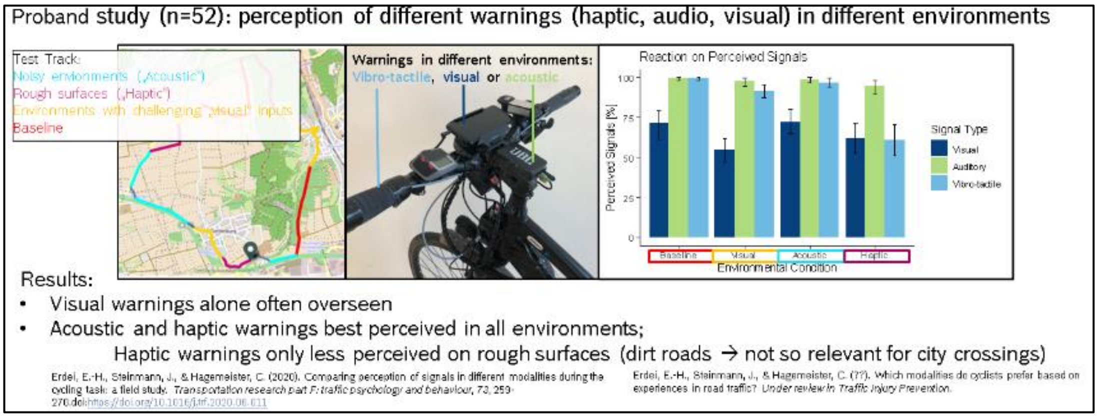


Figure 25: Comparing the cyclist's perception of haptic, acoustic and visual warning while riding in different environments

For Group E (**LGE**), users can receive audio, visual and haptic alert (regarding pedestrian/car/cyclist/school bus/school zone) using their smartphones. The notification method for the warnings can be customised by the user, by adapting settings on the VRU protection service application installed in the smartphone. In addition, three different types of warning messages (or level of urgency/sensitivity of warnings) can be provided using the smartphone, i.e. advisory warning, (normal) warning, urgent warning. Users can select the types of warnings they want to receive according to their preference. Also, depending on the situation (e.g. screen of the phone is off, an app is running in the background, phone

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[9] Erdei, E.-H., Steinmann, J., & Hagemeister, C. (2020). Comparing perception of signals in different modalities during the cycling task: a field study. Transportation research part F: traffic psychology and behaviour, 73, 259-270.doi:https://doi.org/10.1016/j.trf.2020.06.011

[10] Elke-Henriette Erdei, Jochen Steinmann & Carmen Hagemeister (2021) Which signal modalities do cyclists prefer based on experiences in road traffic?, Traffic Injury Prevention, 22:8, 640-645, DOI: 10.1080/15389588.2021.1985113

is in the pocket of pedestrian, etc.) different ways to provide the warning should be considered (e.g. visual, audio, haptic warning). Sometimes the different ways of warning can be used at the same time in a complementary way.

3.2.3 Conclusions

The following tables summarise the conclusions for different use cases:

Table 3: Conclusions reached for pedestrian and cyclist warning use cases

Pedestrian warning (Car-to-Pedestrian)		
	Warning (moderate reaction necessary to mitigate dangerous situation)	**Urgent warning (strong reaction necessary to mitigate dangerous situation)**
Car	Recommendation: infrastructure warning triggered based on the maximum warning distance (as specified in subsection 2.3 Test Case Scenario 1)	Recommendation: infrastructure warning triggered based on the minimum warning distance (as specified in subsection 2.3 Test Case Scenario 1)
Pedestrian	Not analysed in detail	Not analysed in detail
Cyclist warning (Car-to-cyclist)		
	Warning **(moderate reaction necessary to mitigate dangerous situation)**	**Urgent warning** **(strong reaction necessary to mitigate dangerous situation)**
Car	Recommended: moderately urgent sound Supportive: yellow indication Timing: ~2-3s* TTC	Recommended: urgent sound Supportive: red indication Timing: ~1-2s* TTC
	Warning **(moderate reaction necessary to mitigate dangerous situation)**	**Urgent warning** **(strong reaction necessary to mitigate dangerous situation)**
Car	Recommended: moderately urgent sound Supportive: yellow indication Timing: ~2-3s* TTC	Recommended: urgent sound Supportive: red indication Timing: ~1-2s* TTC
Cyclist	recommended: Moderately urgent sound optional: haptic warning supportive / explanatory: Yellow indication timing: ~3-4*s TTC	recommended: Urgent sound optional: haptic warning supportive / explanatory: Red indication timing: ~2*s TTC**

*This is the timing that was used in the two-step-warning approach in the Group D demo, which turned out to be suitable, but which is not based on extensive timing testing.
**In an additional user study (under review for publication), a single warning was emitted at 2sec TTC to cyclists at 20km/h which was well accepted.

Table 4: Conclusions reached for School-bus warning use cases

School-bus warnings (Car-to-Bus)		
	Warning* (moderate reaction necessary to mitigate dangerous situation)	Urgent warning**

		(strong reaction necessary to mitigate dangerous situation)
Car	Audio and Visual alert (soft melodic sound)	Audio and Visual Alarm (Louder and harsher sound)
School-zone warnings (Car-to-Infra)		
	Warning* (moderate reaction necessary to mitigate dangerous situation)	Urgent warning** (strong reaction necessary to mitigate dangerous situation)
Car	Visual only alert	Audio and Visual Alarm (Louder and harsher sound)

*Warning happens when school bus is stopped ahead, and vehicle is approaching (Car-to-bus). Warning happens when the vehicle is entering the school-area
**Urgent warning happens when vehicles is detected not to slow down (Car-to-bus). Urgent warning happens when vehicle is driving more than 5 miles over the speed limit (Car-to-infra)

General remark concerning the use of warning symbols

Even though the look-and-feel of an HMI is a differentiating factor for OEMs, it is recommended to use commonly used or regulated symbols to indicate certain types of warnings (e.g. use a symbol which is similar to the ones used on signs in that region).

Remaining questions

- How and when should the user be informed in case the warning system is not working properly, e.g. when loosing connectivity? Such information should be perceived, but not distract. The need to inform about non-availability might also depend on the overall trust level of the warning system.
- Should the driver/cyclist be allowed to turn off the warning system (ego warnings as well as ego communication, hence prohibiting a warning of the incoming driver/cyclist)?
- What is the most suitable way to provide warnings to pedestrians when the they receive the warnings using their smartphones? Depending on the situation (e.g. screen of the phone is off, an app running in the background, the phone is in the pocket, etc.) different ways to provide the warning should be considered (e.g. visual, audio, haptic warning).

3.3 Define minimum triggering conditions for transmitting VAM/PSM (MNOs, handset makers, OEM)

3.3.1 Definition of the recommendation

In ETSI TS 103 300-3, trigger conditions and generation rules were proposed for transmitting VAMs. The frequency of VAM generation can vary between 10Hz to once every 5sec. Low-frequency containers of the VAM are sent at most every 2sec. The VRU is either considered Idle, Active or Passive. Active VRU can be part of a cluster of VRUs, in which case a leader is transmitting VAMs while the others remain silent. The generation and transmission of a VAM is managed by the VRU Basic Service (VBS). The generation frequency is determined based on the change of kinematic state, location of the VRU, and congestion in the radio channel. Triggering of a new transmission is dependent on many factors: the content and timing of the last ego-message; the time lapsed, the distance, the speed change, the orientation change; but also other factors such as the likely interaction with other vehicle trajectories (increase), or joining a cluster (stop). Finally, the transmission frequency of the VAM is increased if another vehicle is detected (enters a 3D perimeter) around the ego-position and depends on the distance travelled over 5sec (min 2m laterally, 5m vertically).

This section is considering different practical issues in the generation and transmission of VAMs:

- When does the VRU_ROLE switch 'ON': As most of the demonstrations were related to the use of a smartphone, how practically did the Groups handle switching the VRU mode 'ON' or 'OFF'?
- When the VRU_ROLE is 'ON' already, when should the VRU trigger the generation and transmission of the VAMs?
- How often should the VAM be transmitted and what changes this frequency: Today, an Active VRU sends VAMs at regular intervals or as mentioned above. Also under some conditions, a VRU can skip transmission (a process called VAM redundancy mitigation).

The goal of defining these 'trigger conditions' is to send messages only as often as necessary to avoid signal congestion and to save power.

3.3.2 Findings

None of the Groups implemented the full set of VAM generation and transmission triggering conditions listed in the ETSI TS 103 300-3. So no full PoCs could be achieved when it comes to the message generation and transmission. However, some basic observations could be made based on the restricted implementations.

Practically, and especially when short-range radio penetration is low, it should be allowed for a VRU to slow down the VAM transmission rate, when no one else is present to receive the message.

If the VRU protection service works everywhere and includes VRU-to-VRU situations (as foreseen in ETSI 103300-1), a complete stop on the sending of VAMs is not possible because, in that case, two approaching VRUs could not detect each other at all. The most basic VAM, stripped down of optional containers, could thus continue to be sent at regular intervals, e.g. 0.2 Hz.

It might be appropriate to completely stop sending VAMs when in a safe zone (e.g. pedestrian area) and the speed is not higher than walking speed, since collisions would not be harmful. Another approach is to limit the service to certain geofenced areas. The choice of these 'fences' might be based on historic observations. In this case, the VAM/PSM is only sent out when entering the geofenced zone. If Uu is used to transmit the information to a server-based service, it might then request VAM/PSM transmission rate instead of using elaborated conditions listed in the TS 103 300-3 standard.

Group D focused on VAM/PSM transmission from bicycles and found that a cyclist path prediction of 1-2secs was realistic in many situations (see Section 3.4). So when a motion container is used which includes path prediction it appears to be a good approach to tune the VAM/PSM transmission rate according to the standard deviation detected by the path prediction algorithm and, thereby disregarding the VAM generation guidelines. In this case, send messages at 1Hz as a default (anticipatory) retransmission if the current position deviates from the predicted path (any flags changed/analogue values changed by more than a given threshold). Similarly, delay retransmission if nobody is around down to the minimum frequency of 0.2Hz, keeping the frequency high enough that two approaching VRUs would still see each other in time. Indeed, this is the reason that the minimum sending frequency (slower than 1Hz) depends on the speed and communication range. This situation is common on long straight bicycle paths. At a speed of 36km/h, the bicycle would need to retransmit every 4m (i.e. 2.5 Hz according to ETSI TR 103 300-3) whereas thanks to the use of the prediction path, it could retransmit every 50m (i.e. 5sec).

It was also observed by Group E (using PSM over Uu) that the relevance of warnings deteriorates very rapidly if the VRU type is set incorrectly or if the VRU profile changes. For example, a pedestrian waiting at bus stop or a bicyclist stepping off his/her bike, etc. Many of these situations could potentially result in false warnings if the PSM transmission is not stopped, which needs to be addressed with additional logic outside the scope of the standards. Moreover, Group E tried to implement automatic detection of the change of VRU type, and switch off the PSMs when necessary, or when a change of VRU profile has been detected (see also Section 3.9).

3.3.3 Conclusions

A detailed validation of the current standard for VAM/PSM trigger conditions has yet to be done. The above observations could inform such changes in the ETSI standard. For example, when using the VAM motion container, relaxed VAM retransmission rates could be considered. However, receivers would have to calculate the expected VRU position based on the path prediction information.

While generic triggering approaches are important, little consideration has been given so far to the VAM/PSM triggers for specific use cases. Moreover, the current standards give little space for VRU protection use cases that are triggered from infrastructure or the edge, e.g. at busy and dangerous intersections. The service should be able to request increased VAM transmission rates to all mobile ITS stations in specific areas (via Uu or RSU).

For further theoretical assessment, the following would be needed:

- A definition of use cases including their detailed requirements (accuracy and timeliness of received data)
- A detailed analysis of the expected movement of VRUs and the corresponding need to resend a message (because the old message no longer adequately represents the current status)

Testing would require realistic/high numbers of equipped VRUs and other traffic participants in the individual scenarios.

3.4 Set requirements for efficient use of spectrum, e.g. reduction of VAMs/PSMs in clusters (SDOs)

3.4.1 Definition of the recommendation

The number of road users can be very high, especially in urban areas where many pedestrians, cyclists and others can be collocated. Thus, it is not realistic to send PSM/VAMs from each VRU on the road all the time or at the highest frequency for urban areas with very high number of VRUs. To mitigate the issue, PSM/VAM standards have provisions to group VRUs that are close to each other into clusters (see ETSI TS 103 300-3). This is in addition to the congestion avoidance measures achieved via intelligent trigger conditions (see Section 3.3). VRU clustering enables the grouping of separate VAM transmissions into a single PSM/VAM transmission by the leader or 'cluster head', thus allowing other cluster members to skip individual PSMs/VAMs.

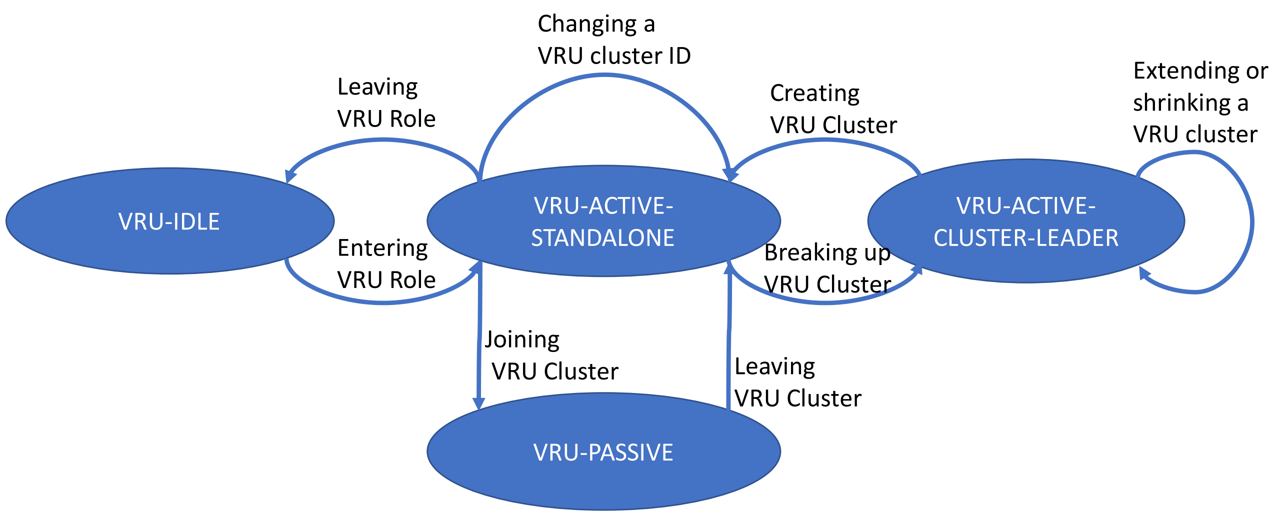


Figure 26: VRU cluster state diagram (ETSI TS 103 300-3)

In the PSM/VAM aggregation, when the RSU or server receives a large number of PSMs/VAMs, it relays them in aggregated form by creating a single message which can contain information about multiple VRUs. The number of generated PSM/VAMs can increase significantly in a local area with a high VRU density, but there is potential to reduce the overhead and bandwidth when the RSU or server sends out the received information. This is because many of these messages have similar contents, such as the VRU location, so the RSU/server can avoid repeating the protocol overheads like the transmission control protocol (TCP)/ header in each VRU message. One of the ways to do PSM/VAM aggregation is to concatenate the received messages, extracting the common information repeated in all the messages. This PSM/VAM aggregation concept is not yet described in the current draft standards.

Note: VRU clustering was not implemented per se in the experiments. However, there are some learnings to be derived, leading to improved spectrum efficiency and, in this case, even extend the definition of spectrum efficiency to 'amount of useful information per Hz"' rather than bit/Hz.

3.4.2 Findings

Main findings on spectrum efficiency related to V2N: Group B (DT/CONTI) and Group E (LGE)

The VRUs run an application on their smartphones while vehicles generate CAMs and DENMs. If vehicles enter a designated geo-zone, they upload the information to a Collision Warning (CW) cloud. Additionally, generated CAMs are also uploaded to the CW cloud. Based on the uploaded information, the cloud computes the likelihood of conflicts or dangers, and triggers the generation of DENMs. The vehicles then receive DENMs from the CW service in order to generate a warning to drivers. To reduce the generation of too many DENMs, the VRUs are grouped into clusters based on their proximity to each other and their heading. Furthermore, clustering could be created in real time; in which case the total daily transfer of a maximum of 1.1MB with 900kB/s rate in the uplink (mostly CAMs and negligible for the sporadic DENM transmission at the downlink) is sufficient. Considering limited geo-zones, a maximum of 1MB/day data volume was estimated.

When VRU protection services are based on V2N/Uu, cloud/MEC can support data processing/analysis and/or information routing. And, depending on the amount of data processing/analysis performed by the MEC/cloud, different deployment models can be considered (as below) and different approaches for DL/UL/server-to-server traffic reduction are required for each model.

- Data processing and analysis are performed by the MEC/cloud
- Data processing and analysis are performed at device-side (i.e. VRUs and vehicles)
- Combination of above scenarios (e.g. selective/hybrid operation between those two scenarios)

In general and in all scenarios above, as the amount of data processing/analysis at the cloud increases, the amount of outgoing traffic (from cloud-to cloud/device) can be more reduced:

- In the first scenario, if most data processing/analysis can be carried out by the cloud/MEC, (event-triggered) warning message transmissions could be most of the (or the only) outgoing traffic and thus the traffic could be decreased drastically.
- In the second scenario, to improve accuracy (e.g. awareness of environments, assessment of collision/risk) on the device side, it would be beneficial to transmit enough (or all relevant) information from MEC/cloud to receivers, and this operation leads to increased outgoing traffic compared to the traffic in the first scenario. However, there is room to reduce the data traffic from cloud-to cloud/device, and message clustering and aggregation can be considered as candidate solutions for the traffic reduction.
- The Group E demo showed that traffic can be reduced up to 18~20% by compressing the location information of multiple VRUs and packaging it into a single message (tan example of message aggregation schemes).

Finding related to use of PC5 in Group C/D

Group C focused on collective prediction messages (CPM-SAE SDSM) generated from smart RSU over 5.9GHz PC5:

- Provisions for CPM generation can be applied to achieve more efficient use of the spectrum. Although a newly detected VRU is always reported in the next CPM instance, VRUs already being reported periodically in the CPM can be skipped in some instances when a shorter CPM periodicity (<500ms) has been configured. While skipping VRU reporting in CPM instances, it must be ensured that all detected VRUs are reported in a CPM at least once within 500ms.

Group D focused on VAM/PSMs from bicycles over 5.9GHz PC5/11p. Approaches considered in Group D to minimise/save bandwidth requirements include:

- Well-chosen trigger conditions, e.g. only send new information if 'old' message content is no longer valid; use path prediction to extend the validity duration of a message (see Section 3.3)
- Minimise message size
    - By using required fields only

- By thorough analysis of the requirements for VRU use cases as an input for standardisation (e.g. analysis of the resolution of transmitted values resulting in message field sizes)

3.4.3 Conclusions

It is crucial to pay more attention to the use of spectrum when considering battery-driven devices or ITS services with large payloads. These considerations depend heavily on system architecture (e.g. centralised vs decentralised solutions) and use of the mobile network and/or short-range communication.

In the 5.9GHz ITS band, the spectrum needs for VRU protection services (based on observations in the demos) and traffic reduction methods were considered. The main consideration to improve spectrum efficiency is to modify the message retransmission rate based on more accurate path prediction, i.e. do not re-send the full message with the motion container if the former path prediction is still valid. Sending relative position also improved spectrum efficiency. In addition, the reported objects (vehicles and VRUs) in the previous CPM message may be skipped in the current CPM to save bandwidth. In some cases, even the entire message may be skipped.

In Uu bands, the spectrum needs for VRU protection services (based on observation in the demos) and additional UL/DL traffic reduction methods were also considered. To reduce UL/DL or server-to-server traffic, the following methods could be considered:

- Optimisation of message generation/transmission triggering condition for (connection-based) Uu V2X, e.g. event/prediction-based message generation (geofence or zone-based transmission triggering)
- Message processing/filtering at server/cloud/MEC (e.g. computation of collision risk at server level)
- Message clustering and message aggregation

3.5 Identification of high-risk situations and areas

3.5.1 Definition of the recommendation

This recommendation focuses on identifying high-risk areas where VRU safety issues are more likely to occur. This section thus deals with the identification of high-risk areas, and once high-risk areas are identified, how the various VRU Groups are helping to reduce the risk in these zones. Not all high-risk areas will be covered by theses VRU-PRO use cases, where the following information provides more of a general procedure on the identification high-risk situations in various geographic locations (where there will likely be variation in such situations according to location).

Best practices on how to determine or define high risk situations and areas:

- Many high-risk areas are already known to the city managers, thanks to historic or accident data
- Traditionally, urban planners use physical elements, such as traffic lights, a physical barrier, a pedestrian crossing, roadway markings, etc., to reduce risks
- The identification of high-risk areas can be gradually automated via data collection and validation from accident databases, but it goes beyond this by also identifying near-misses which make the streets more insecure or unpleasant to use and/or navigate
- Presence of distracting advertising (digital advertising boards)
- Time-of-day scenarios, such as high traffic, school zones, events, position of sun, etc.
- High-risk areas are also defined as those with a high concentration of VRUs
- High-risk areas are also work zones and where visually impaired communities may be located

3.5.2 Findings

Group A: High-risk situations and areas covered by this demonstration were focused on school children. The two high-risk situations and areas were (1) roads around a school, and (2) school buses.

School zones are areas where the speed is reduced during pre-defined periods when school children are present, for instance at the start and end of a school (when pupils are arriving or leaving the premises). Every year, around the world, thousands of children are killed during school travel hours. Movements to and from school buses are particularly dangerous.

School buses are dangerous for children entering and exiting the school buses. Over 17,000 accidents occur each year with school buses.

The Group found out the following:

- 10-30% improvements (reduced speeding) when a driver receives audible/visual alarms or warnings
- A driver is more likely to increase their perception of a VRU on average around 20-30%

Group B: High-risk situations and areas covered by this demonstration were focused on critical intersections and unguarded rail crossings. Definitions were agreed together with the City of Hamburg, based on the available accident database.

The Group found:

- Critical intersection situations: vehicle turns right (during the green light phase), VRU drives straight (at the same green light phase)
- Mutual warning (of vehicle driver as well as the VRU – especially fast-moving, bicycle/scooter driver) reduces critical accident situations significantly (no statistical data available)

Group D: The cycling accident analysis was carried out include data of all accidents, not only severe and fatal ones. When limited to severe and fatal accidents, the scenario 'upfront riding cyclist' has a higher fraction (risk factor) because those accidents proved more severe or fatal.

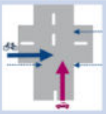
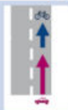
Name	Crossing cyclist	Oncoming cyclist	Lateral riding cyclist	Upfront riding cyclist
Description				
Actors	• Cyclist • Driver • Visual obstructions (e.g. buildings) • Other traffic participants	• Cyclist • Driver • Other traffic participants	• Cyclist • Driver • Visual obstructions (e.g. vehicle design) • Other traffic participants	• Cyclist • Driver
Includes	• Cross road	• Turning	• Start of cycling	• Blind spot for cyclists • Lane change • Start of cycling • Sudden braking by cyclist
Accident frequency*	(36%)	(10%)	(6%)	(1%)
Cyclist fears**	-		Top 1 (88%)	Top 2 (83%)
Further use-cases (w/ minor accident frequency)	• Parking: Vehicle exists parking lot alongside the road • Dooring: Vehicle driver opens door after parking alongside the road (Top 3 of cyclist fears rated with 69%)			

Figure 20: most critical vehicle-cyclist high-risk situations

3.5.3 Conclusions

Establishing high-risk situations and geographic locations is an important factor in determining where to deploy technology to help improve VRU safety on the roads. As a first conclusions, there is still plenty of **room for development** and even research on high-risk situation.

The first step is to establish the high-risk situations/areas using traditional methods and accident data collected. Also, make sure that existing accident databases and regional statistics of risk areas are taken into consideration.

Once a high-risk situation is determined then ascertain what technology and systems will be required to assist in the reduction of accidents reported at that specific location.

The Groups agreed that **better identification of high-risk situations and places** via novel methods like data-fed **AI algorithms** is a key ingredient to help reduce accidents at these places, while reducing dramatically false warnings, and thereby increasing user acceptance.

3.6 Research into pedestrian/cyclist path prediction

3.6.1 Definition of the recommendation

In ETSI TR 103 300-2, three VRU path predictions are mentioned:

- Cyclist/e-bike/PTW path prediction
- Pedestrian path prediction
- Animals path prediction

Animals exhibit erratic behaviour and were not addressed by any VRU-PRO Groups, so in this section the focus is only on two-wheelers and pedestrians.

A typical time horizon for path prediction in the context of ITS is around 2-5sec in most of the groups (ETSI mentions 8sec):

- 5sec path prediction is desired for collision warnings or adaptive speed changes
- When considering interventions like AEB functions, the required time horizon might be shorter, but requires more precise prediction

Path prediction can be calculated by the vehicle's on-board unit (bicycle, car, etc.) or by the cloud via collection of PSM/VAM (CAM) and other information.

Path prediction based only on smartphones was not addressed by the VRU-PRO Groups.

3.6.2 Findings

Group B: Path prediction was done both for pedestrians and cyclists in an edge-cloud application. Each road user was assigned a position and likely path based on received CAM messages from the VRUs and sensor fusion with MAPs, SPAT and CPM signals and historical data. The path prediction based on HD maps and (anonymised) historical data works very well and extends the collision warning time. The centralised (MEC-based) system architecture allows for the re-use of anonymised historical data; a machine-learning algorithm utilising that data improves the prediction accuracy.

The following data turned out to be the most relevant:

- Road user position (heading/speed) 1Hz,
- Cloud:
  - HD map (crucial for path prediction)
  - Optionally from infrastructure: SPAT (MAP) helpful to predict manoeuvres and reduce probability of false warnings
  - Optionally from infrastructure: CPM for consideration/inclusion of more (not yet registered) road users by the CW algorithm

Further Details and findings are described in section 3.8.

Open topics to be further addressed:

- Path prediction for pedestrians require an additional path model (still to be researched)
- HD map not available at all sites
- Comprehensive road user feedback loop (due to COVID)

Group D: Bicycle path prediction was calculated using bike sensors. The prediction was intensively studied using various bicycle models and methods and compared to the 'real' path. It turned out that the future path can be well predicted for 1-2sec based on sensor information alone; and over a longer time horizon, further information will probably need to be considered (under investigation).

The following graph shows some results of a bicyclist's path prediction based on bike sensors (inertia sensors and more) and bike models (dots: real positions; lines: predicted path):

Figure 21: Bicyclist's path prediction based on bike sensors (inertia sensors and more) and bike models (dots: real positions; lines: predicted path)

Further results are discussed in the conclusion below.

Group F: Path prediction was done on the basis of the sensor information (phone camera) sent from the vehicle to the edge from which VRU speed, heading, position, acceleration, etc. were derived. Similar data was attempted to be derived on the phone itself, but this proved impractical (in terms of power consumption). VRU 'posture' could be added to the data collection criteria to reduce false warnings.

3.6.3 Conclusions

The results of Group B show that a combination of different sources can be used to predict the path of cyclists and pedestrians in an edge-cloud application. Adding more information led to improved results, i.e. position/heading/speed + Map + Historic data (using AI/ML) + SPAT (see Section 3.8 on sensor fusion). While the first results were very promising and led to a neat integrated solution, it is agreed that improvement would be necessary to benefit more fully from the combination of the different data sources.

The preliminary results of Group D show that the future path of bicycles just based on bike sensor data of can be well charted for 1-2sec, which is good for close-to-accident predictions and for avoiding false positives. For a longer time horizon, additional information needs to be included (work is ongoing).

It could be shown that the 'path prediction' data-field in the ETSI VAM format (ETSI TS 103 300-3 v2.1.2) is well-suited to describing the future path of a bicycle, but can result in large messages if not used carefully:

- In order to reduce traffic, the predicted path should only be used if the coming manoeuvres cannot be described well withing the HF container

- Using all available (40) predicted path points is not recommended and not necessary (in order to reduce traffic); ~5(-10) are considered enough to describe even complex riding manoeuvres
- Using 'relative' instead of 'absolute' path points would reduce size significantly (this is a proposed change for the VAM 'path prediction' format).

A change to address those findings is ongoing.

Note: Especially in the case of an accident, the 'VRU' and the 'VRU vehicle' might be separated. It is important that the VRU is regarded as a pedestrian again, to allow the car to distinguish between the VRU's and the VRU vehicle's position and path prediction. The VRU's protection needs to be prioritised.

3.7 Minimise power consumption in smartphone operating VRU protection service

3.7.1 Definition of the recommendation

Power consumption is an important issue for small battery based devices.

A 'socialised' VRU protection approach should allow all kinds of client devices to be integrated into a VRU protection service as an active contributor. Each client device should be able to create a so-called 'protection shield' for all occupants of the road including vulnerable road users.

Assuming that vehicles, e-bikes, e-scooters have higher battery capacity, a large majority of VRUs carry smartphones (85% of all pedestrians in cities) with lower power capacity. A similar challenge faces smartwatch-based solutions as well as digitalised wearables.

Implementations must therefore consider and support technology driven approaches which integrate power-limited devices into the VRU protection solution.

3.7.2 Findings

Only Group B addressed the recommendation to minimise power consumption in smartphones operating VRU protection services, as follows:

- HW split: Separation of dedicated functionality from smart devices, e.g. positioning module, HMI module; connect separate HW modules via BLE connectivity
- HW integration: Integrate smart devices into the mobility system, e.g. integrate smartphone device with e-scooter power supply system (wireless charging, USB C, etc.)
- Lean SW client: Define a system architecture for the VRU P solution based on a client/server architecture; client as part of the smart device, server as a cloud solution. The 'brain' of the solution is allocated to the server part with flexible and scalable processing power, the 'client' is kept very lean and the only tasks of the client are to send a minimum location information via CAMs (position, heading, speed), receive warning messages if necessary, and serve the user HMI
  Notes: Integrating infrastructure-based data important for the calculation of potential collisions is provided to the 'server brain' only (e.g. HD map data, traffic light information via SPAT/MAP, environmental data via CPM, etc.)
- Hotspot-driven solution architecture: One reason for heavy energy consumption on smart devices is the permanent GNNS positioning request and messaging to the cloud. One of the options to reduce this procedure is to introduce 'critical accident areas' – so-called hotspots or geofenced areas. The permanent sending of CAMs will be focused on the hotspot areas only: a smart device within the hotspot sends CAMs, a smart device outside a hotspot area is 'silent'
- Socialised VRU protection support includes smartphones as client devices
- Lean-client strategy uses COTS smartphones with no specific HW changes, easy-to-deploy SW upgrades, strong positioning capabilities, and the ability to switch off precise positioning in non-critical situations, based on the hotspot concept

3.7.3 Conclusions

'Socialised' VRU protection support means using smartphones as client devices. For smartphones and similar smart client devices, an optimised approach to minimise power consumption is essential. Several architectural solutions for the VRU protection can help to reduce power consumption. They considers aspects of hardware optimisation as well as SW solutions. It is crucial to deploy a 'lean-client device' approach.

The current C-ITS standardisation considerations do not consider a centralised client/server architecture; C-ITS messages are indeed 'broadcasted'. A key recommendation is to augment the current C-ITS considerations in terms of extended use case descriptions based on a centralised client/server approach. The impact on the current C-ITS message specification has to be evaluated, potentially leading to a message format adaptation as well.

3.8 Sensor fusion

3.8.1 Definition of the recommendation

Sensor fusion is necessary for aggregating diverse information coming from various sensors. With the non-equipped road users as well as vehicles to remain on the road at least for the next 30 years, sensor fusion is fundamentally important for putting together many difference sources of information. For instance, autonomous vehicles have a plethora of on-board sensors needed to perceive their environment, and such vehicles perform sensor fusion to generate various critical environmental analytics. Now, for VRU protection, having sensor fusion at the client side may prove impractical in the long term – having sensor fusion take place via roadside infrastructure/sensors would improve the usability of various sensor data including HD maps and historical data. Such sensor data can then be processed at the roadside and warnings can be generated from that – ready for disseminating to nearby smartphones. With the advancement in cloud/edge computing, such sensor fusion at the roadside is now becoming more and more viable, while pre-fusion at the client side is out of scope.

3.8.2 Findings

Group B: The sensor fusion is performed in the cloud and is extendible for various additional sensors such as MAP, traffic lights, teal-time data, and historical data. Since most of the data is being gathered by the cloud, the dynamic information is mainly the position and speed of the moving vehicles, while additional data can include HD maps and map-matching (due to mismatch between HD map and MAP). HD maps can be received via cloud-edge interfaces or stored at the edge. Historical data from vehicle trajectories can be created by using AI/machine-learning techniques, while traffic light information can be extracted from the infrastructure via SPAT/MAP messaging with a default periodicity of 1Hz. The road infrastructure is typically equipped with detection loops and cameras, but might also be equipped with additional sensors to detect the presence of the vehicles and VRUs.

A mismatch between different sources of sensor information may occur and lead to a fused object into one single target or two different targets. Thus, such mismatches need to be treated in real time. Warnings are generated and delivered over the mobile network to the smart devices running the application.

During the test RSU, two suppliers (CONTI and VITRONIC) were active where CPM/DENM are created from the smart RSU and tried to detect unequipped vehicles/VRUs. POLISCAN from VITRONIC was used for speed enforcement.

Since smartphones did not provide the positioning as originally expected (precision levels are still evolving/improving), the received positions need to be integrated into a HD map. To this end, use of AI algorithms provided significant improvements in detection performance for moving vehicles. Furthermore, fusion helped to reduce false positive warnings. Four different fusion setups were used: 1) position, 2) position and HD map, 3) position, HD map and AI, and 4) HD map

Group C: The setup focuses on a single intersection where the smart RSUs are equipped with a series of sensors/cameras used to detect the VRU at an intersection. Sensors are fully covering the intersection. An edge (known as "on-premise edge computing") is running at the intersection. Sensor fusion was used to generate CPM PSM warnings. The RSU uses the 5.9GHz channel to convey the CPS-based warnings to the equipped vehicles. In the future, CPMs received by smart RSUs in vehicles will also be addressed in the data fusion preceding the analytics.

3.8.3 Conclusions

Sensor fusion is seen as an important topic to increase the reliability of VRU position detection and path prediction. Algorithms should be as flexible as possible where it makes most sense: in some case, it is best to execute sensor fusion right at the client side (e.g. mobile phone) but also at infrastructure/cloud level. A balanced approach is optimum.

In terms of latency, it was observed that sensor fusion computation time never exceeded 20ms and round trip time was always kept below 200msec.

3.9 VRU profile

3.9.1 Definition of the recommendation

In ETSI TS 103 300-1, TS 103 300-2 and TS 103 300-3, various types and subtypes of VRUs are defined in terms of various profiles. Pedestrians, bicyclists, motorcyclists, and animals are the different types of VRUs classified into profiles.

The following VRU profiles are specified in clause 6.1 of ETSI TS 103 300-2:

- VRU Profile 1 – Pedestrian. Typical VRUs in this profile: pedestrians, i.e. road users not using a mechanical device for their trip. It includes for example pedestrians on a pavement, but also children, prams, disabled persons, blind persons guided by a dog, elderly persons, persons walking beside their bicycle.
- VRU Profile 2 – Bicyclist. Typical VRUs in this profile: bicyclists and similar e.g. light vehicles riders, possibly with an electric engine. It includes bicyclists, but also wheelchair users, horses carrying a rider, skaters, e-scooters, personal transporters, etc.
- VRU Profile 3 – Motorcyclist. Typical VRUs in this profile: motorcyclists, which are equipped with engines that allow them to move on the road. It includes users (driver and passengers, e.g. children and animals) of Powered Two Wheelers (PTW) such as mopeds (motor scooters), motorcycles or side-cars.
- VRU Profile 4 – Animals presenting a safety risk to other road users. Typical VRUs in this profile: dogs, wild animals, horses, cows, sheep, etc. Some of these VRUs might have their own ITS-S (e.g. dog in a city or a horse) but most of the VRUs in this profile will not be able to send the VAM and only be indirectly detected, especially wild animals in rural areas and highway situations.

The VRU profile is provided in every VAM under the Station_Type parameter which can take the value pedestrian(1), bicyclist(2), moped(3), motorcycle(4), lightVRUvehicle(12), or animal(13). Harmonisation is currently ongoing, and SAE2945-9 is dealing with VRU in the US. In the US, motorcycles are not classified as VRUs. The harmonised classification of VRUs between ETSI and SAE have started.

From the V2X systems perspective, it is not clear to what extent the VRU profiles need to be defined and harmonised. A separate assessment may be needed for defining the importance of VRU profiling in V2X messages based on specific use cases. For instance, for motorcycles, CAM is used instead of using VAM, with a special container for motorcycles defined in TS 103 300-3 Annex D. It is however, not clear if current receivers use the motorcycle container at all if received. Also, note that UNECE defines PTW in a practical way. Such discussion in VRU-PRO should influence an eventual revision of the TS 103 300 series and/or SAE2945.

3.9.2 Findings

The VRU-PRO activities mostly focused on the pedestrian and cyclists profiles.
In Group C (Intel), only pedestrians' profile were used. Smart RSUs detected pedestrian presence and relayed the CPM to oncoming traffic. The vision classifier on the Smart RSU compute host did have the capability to differentiate between pedestrians and cyclists. However, only pedestrian detection was used during the VRU-PRO WI. The pedestrian VRU profile is one of the main profiles as defined by ETSI (see TS 103 300-1). In particular, VRU profile 1 is mainly concerned with pedestrians. VRU profile 1 features include unpredictable behaviour, limited velocity range (for instance, for an adult pedestrian, from 0 to 4 m/s), potentially limited capacity to react to warnings, presence as isolated individual or as large group (e.g., at a busy intersection) .

Group D (Bosch) was only dealing with Profile 2 (cyclists). The change between cyclist and pedestrian profile when getting on/off the bike was not yet studied. Nonetheless, we have some comments on Profile 3 – motorcycle. Since pedestrians have a different dynamic range than motorcycles (so far), the standards are not efficiently defining these differences. It is not clear what kind of impact this has on the current systems. Criteria listed in 103 300-2 may need some more adaptation, especially with the speed ranges of Profile 3 (too low). There may be a need to have a better classification of VRUs related to their 'dynamic capability' rather than fixed criteria such as maximum speed and weight, etc.

Lastly, in **Group E** using LGE's VRU protection service app, a user mode (e.g. pedestrian, e-scooter, cyclist, emergency vehicle, kids) could be selected and changed manually or even automatically. When the VRU profile (aka 'mode' by LGE) is selected automatically by the app, the VRU profile is determined using sensor data collected by the VRU device (smartphones, wearables, known BLE devices, etc) and learning algorithm provided by the app. The VRU profile mode was a very important feature to tune the warnings in the app. In the demo, the automated VRU profile choice and transition proved to work very well. It was observed that the mode-switching between vehicle and pedestrian can be detected with almost 100% accuracy. As the number of user modes to be distinguished increases, the accuracy of the mode detection could be degraded slightly, but optimisation using an AI algorithm is ongoing, to achieve detection performance close to 100%.

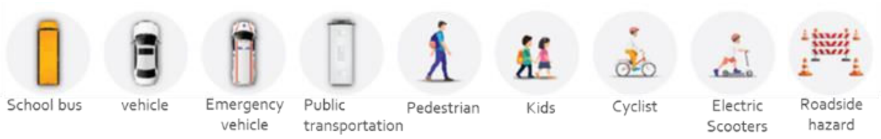


Figure 28: Different types of user mode (VRU profile) supported by LGE's VRU protection

3.9.3 Conclusions

The VRU profiling definition proved to be very important for the VRU-PRO Groups.

VRU profiling could be done automatically based on sensor inputs (even from simple sensors found in smartphones).

The transition between VRU profiles should be considered more seriously in standardisation. This remains an open discussion that ETSI could consider.

Many cars or motorbikes, even e-bikes, today have some sort of incident detection capabilities. A driver or rider ejected from his/her vehicle due to an accident should be considered as an important safety critical use case: VRUs equipped with a smartphone combined with a bicycle/motorbike equipped with PC5/Uu radio. When separated from its vehicle, the rider needs to be instantly detected as a pedestrian independent of the vehicle whereabouts, and should be given priority protection as a potentially injured person lying on the road.

3.10 Integration with existing systems

3.10.1 Definition of the recommendation

In demos/PoCs presented in VRU PRO WI, the provision of VRU protection services based on Uu-based communication was considered by several companies. However, according to some current ITS specifications, it seems Uu-based VRU protection services (or VRU device operation) are not supported by the specification or have not been optimised yet. For example:

- In [Reference : SAE J3161/1], the standard specifies the system requirements for an on-board "vehicle-to-vehicle (V2V)' safety communications system and the system is capable of transmitting and receiving BSM "over a PC5 Sidelink V2X (Mode 4) communications link" as defined in 3GPP Release 14.
- [Reference : SAE J3161 (C-V2X deployment profiles)] defines how to prioritise and deliver different messages between vehicles (V2V) and between vehicles and roadside infrastructure (I2V/V2I) with one 20MHz C-V2X radio channel at 5.9GHz. The focus of this standard is short-range communication based on C-V2X and the support of Uu V2X (V2N/N2V) is not considered in this standard.
- Also, in [Reference : SAE J2945/9], it is mentioned the recommended practice is limited at this time to "communications between the VRU device carried by walking pedestrians and DSRC equipped vehicles". The

revision of [Reference : SAE J2945/9] is currently ongoing, and it is desirable to change [Reference : SAE J2945/9] to concentrate on message content and be as technology agnostic as possible in future.

- In [Reference : SAE J3224 (V2X Sensor-Sharing for Cooperative & Automated Driving)], the term "V2X" refers to only short range communication technologies (including 3GPP cellular V2X (PC5) and DSRC) and Uu-communication-based sensor-sharing service is not supported by the specification.

Taking the current state into consideration, it needs to be considered how to protect more VRUs efficiently even if they are carrying devices that do not support direct communication from specification and implementation perspectives. Integration of the Uu-based V2X system with the legacy short-range V2X system can be a solution for the protection of VRUs carrying devices without direct communication capability. And this might mean the server/cloud connects various ITS players (vehicles, RSUs, VRUs) not only via mobile network communication but also using direct communication, and, in this scenario, VRU devices that do not have direct communication capability can communicate with legacy ITS stations in short-range V2X system.

3.10.2 Findings

With the introduction of the above-mentioned integrated ITS system, even VRUs carrying devices that support only Uu-based communication can be efficiently protected based on information exchange between the Uu V2X devices and short-range communication-based V2X devices, and the VRU accidents can be further reduced in this system. However, further discussion on how to combine these two different V2X systems is necessary (e.g. who and how to translate information/messages exchanged between these two different systems/devices, how/whether to define the interface between app server and RTA server or between app server and RSU in ITS standard, etc.).

3.10.3 Conclusions

To protect VRUs that carry devices having only Uu communication capability, the integrated ITS system that combines Uu-based V2X system and direct communication-based V2X system needs to be seriously considered. Also, investigation of the technical enablers and impact on the relevant standards required for the implementation of this integrated system is necessary.

4 Needs and gaps on standardisation

Some findings and recommendations on the technologies and implementation methods for VRU protection are described in the previous chapters. Based on the findings and recommendations, 5GAA identified needs and gaps on some ITS standards including ETSI TC ITS, SAE, ETSI ISG MEC, and this chapter describes which aspect/requirements should be considered by relevant SDOs in their standardisation work, to further improve the safety of various types of VRUs.

The VRU-PRO WI was realised at the same time that new types of messages were being standardised, such as PSMs at SAE, and VAMs and CPMs at ETSI. These standardised messages proved to be useful independently of the choice of architecture adopted in the experiments, i.e. messages could be transported via PC5 but also via Uu on an IP network. It is therefore essential that the ongoing ETSI Release 2 is transport layer agnostic so that messages can be used both via the cellular network and direct communication. Similarly, it is recommended that SAE-defined messages also are made transport layer agnostic.

4.1 ETSI TC ITS

TR 103 300-1 (Part 1: Use cases definition)

In demos presented in this WI, some companies tested Uu/V2N-based VRU protection using smartphones and it was observed that the Uu/V2N can help protect VRUs carrying devices that do not support short-range communication. Therefore, to protect more VRUs efficiently, the integration between Uu communication-based V2X systems and short-range (direct) communication-based V2X systems needs to be considered in ITS standards. More specifically, the integration of these two different communication systems might mean the ITS application server can connect various ITS players (vehicles, RSUs, VRUs) not only via mobile network communication but also using direct communication, as shown in the figure below. In the integrated system, the number of VRUs that can exchange information with other ITS stations will increase, and thus it is expected that VRU accidents can be further reduced.

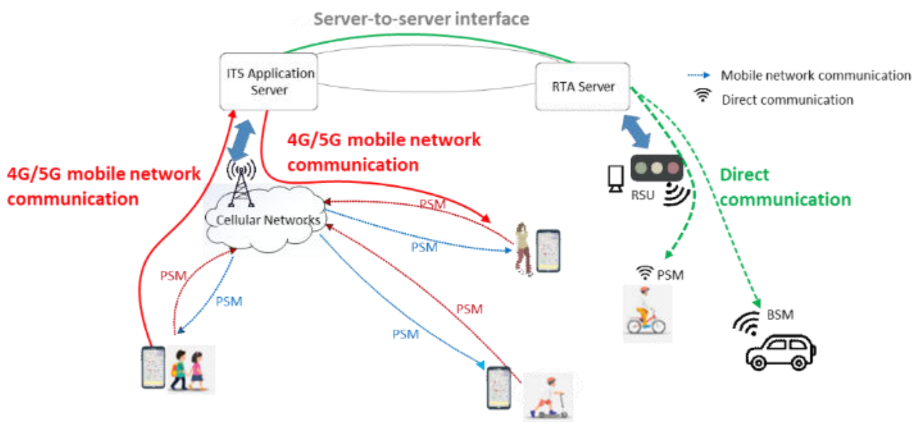


Figure 22: ITS application server connects with various ITS players via various communication channels

A Work Item to include new VRU use cases is ongoing in ETSI TC ITS, and it could be desirable to consider new use cases that can be supported by this integrated system under discussion.

TS 103 300-2 (Part 2: Functional architecture and requirements definition)

VRU profile: In 103 300 series, various types and subtypes of VRUs are defined in terms of different profiles, e.g. pedestrians, bicyclists, motorcyclists, and animals. From the V2X systems perspective, it is not clear to what extent the VRU profiles need to be defined by ITS standard. Also, a separate assessment is needed for defining the right extent of VRU profiling in V2X messages. For example, even though different types/subtypes of VRUs have different dynamic ranges (e.g. speed), current standards have not effectively defined the differences. Therefore, better classification of VRUs considering the dynamic capability of the VRUs (rather than fixed criteria such as maximum speed and weight, etc.) might be required, and the current criteria listed in TS 103 300-2 may need more adaptations.

Security requirement: As explained above, companies tested Uu/V2N based VRU protection services. However, it is not clear how the system can address the privacy and security issues in the Uu/V2N scenario. The current ITS privacy and security solutions are defined for the connection-less V2X communications, and thus they might not be suitable for Uu-based solutions that can use the connection-oriented communications.

Consideration on functional architecture

- For the support of Uu/V2N: It is recommended to discuss/identify whether functional/operational requirements need to be extended or modified considering the Uu/V2N-based VRU protection services (e.g. whether to define interface between servers (e.g., central ITS station) and/or role of the servers).
- For the support of integration between long- and short-range communication systems: As described above, consideration of integration between Uu V2X and short-range communication- based V2X would be needed to improve VRU safety. However, study/discussion on who and how to translate information exchanged between these two different V2X systems is necessary. Also, it would be needed to discuss whether/how to define the interface between server and RSU in ITS standard.

TR 103 300-3 (Part 3: Specification of VRU awareness basic service)

Path prediction: Demos in some companies observed that the “path prediction” data-field in the VAM format is well-suited to describe the future path of a bicycle, but can result in large-sized messages. The usage of relative path points instead of absolute path points could be a solution to reduce the size of VAMs. For VAM/PSM transmission from bicycles, a cyclist path prediction of 1-2sec turned out to be realistic in many situations (see Section 3.4). So when the motion container is used including path prediction, it appears to be a good approach to tune the VAM/PSM transmission rate according to the standard deviation detected by the path prediction algorithm, and thereby disregarding the VAM generation guidelines. Send messages at 1Hz as a default (anticipating) retransmission if the current position deviates from the predicted path (any flags changed/analogue values changed by more than a given threshold). Similarly, delay retransmission if nobody is around down to the minimum frequency of 0.2Hz, keeping the frequency high enough that two approaching VRUs would still see each other in time. This is why the minimum sending frequency (slower than 1Hz) depends on the speed and communication range. This situation is common on long straight bicycle paths. At a speed of 36km/h, the bicycle would need to retransmit every 4m, i.e. 2.5Hz according to ETSI TR 103 300-3, whereas thanks to the use of the prediction path, it could retransmit every 50m, i.e. 5sec.

For PC5, as always when using a fluctuating message transmission rate, receivers would have no means to know how long they need to keep received messages alive; this may result in ghost detection at the receiver side, made even worse if the transmitter changes its ID at the same time, i.e. the receiver does not receive the last message and tracks a sender based on an outdated received message.

Message format for Uu/V2N support: Further discussion on whether VAM needs to be extended or modified when the message is transmitted using Uu communication for VRU protection.

ETSI ITS EN 302 637-2 V1.3.1 (2014-09)

According to TS 103 300-2 and TS 103 300-3, ITS stations in VRUs profile three devices (e.g. motorcyclist) already transmit CAMs. Accordingly, they do not transmit the full VAM but may transmit a VRU special vehicle container (motorcyclist special container with complementary data elements) in the CAM they already transmitted. In TS 103 300-3, it is recommended to add *MotorcyclistContainer* specified in clause D.2 of TS 103 300-3 to the CAM standard.

4.2 SAE

General remark

Some companies in 5GAA are interested in Uu/V2N-based VRU protection and various activities to test/promote Uu/V2N-based ITS services are ongoing by the companies. However, it seems the scope of the following standards is limited to short-range communication (e.g. LTE V2X PC5, DSRC) and the support of Uu V2X (and integration between short-range communication and Uu V2X) is not considered. It is desirable to make these standards technology agnostic by revising the current standards or having a new mirror/delta specification for Uu V2X.

- o SAE J3161 (LTE Vehicle-to-Everything (LTE-V2X) Deployment Profiles and Radio Parameters for Single Radio Channel Multi-Service Coexistence)
- o SAE J3161/1 (On-Board System Requirements for LTE-V2X V2V Safety Communications)
- o SAE J2945/9 (Vulnerable Road User Safety Message Minimum Performance Requirements)
- o SAE J3224 (V2X Sensor-Sharing for Cooperative & Automated Driving)

SAE J2945/9 (VRU Safety Message Minimum Performance Requirements)

The revision of SAE J2945/9 is already ongoing. The standard is expected to be published E2022/A2023.

Recommendations from this document:

- Formulate the standard as technology agnostic as possible (see above)
- Further harmonisation with ETSI VAM is desired while taking into account new insights, e.g. from this document, and include path prediction based on accurate individual path points

4.3 ETSI ISG MEC

The ETSI Industry Specification Group (ISG) for Multi-access Edge Computing has developed and been updating the Group Specification (GS) MEC 030 on a MEC V2X Information Service (VIS). The objective is to facilitate V2X interoperability in a multi-vendor, multi-network and multi-access environment, considering the relevant work of other industry bodies relating to V2X communication such as ETSI TC ITS and 5GAA. The document describes the V2X-related information flows, required information and operations. GS MEC 030 also specifies the necessary API with the data model and data format.

The requirement of MEC operation in a multi-vendor, multi-network and multi-access environment is essential for VRU protection use cases. 5GAA already contributed directly to GS MEC 030 with inputs on the support of end-to-end predictive QoS notification in multi-MNO scenarios (MEC(22)000289r3). This feature has not primarily focused VRU protection use cases, but those could also benefit from it. Specific enhancements to the MEC VIS supporting VRU protection are under discussion and could enable some of the use cases demonstrated by 5GAA member companies. Additional enhancements under discussion are the support of V2X interoperability in a MEC federation, enhanced predictive QoS information, gathering information from additional sources (beyond Uu and PC5 interfaces) for V2X services, supporting deployment of in-vehicle MEC hosts.

5 Conclusions

The objective of the VRU-PRO WI was to identify and test different practical approaches to address VRU protection enabled by V2X communications. It aimed to provide enough learnings to commonly conclude on ten recommendations and possibly identify gaps or further areas of work.

The Work Item was realised at the same time as new types of messages were being standardised, such as Personal Safety Messages at SAE, and VRU Awareness Messages and Collective Perception Messages at ETSI. It is recommended that ongoing ETSI Release 2 and SAE message types are specified to be transport layer agnostic so that the messages can be used both via the cellular network and direct communication.

The Work Item participants identified a common approach to plan, execute and report their experiments. Six Groups were eventually established, each represented by one or more 5GAA members. In Chapter 2, the groups individually described the scope of their experiment, listed their own research questions, proposed their methodology and reported on their results and/or conclusions. Some Groups also proposed related readings, e.g. collaboration with research or academic groups.

The six experiments ended up having pretty distinctive features that made their approach unique compared to the others: radio interface (Uu and/or PC5), technology enablers (MEC and/or 5G SA), type of ITS messages used (CPM, PSM/VAM, BSM/CAM-DENM, SPAT/MAP), source of sensor data (vehicle, infrastructure, mobile phones), etc.

It is important to mention that the definition of a Vulnerable Road User is wide, whereas the six experiments mainly targeted pedestrians and cyclists including e-bikes. Further exploration may be needed for other types of VRU such as young people or the elderly, and people with disabilities. Additional considerations for motorcycle use cases may be derived from the findings of this WI in the future (e.g. in the CPTW WI).

Following the experimentation in the six individual Groups, the WI participants gathered their experience to contribute to the Chapter 3 based on the ten recommendations listed in an earlier 5GAA VRU White Paper.

Minimum triggering conditions for delivery of VRU warnings were addressed. Traditional decentralised delivery vs edge-generated warnings were discussed. Three types of VRU warnings were considered: to vehicle drivers, to pedestrians, and to cyclists. Some guidelines for common presentation of VRU warnings were tested using haptics, audio, and visual. Urgent audio warnings (sound) was in general considered effective in cars and for cyclist. For the latter, the addition of haptic warning on bike handlebars showed good results as well. The difference between awareness, warnings and critical warnings were made. A 3sec time-to-collision (TTC) alert was agreed to be a good target to initiate awareness (e.g. visual) while audible and/or haptic warnings below 1sec to TTC could be reliably issued in most cases. Other types of interaction were discussed, e.g. on wearables.

Minimum triggering conditions for transmitting VAM/PSMs could only be partly assessed. Different VAM/PSM transmission policies would help for specific use cases. It was found that some optional features in the VAMs such as the motion container (including path prediction) are essential to improve VRU protection. Also depending on the use of the motion container, VAM/PSM repetition rate may be relaxed. Indeed, the results for path prediction were quite conclusive especially for cyclists. The future path of bicycles based purely on bike-sensor data could be well predicted for 1-2sec, which is good for close-to-accident predictions and for avoiding false positives. Further quantitative analysis could help to derive harmonised methods for path prediction confidence levels.

The discussions on high risk situations led to two distinct topics. First, the high-risk geo-location needed to be identified, e.g. at an intersection; second, enough real-time data was required for dynamic identification of high-risk situations between road participants. The first is a semi-static attribute mainly based on road geometry and topology with regular periodicity related to weather, time of day, type of day (week day, weekend, holiday, etc.). It could be addressed using longer-term observations, thanks to historic data, collected data and/or incident data, together with simple machine-learning which proved helpful. The second is highly dynamic, and requires enough computation resources to consume the real-time collected data from many different sources e.g. app-enabled phones, equipped vehicles, road sensors, signal phases, etc. Sensor fusion discussions clearly led to the conclusion that the geo-correlation of the high-risk information described above plus the improved path prediction could reduce greatly the false warning rate. Sensor fusion proved promising based on simple machine-learning techniques combining both statistical observations over some time and real-time feeds.

Efficient use of spectrum was discussed both for Uu- and PC5-based VRU protection applications. For Uu supported by a MEC as well as PC5-based smart RSUs, data rate improvements are suggested by optimisation of message generation/transmission triggering condition for all types of V2X messages, e.g. event/prediction-based message generation and geofenced or zone-based transmission triggering. Increased message repetition rate did not lead to further improvement of the positions and paths, nor the identification of higher risk. Further, edge-computing enabled the centralised computation of a potentially high-risk situation and could target where and to whom to deliver the relevant warning messages – this could be delivered via unicast or a groupcast. The edge generation of warnings led to a considerable saving both in computation power needed at the terminals and the required bandwidth to deliver warning messages in the form of DENMs rather than VAM/CAMs. For VRU app-based solutions, where computing power at terminals is limited, it is highly interesting to address it from an edge-computing point of view.

The lack of integration between Uu-based and direct communication-based V2X system showed that some more work needs to be done. It was agreed that the combination of the two systems would bring the best of both worlds for VRU protection.

Finally, VRU profiling, i.e. whether VRU is located in a car, in a bus, on a bike or is walking, could be realised automatically based on sensor inputs (even based on smartphone sensors). The switch between driver and pedestrian profiles was observed with almost 100% reliability by one of the Groups.

Note that, due to anticipated complexity, the ETSI standard for VRU clustering was not implemented and, unless simplified, may not be adopted in the future. Alternative approaches were adopted when using Uu/V2N.

As a final closing statement, the VRU-PRO clarified three main points: first, VRU protection from its simplest to most complex form proved to be within reach from a technical and deployment point of view. Second, combining network and direct modes for new messages offers synergies in VRU protection and ought to be exploited. Finally, given the limited computing and battery power on smartphones or wearables, a decentralised messaging for VRU becomes less attractive and the generation of warnings targeted at VRUs computed by the network (edge) and/or the car (edge) may become a favoured option.