Study on Dynamic V2X Use Cases

CARTS Work Item

5GAA Automotive Association
Technical Report

CONTACT INFORMATION:
Executive Manager – Thomas Linget
Email: liaison@5gaa.org

MAILING ADDRESS:
5GAA c/o MCI Munich
Lindwurmstraße 25,
80337 München, Germany
www.5gaa.org

VERSION:	1
DATE OF PUBLICATION:	1 July 2026
DOCUMENT TYPE:	Technical Report
EXTERNAL PUBLICATION:	Yes
DATE OF APPROVAL BY 5GAA BOARD:	23 April 2026

Contents

Executive summary

This technical report, developed within the 5G Automotive Association (5GAA) CARTS Work Item (WI), evaluates the applicability of cellular vehicle-to-everything (C-V2X) technologies to selected transportation safety use cases beyond basic informational services. The study analyses representative scenarios – including intersection safety, soft intersection approaches, vulnerable road user (VRU) presence awareness, and high-speed rear-end collisions, using analytical models that capture vehicle kinematics, driver behaviour, positioning uncertainty, and communication performance. Both direct (PC5) and network-based (Uu) C-V2X communication are assessed, highlighting their complementary roles in extending situational awareness beyond the limitations of onboard sensors, particularly in non-line-of-sight and complex traffic environments. Results, supported by simulations, field measurements, and latency and positioning data all indicate that C-V2X can provide timely and reliable information within well-defined action windows – enabling effective risk mitigation when realistic assumptions on latency, reliability, GNSS accuracy, and human factors are applied.

V2X has been included in regional NCAP (New Car Assessment Programme) specifications currently under discussion and development, which means it can be expected that the path to deployment for the technologies supporting use cases described in this report will be established, leading to real-world implementations that 5GAA will continue to track. However, it has been noted that services addressing VRU awareness and safety are not specifically mentioned in NCAP, and from previous 5GAA work it is understood that the overall business case for VRU is difficult. As a result, 5GAA has established a further Work Item to better understand the values/attributes for VRU safety and awareness services (VRU Awareness and Protection VRU-AP), which will report later in Q4 2026.

1 Definitions, symbols and abbreviations

For the purposes of the present document, the following definitions apply:

3GPP:	3rd Generation Partnership Project – the organisation responsible for standardising mobile communication technologies, including V2X interfaces like PC5 and Uu.
ACC:	Adaptive Cruise Control – an advanced driver assistance system that automatically adjusts vehicle speed to maintain a safe distance from vehicles ahead.
ADAS:	Advanced Driver Assistance Systems – electronic systems in vehicles that assist drivers in driving and parking functions, enhancing safety and convenience.
AEB:	Autonomous Emergency Braking – an advanced safety feature that automatically applies brakes to prevent or mitigate collisions.
BSM:	Basic Safety Message – a message format used in V2X systems to broadcast safety-related information such as location, heading, and speed.
CAM:	Cooperative Awareness Message – a standard message in V2X communications, used to share position, speed, and status information among vehicles and infrastructure.
CCRH:	High Speed Car to Car Rear – refers to scenarios or tests involving high-speed interactions between vehicles, specifically focusing on rear-end situations.
CIWS:	Cooperative Intersection Signal Information and Violation Warning Systems – systems designed to provide vehicles with signal information and warn drivers of potential intersection violations.
C-V2X:	Cellular Vehicle-to-Everything – a form of V2X communication that utilises cellular networks to enable interactions between vehicles and other entities.
E2E:	End-to-End – refers to communication or processes covering the entire path from source to destination.
FCW:	Forward Collision Warning – a system that alerts drivers to potential frontal collisions.
GNSS:	Global Navigation Satellite System – provides positioning, navigation and timing information for vehicles.
GVT:	Global Vehicle Target – typically used to describe a reference vehicle or object in testing scenarios.
ISO:	International Organisation for Standardisation – develops global standards, including those relevant to automotive safety and communications.
KPI:	Key Performance Indicator – a measurable value used to assess the effectiveness or success of a system or process.
LIDAR:	Light Detection and Ranging – a sensor technology used in vehicles for object detection and environmental mapping.

LTE:	Long Term Evolution – a standard for wireless broadband communication, foundational for cellular V2X (C-V2X) technologies.
MAP:	Map Data Message – provides detailed intersection geometry and lane information to support cooperative driving and safety applications.
MEC:	Multi-access Edge Computing – a technology enabling cloud computing capabilities at the edge of mobile networks, supporting low-latency V2X applications.
NCAP:	New Car Assessment Programme – a safety rating programme that evaluates the safety performance of new vehicles.
OEM:	Original Equipment Manufacturer – a company that produces vehicles or components used in vehicles.
PC5:	Sidelink interface for direct V2X communication – the radio interface used for direct communication between vehicles and other devices without relying on the cellular network.
SPAT:	Signal Phase and Timing Message – conveys traffic signal status and timing information to vehicles for improved intersection safety and efficiency.
UE:	User Equipment – refers to any device (such as a mobile phone, tablet, or vehicle) that connects to a mobile network.
Uu:	Conventional cellular interface between user equipment and network – the standard interface used for communication between devices (such as phones or vehicles) and the mobile network infrastructure.
V2N:	Vehicle-to-Network – a V2X communication scenario where vehicles interact with network entities such as servers or traffic management systems via the Uu interface.
V2X:	Vehicle-to-Everything – a set of communication technologies that enables vehicles to interact with other vehicles, infrastructure, pedestrians, and networks for improved safety and efficiency.
VRU:	Vulnerable Road User – refers to pedestrians, cyclists, and other non-vehicle participants in traffic.
VT:	Vehicle Target – a vehicle used as a target in safety performance tests or demonstrations.
VUT:	Vehicle Under Test – the vehicle being evaluated in a given scenario or experiment.

2 Introduction and objectives

The objective of this document is to analyse selected V2X use cases and evaluate their feasibility, applicability and advantage for the communication technologies (PC5, Uu) under consideration while taking into account capabilities of the onboard vehicle sensors and ADAS functions commonly available. It aims to determine how well these technologies meet the functional and performance requirements of the selected use cases, supported by quantitative insights from key performance indicator (KPI) measurements and analysis.

The overall goal is to apply a practical methodology for the assessment of system performance and technology trade-offs relevant to V2X applications with respect to different communication modes and the complementarity of onboard sensors and functions.

3 Background: V2X, sensors, and key performance indicators

3.1 V2X air interfaces (PC5, Uu)

This report considers two complementary radio interfaces defined by 3GPP for V2X communications: the PC5 interface and the Uu interface. PC5 is a direct V2X interface (often referred to as 'sidelink') that enables device-to-device communication between nearby vehicles or other road users, and it is designed to operate independently of cellular network coverage, making it a key enabler for V2X use cases demanding low latency, high reliability, and localised operation such as safety-critical and cooperative driving functions. The Uu interface, in contrast, refers to the conventional cellular link between a road user equipment (UE) and the 5G network. In V2N scenarios, the Uu interface enables vehicles to exchange information with network-based entities such as application servers, traffic management systems, or cloud services, benefiting from wide-area coverage and centralised coordination. Both interfaces – including their protocol stacks, physical layer characteristics, and operational modes – are specified by 3GPP as part of the 5G standardisation framework.

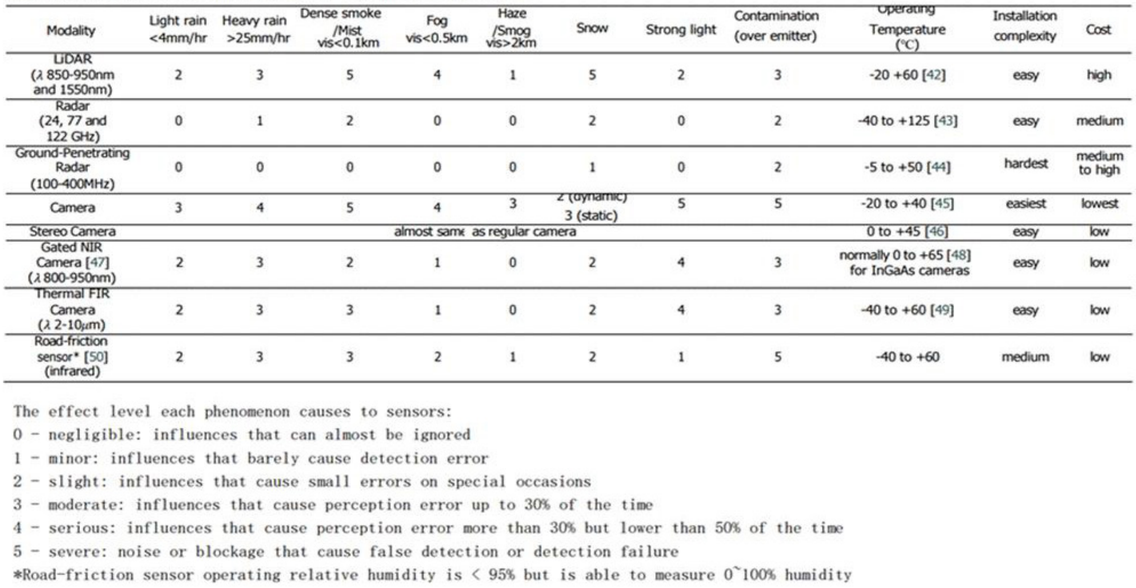
3.2 Onboard sensors, limitations, and complementarity with V2X

Vehicle-integrated sensors (lidar, radar, cameras) are independent and stable but limited by range, weather, occlusions, and damage. C-V2X can extend perception beyond sensor limits, works in all conditions, and provides reliable, real-time object data. C-V2X and onboard sensors are complementary, enhancing safety and decision-making for ADAS and autonomous driving.

In recent years, driven by technologies such as artificial intelligence and perception fusion, 'single vehicle autonomy' has developed rapidly, but keeping up with complex (diverse and dynamic) transportation safety scenarios – and stringent reliability and robustness requirements – is a constant challenge. The limitation of single vehicle autonomy is identified in typical scenarios such as adverse weather, visibility issues, damaged surfaces, and complex traffic accident and danger detection [1].

In adverse weather (i.e. when visibility drops below 200m in fog or misty conditions), the effective detection range of lidar experiences a significant attenuation of more than 50%, while the contrast of visible-light cameras plummets to 30-50% of the baseline value [2]. In heavy rain (i.e. when its intensity exceeds $50\text{mm}\cdot\text{h}^{-1}$) the multi-source sensor system will exhibit collaborative performance degradation. Indeed, the Lidar system shows significant point cloud quality deterioration in a dynamic rain curtain; affected by the raindrop accumulation effect, the effective pixel information loss rate of the visible-light camera exceeds 40% [2]. The propagation attenuation characteristic of millimetre-wave radar exhibits obvious nonlinearity under extreme rainfall conditions, and its maximum detection range shows a nonlinear attenuation of approximately 45% [3]. For other extreme weather (sandstorm, graupel 'snow pellets', hail, sleet), the scattering effect of suspended particulate matter on visible light can reduce the effective visual range of cameras. Severe noise interference is liable to induce distortion in the process of data acquisition, thereby undermining the reliability of subsequent analysis [1].

The diverse sensors may be affected under different weather conditions, and the influence level is summarised in [2] the following table.



Modality	Light rain <4mm/hr	Heavy rain >25mm/hr	Dense smoke /Mist vis<0.1km	Fog vis<0.5km	Haze /Smog vis>2km	Snow	Strong light	Contamination (over emitter)	Operating Temperature (°C)	Installation complexity	Cost
LiDAR (λ 850-950nm and 1550nm)	2	3	5	4	1	5	2	3	-20 +60 [42]	easy	high
Radar (24, 77 and 122 GHz)	0	1	2	0	0	2	0	2	-40 to +125 [43]	easy	medium
Ground-Penetrating Radar (100-400MHz)	0	0	0	0	0	1	0	2	-5 to +50 [44]	hardest	medium to high
Camera	3	4	5	4	3	2 (dynamic) 3 (static)	5	5	-20 to +40 [45]	easiest	lowest
Stereo Camera	almost same as regular camera								0 to +45 [46]	easy	low
Gated NIR Camera [47] (λ 800-950nm)	2	3	2	1	0	2	4	3	normally 0 to +65 [48] for InGaAs cameras	easy	low
Thermal FIR Camera (λ 2-10μm)	2	3	3	1	0	2	4	3	-40 to +60 [49]	easy	low
Road-friction sensor* [50] (infrared)	2	3	3	2	1	2	1	5	-40 to +60	medium	low

The effect level each phenomenon causes to sensors:
0 – negligible: influences that can almost be ignored
1 – minor: influences that barely cause detection error
2 – slight: influences that cause small errors on special occasions
3 – moderate: influences that cause perception error up to 30% of the time
4 – serious: influences that cause perception error more than 30% but lower than 50% of the time
5 – severe: noise or blockage that cause false detection or detection failure
*Road-friction sensor operating relative humidity is < 95% but is able to measure 0~100% humidity

Table 1 The influence level of various weather conditions on sensors

Meanwhile, the radar chart shows the strengths and weaknesses of each sensor in adverse conditions is presented as follows. It can be observed that the degradation of perception is the main limitation of the sensors in adverse weather conditions.

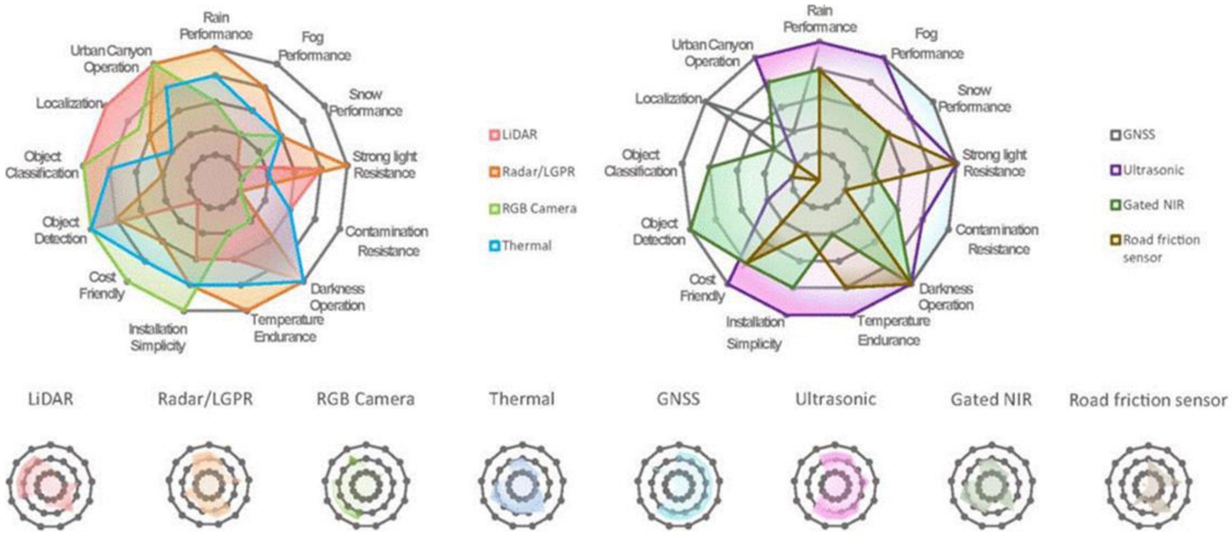


Figure 1 Onboard sensors performance in adverse weather conditions

The limitation of sensors under complex illumination conditions should not be underestimated. For example, insufficient illumination that degrades environmental perception accuracy, strong light and sensors blinding due to glare that interfere with normal sensor operation, and severe exposure state fluctuations caused by rapid light-dark transitions can all reduce perception reliability and compromise system stability and safety [1].

The diverse functional abnormalities and structural defects in damaged surface detection poses severe challenges to single vehicle autonomy. Road defects are easily confused with visual interference such as shadows, oil stains, and black asphalt, and they can affect the accuracy of machine-vision identification. Combined with stringent requirements, these factors can add to the high cost of developing vehicle-mounted sensing and perception systems [1].

In the detection of complex traffic accidents and dangers, individual vehicle intelligence exhibits limited capability to handle diverse scenarios involving corner cases. The robustness of multimodal fusion degrades significantly in heterogeneous environments. Furthermore, it is difficult for a single vehicle to achieve effective multi-agent information exchange on open roads, which further restricts its ability to detect and respond to complex traffic risks [4].

Given the various limitations to the reliability and accuracy of onboard sensors outlined in the above section, it follows that the inclusion of a technology or solution for event or object detection (i.e. a remote sensor connected to the vehicle using C-V2X), not susceptible to the same limiting effects under similar scenarios, would provide a complementary service to improve the reliability of the overall system. C-V2X-based solutions enable equipped vehicles to receive information about external events from other nearby entities in near real time, independent of the phenomena affecting onboard sensors. Additionally, information can be received from remote sensors positioned beyond maximum working distance or the line-of-sight of onboard sensors, thereby extending the ‘sensing range’ of the vehicle. Such event information, provided before an onboard sensor would naturally detect it, can be used to prepare a vehicle or a driver for a future event at an earlier point in time, such that the demands on the driver or vehicle systems closer to the event could be reduced. In some cases, survivability of a crash or incident could be significantly improved through earlier preparation, based on information received using C-V2X.

3.3 Use cases considerations

When evaluating V2X use cases, the following metrics should be considered to determine the functional and technical requirements for each scenario. These KPIs define the operational boundaries necessary for safety-critical, driver awareness, and efficiency-oriented services:

- Latency (end-to-end): The maximum allowable time from message generation at the source to successful reception and processing at the destination.
  - Time-critical: Scenarios involving immediate collision avoidance (e.g. intersection safety or vehicle cut-out) require ultra-low latency, typically under 100 ms
  - Latency-tolerant: Driver awareness or comfort-based alerts (e.g. VRU awareness) can typically tolerate latencies of 300 ms or higher
- Reliability: The probability of successful message delivery within the required latency budget. High-velocity or high-risk scenarios demand higher reliability thresholds (e.g. 99.9% or greater).
- Communication range: The distance over which a message must be reliably received to allow for sufficient perception and reaction time. This varies significantly between scenarios as different speeds would require different reaction time. In the case of direct communication (PC5) the achievable range may be affected by several factors such as line-of-sight conditions, obstructions, and the propagation environment.
- Message frequency (update rate): The number of messages transmitted per second (Hz). Dynamic use cases require high-frequency updates to maintain accurate positioning and trajectory awareness.
- User density: The ability of the communication interface to maintain performance in congested environments, such as a busy intersection with numerous vehicles, pedestrians, and cyclists.
- Service availability: The requirement for the communication link to be operational regardless of cellular network coverage (e.g. in remote areas or during periods of high network congestion).

3.4 Business KPI

The business KPI examines the monetary benefits and costs, both of which are difficult to quantify. Consequently, a qualitative model was developed instead.

The cost of direct V2X is primarily driven by the one-time installation cost, which is expected to operate throughout the vehicle's lifespan. Expanding services, such as transitioning from local hazard warnings to collision avoidance and cooperative perception, do not increase costs, yet the benefits grow.

The V2N model operates differently and is a combination of both communication and cloud services. Some semi-static use cases (like 'local hazards' services) involve infrequent communication which translates to limited computational requirement. Other, more dynamic use cases (like 'road user awareness' services) require more frequent messaging and a corresponding increase in the cloud computational requirements (see [7] for more information).

The initial one-time cost of V2N is negligible, as vehicles already include a cellular modem. The ongoing operational costs consist of communication and cloud computing expenses, and they persist throughout the vehicle's lifespan. While the OEM may choose to discontinue the service, this decision would deprive older vehicles of the protection to which drivers have become accustomed to.

It should be noted that supporting other non-safety use cases, such as tolling by the network and/or direct V2X, has the potential to improve the business case.

	Initial/one-time cost	**Operational cost**
Direct V2X	Equipment cost	Negligible
V2N	Negligible	Communication and cloud services

Table 2 V2X cost comparison

4 Representative V2X use cases

4.1 Overview and selection rationale

Use case name	Radio	Interaction	V2X message	Scenario	Intervention	Interaction with ADAS	Comment
Soft intersection approach	PC5 Uu	I2V I2N- N2V	SPAT	Rural-urban Intersection with traffic light	Automated with pre-warning	Traffic light sensors	Automated Full stop at stop line; ACC settings
Intersection movement	PC5	V2V	CAM/ BSM	Intersection	Manual with Warning	Bicycle or vehicle detection	Emergency stop needed
VRU presence awareness – mid-block	Uu	P2N-N2V	CAMv2	Straight Roadblock	Manual with awareness info	Pedestrian detection	Deceleration only to void danger
High-speed car-to-car rear	PC5	V2V	CAM/ BSM	Straight Roadblock	Manual with warning	Vehicle detection	(Non-) emergency deceleration

Table 3 Use cases overview

4.2 Soft intersection approach

This use case considers a signalised intersection scenario in which an ego vehicle approaches the intersection at the maximum authorised speed with a connected intelligent adaptive cruise control (ACC) system engaged and under continuous driver supervision. At the time of approach, the traffic signal is green and is expected to transition to yellow and subsequently to red within a short time horizon. The scenario requires a timely decision regarding speed adaptation or stopping in order to safely negotiate the intersection.

ISO 26684:2015 [5], which addresses Cooperative Intersection Signal Information and Violation Warning Systems (CIWS), provides a reference framework for this type of scenario. While the standard defines Class III CIWS with assisted braking or automatic stopping, such functionality is outside the scope of the ISO document. In addition, ISO 26684 does not explicitly consider intersections employing actuated signal control with variable signal timing.

4.2.1 Sensor-based baseline approach

The use case can be addressed using vehicle onboard sensors capable of detecting traffic signal phase information. In this baseline configuration, a two-step warning and intervention sequence may be considered. First, the vehicle detects the transition of the traffic signal to yellow and provides a warning to the driver. Second, if the signal transitions to red and no appropriate driver reaction is detected, the vehicle may apply braking force to bring it to a stop before the intersection.

While technically feasible, this sensor-based approach may raise acceptance considerations, as many vehicle manufacturers prefer to leave the decision to proceed or stop to the driver, even when a potential signal violation is detected.

4.2.2 V2X-assisted approach using SPAT infrastructure information

A more acceptable realisation of the use case for users can be achieved by leveraging infrastructure-based information conveyed via standardised signal phase and timing (SPAT) messages. The availability of SPAT information enables a graduated, three-step approach to speed adaptation:

- Prior to the signal turning yellow, the ego vehicle receives SPAT information indicating a possible upcoming phase change, allowing an early advisory indication to be presented to the driver.
- As the vehicle approaches the intersection and the reliability of the SPAT information increases, the vehicle can initiate a smooth and comfortable deceleration to reduce approach speed.
- At the moment the signal switches to yellow, the vehicle can confirm the signal state using onboard sensors and, if required, apply additional braking force to stop at the marked line.

This approach supports earlier and smoother speed adaptation, reducing the need for abrupt braking while maintaining driver awareness and control.

The use case is independent of whether the SPAT information is delivered via direct V2X communication (PC5) or via network-based communication (Uu).

4.3 Intersection movement use case

At an urban intersection several unsafe situations may arise when a cyclist or another vehicle intentionally or unintentionally runs the red light or stop sign and is confronted with oncoming traffic. The following analysis considers scenarios where an offending cyclist (VRU) or vehicle is approaching the intersection from the left after running a red light or stop sign. The ego vehicle is approaching the intersection from the bottom at a speed of 60 km/h and has a green light. There is no line of sight between the ego vehicle and the offending vehicle/VRU. V2X messages may be useful for such scenarios which make the oncoming traffic aware of the impending danger ahead of time by alerting the ego vehicle's driver to reduce speed or stop in order to mitigate/avoid an imminent accident.

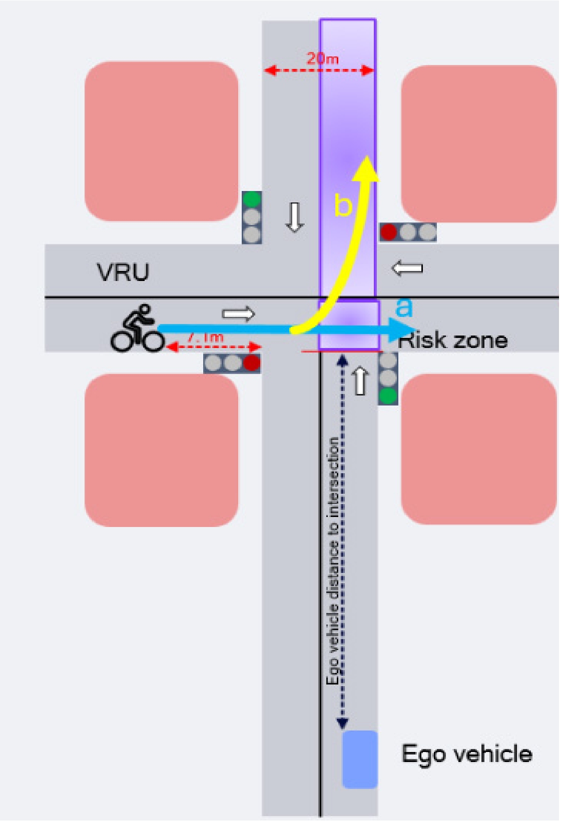


Figure 2 Scenario 1 (1a and 1b) with VRU approaching from left

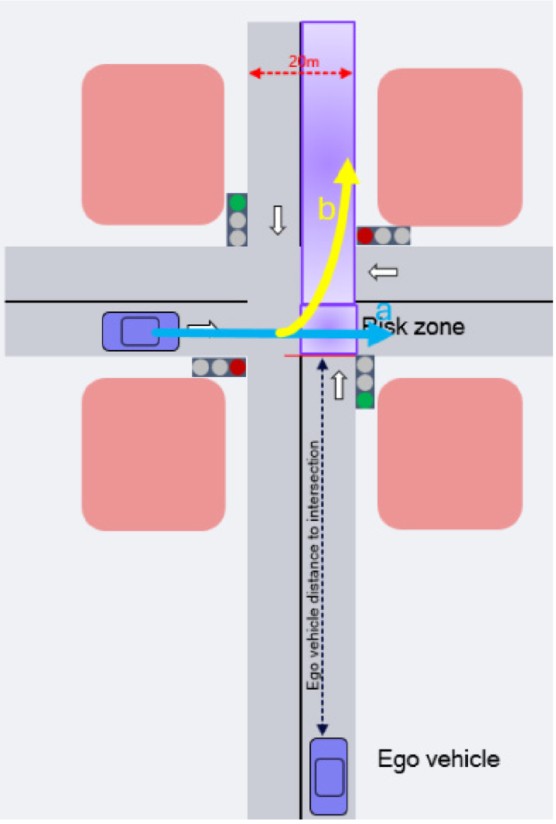


Figure 3 Scenario 2 (2a and 2b) with vehicle approaching from left

The analysis defines a risk zone at the intersection where the trajectories of the ego vehicle and the offending vehicle/VRU may intersect. A collision may occur when both the ego vehicle and the offending vehicle/VRU are simultaneously present within this risk zone. To avoid a collision, the ego vehicle must not enter the risk zone before the VRU has exited it. An action window is further defined as the time interval during which, if V2X messages are successfully decoded, the ego vehicle can reliably execute an appropriate response.

Action window for safety: Defined by a start time and an end time for evaluating communication performance in the safety scenario. V2X messages need to be successfully received within the window to perform an action.

Start of the action window (for safety): Defined by the kinematic parameters, i.e. when an action starts to become necessary. Messages received before the start of the window may not be used to initiate actions within the window.

End of the action window (for safety): Defined by the kinematic parameters, i.e. the late message that can be successfully received based on which an appropriate evasive manoeuvre must be taken to prevent an accident. The ego vehicle may receive messages and process the trajectories before the start of the window. However, no action needs to be taken as the situation is not deemed critical. The detailed analysis in Section 5.2 explains the scenarios if the action is performed at the start of the action window or the end of the action window.

4.4 VRU presence awareness – mid-block crossing

This use case considers the application of vehicle-to-network (V2N) communication to improve awareness of vulnerable road users in mid-block crossing scenarios, where pedestrians may come into conflict with approaching vehicles as they attempt to cross the road.

In this context, V2N systems complement onboard sensing and other safety mechanisms by enabling early dissemination of VRU presence information to nearby vehicles. The expected benefit of V2N for VRU protection is supported by a wide coverage of cellular networks, high penetration of consumer smartphones among VRUs, and the increasing availability of cellular connectivity in vehicles.

The primary function of V2N in this use case is to support **VRU presence awareness**, whereby the ego vehicle receives an early indication that a pedestrian is likely to cross the road ahead. Upon receiving such information, the driver is expected to consider reducing vehicle speed to allow the pedestrian to complete the crossing safely. The use case assumes that speed reduction is performed in a controlled and comfortable manner rather than through abrupt braking.

VRU presence information may be generated through a variety of sources, including consumer smartphones, dedicated VRU devices (e.g. bicycles or scooters), wearables, or roadside sensors such as cameras or radar/lidar systems. These sources provide input to the V2N system, which distributes the relevant information to vehicles in the vicinity.

An important aspect of this use case is the timing and reliability of the VRU presence information. Messages must be delivered with sufficient accuracy and timeliness to enable an appropriate driver response, while avoiding excessive or unnecessary alerts in dense urban environments. Discrimination between VRUs actively crossing the roadway and those merely adjacent to it is therefore assumed.

Aspects related to the presentation, formatting, or user interface of VRU awareness messages are outside the scope of this document. This study focuses on the ability of V2N systems to deliver VRU presence information within the required time constraints, taking into account the dynamic relationship between the ego vehicle and the VRU.

A simplified analytical model used to derive the performance requirements for V2N-based VRU presence awareness, along with a discussion of achievable system performance, is provided in Section 5.3.

4.5 High-speed car-to-car rear

This use case addresses high-speed rear-end collision scenarios on highways, aligned with the High-Speed Car-to-Car Rear (CCRH) scenario defined in the 2024 version of C-NCAP. CCRH is one of the scenarios introduced to evaluate the application of C-V2X communication for vehicle safety. In this scenario, the ego vehicle collides with a remote target vehicle at high speed following a sudden cut-out manoeuvre.

In the CCRH test scenario, the remote vehicle, leading vehicle, and ego vehicle travel in the same lane at a constant speed while maintaining a fixed longitudinal separation. The stable condition is established when the distance between the ego vehicle and leading vehicle reaches a predefined value A. Test speeds of 80 km/h and 120 km/h are considered, with corresponding distances A of 50 m and 100 m, respectively. When the distance between the front ends of the leading vehicle and remote vehicle reaches predefined values, the leading vehicle performs a lane-change manoeuvre to an adjacent lane, either to the left or right, until the leading and remote vehicles are aligned. The duration of the lane-change manoeuvre is 2.2 seconds. The complete sequence is illustrated in Figure 4.

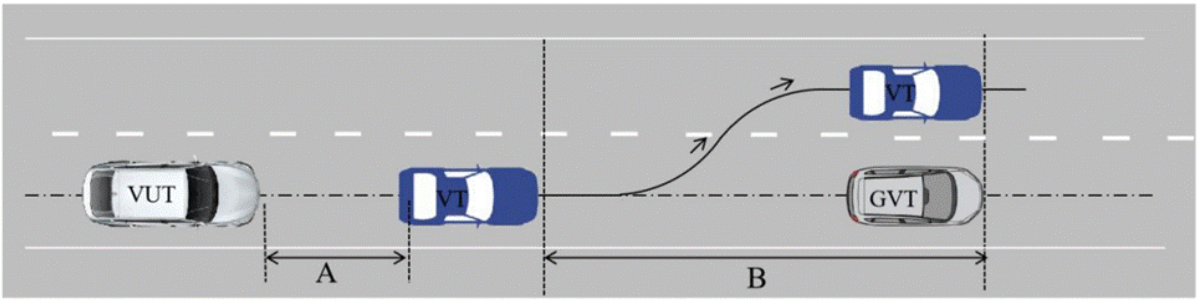


Figure 4 CCRH (High-Speed Car-to-Car Rear) scenario

Note: VUT is ego vehicle, VT is leading vehicle, and GVT is remote vehicle

In the CCRH definition, the deceleration behaviour of the ego vehicle is not explicitly specified. For reference, non-emergency deceleration levels are defined as 4-4.25 m/s^2 in FCW/AEB testing, along with 7 m/s^2 maximum braking conditions for emergency braking in FCW. These reference values are used to contextualise the deceleration assumptions considered in this study.

In this technical report, the CCRH scenario is further analysed using assumptions intended to reflect realistic operating conditions. These include variations in relative vehicle speeds, conservative and aggressive driver reaction times, and both non-emergency and emergency deceleration profiles for the ego vehicle.

Consistent with the intersection movement use case described in Section 5.2, the concept of a risk zone is introduced to define the region in which the ego vehicle and the remote vehicle may collide. The analysis evaluates how timely reception of V2X information can extend the effective perception range of the ego vehicle and increase the available reaction time to avoid or mitigate a rear-end collision.

5 Analysis of use cases

5.1 Soft intersection approach

This section analyses the **soft intersection approach** use case, focusing on the distance and time window in which SPAT information enables a comfortable and user-acceptable deceleration strategy, leading to a full stop at the line before the traffic signal turns red.

The objective is to quantify when SPAT information provides the highest value compared to a sensor-only signal phase detection approach.

5.1.1 Scenario and assumptions

The analysis considers an ego vehicle approaching a signalised intersection at an initial speed close to the maximum authorised urban speed, assumed to be approximately 50-55 km/h (≈ 15 m/s). The traffic signal timing includes a yellow phase of duration 3 s prior to transitioning to red. The ego vehicle is required to come to a complete stop at the stop line when or before the signal turns red.

SPAT information is assumed to be available at distances of up to 200 m from the intersection. For comparison, a sensor-only configuration relying on onboard detection of the signal phase transition is also evaluated.

5.1.2 Sensor-based signal detection

In a sensor-only configuration, the ego vehicle detects the transition from green to yellow when the vehicle is less than 3 s from the stop line, i.e. 45 m, at which the ADAS system should be able to detect the traffic signal change.

On a dry surface with a maximum deceleration of 7 m/s^2, the stopping distance is 16 m whereas it would take up to 40 m on a wet road (4 m/s^2). Even if we would consider a system response delay of approximately 300 ms (~5 m), the effective detection distance increases to roughly 21-45 m. This would give just enough time for the ADAS to respond and apply brakes appropriately to reach a full stop before the traffic light turns red.

However, from a user-centric point of view, the common practice would be to warn the driver prior to engaging any braking manoeuvre so that the driver remains in control of the vehicle motion. The minimum for such a warning is deemed to be 1 s – enough time for the driver to decide to take control before the brakes are engaged. This delicate window of time is often referred to as the 'dilemma zone'.

So, including a driver warning of 1 s, the time budget until full stop is much tighter: the light turns yellow 3 s before (45 m), the detection takes 300 ms (5 m), the warning takes 1 s (15 m), which leads the vehicle to initiate a full-stop manoeuvre over the last 25 m, i.e. a 4.5 m/s^2 deceleration.

Under these conditions, however, deceleration is quite abrupt and leaves limited margin for comfortable speed adaptation. It also runs the risk of undermining driver acceptance of such harsh automated braking manoeuvres, notwithstanding the risk of rear-end collision.

One unknown in this scenario is the exact duration of the yellow phase, which differs from one country to another.

5.1.3 V2X-assisted approach using SPAT infrastructure information

When SPAT information is available, the ego vehicle can initiate deceleration prior to visual confirmation of the signal phase change. Assuming a comfortable constant deceleration of approximately 2 m/s², deceleration must begin approximately 60 m before the stop line. The vehicle would therefore trigger a warning 2 s (75 m) before the signal transitions to yellow and 1 s (60 m) before it would engage in a soft braking manoeuvre.

Under these conditions, deceleration begins at a distance of approximately 60 m from the stop line. As the vehicle decelerates towards the intersection at 2 m/s², onboard sensors can confirm the actual signal phase transition 3 s before the red light and, therefore, confirm the manoeuvre initiating a full stop when the vehicle is travelling at approximately 13 m/s, and is around 42.5 m from the stop line. In this case, confirmation delay is negligible, and the deceleration profile remains smooth at 2 m/s, indicating to the driver that the vehicle will stop with a comfortable deceleration.

An intermediate strategy involving a two-stage deceleration (initial comfortable braking followed by stronger deceleration upon confirmation of yellow) is technically feasible but provides limited benefit at typical urban speeds, and is therefore not considered further.

5.1.4 Discussion

The analysis shows that SPAT information is valuable during the interval when the traffic signal is still green but the remaining distance to the stop line is insufficient to safely clear the intersection without violating the signal. For an initial speed of 50-55 km/h, this critical region lies approximately between 75 m and 45 m from the stop line, corresponding to between 5 s and 3 s before the signal turns red. One could also argue that the full-stop manoeuvre should be triggered even if the vehicle has enough time to reach the line before turning red (during the yellow signal phase); this is also a recognised ‘dilemma zone’ problem.

Prior to this, SPAT information has the advantage that drivers receive preliminary advisory/awareness information and thus have more time to react to or prepare for the automated manoeuvre. Indeed, depending on the driver interaction design, a visual warning can be displayed as early as 90 m before the stop line, followed by an audible one at the 75 m mark, before engaging soft-deceleration mode at 60 m. Any later than this zone, deceleration is more abrupt and primarily sensor-driven by necessity.

This analysis did not include the time for the system to respond to the SPAT information received. However, this timing is irrelevant as we assume the vehicle receives the SPAT at distances up to 200 m before reaching the intersection, i.e. higher than the distances mentioned in the analysis.

It also does not take into account the time the vehicle system takes to detect and respond to the signal phase transition from green to yellow. If the system is only sensor based, this delay time can be as much as 300 ms. However, if SPAT information is received, the system can rely on the predicted timing of the signal to anticipate the switch and detect it quicker.

Uncertainty in the yellow phase duration (assumed here to be 3 s) and system response delays further emphasise the benefit of predictive SPAT information for enabling comfortable and timely speed adaptation.

There is also a challenge with quickly changing phase times in adaptive traffic signal controllers due to a trigger such as a bus or a pedestrian requesting priority or passage.

5.2 Intersection safety

This section provides details for the scenarios for intersection safety for cyclists or vehicles as described in Section 4.3.

5.2.1 Scenario 1: VRU approaching the intersection from left

Consider a vulnerable road user travelling at 25 km/h and an ego vehicle travelling at 60 km/h towards an intersection of width (w) of 20 m, at t0, as shown in the figure above. Assume that hard deceleration corresponds to the VRU slowing down at 3.4 m/s^2 and the ego vehicle slowing down at 4 m/s^2.

We define a collision risk zone as a square of width w' whose centre is the intersection point of the trajectories of the VRU and the ego vehicle. Here, we set $w' = \frac{w}{2} = 10m$.

The risk zone for VRU safety evaluation refers to the quadrant of the intersection where the lanes of the vulnerable road user and the ego vehicle intersect, represented by a purple square. To ensure safety, the ego vehicle must maintain a minimum distance of at least 1 m from this risk zone when the VRU exits it. To avoid a collision, the VRU and the ego vehicle cannot be inside the risk zone at the same time. Further, if the ego vehicle is entering the risk zone at the same time as the VRU is exiting it, then the ego vehicle should enter the risk zone at a reduced speed.

In this setting, if the VRU is less than 7.1 m from the edge of the intersection, it can no longer come to a complete stop without crossing into the intersection. This triggers a risk assessment and a transmission time window for safety events at the ego vehicle. The VRU has a physical length of 2 m, and its GNSS position estimate carries an error radius of approximately 2 m. At the time of approach, the VRU faces a red light or a stop sign. It has a hard deceleration capability of 3.4 m/s^2 and is positioned in the rightmost lane. If the VRU travels at a speed of 25 km/h toward the intersection, at a distance of 7.1 m, it is assumed that its incapable of stopping before the intersection and will run the red light or stop sign, which is the trigger for reaction in the ego vehicle.

The ego vehicle is travelling at a speed of 60 km/h toward the intersection. It has a deceleration capability of 4 m/s^2 and is in the rightmost lane. At the time of approach, the ego vehicle has a green light. Its GNSS position estimate carries an error radius of approximately 2 m. The ego vehicle monitors events ahead that may require slowing down or stopping. At a speed of 60 km/h and a deceleration rate of 4 m/s^2, the braking distance is approximately 36.72 m. Including a driver reaction time of 1 s and a safety action window of 0.66 s (based on the analysis in the following sections), the overall stopping distance is approximately 64 m. Considering a position error of 2 m, the ego vehicle should account for a minimum distance of 66 m. If an upcoming intersection falls within this range, the ego vehicle must remain aware of any activity occurring there. The VRU transmits a safety message every 100 ms, including its positioning, position accuracy, speed, heading, and length. Using this information and an assumed deceleration profile, the ego vehicle determines that it should alert the driver if the VRU's position indicates it is 7.1 m from the intersection and is going at the speed of 25 km/h.

In the following analysis, we derive the action window requirements and quantify the success rate of using V2X messages to avoid the imminent safety event. We start with the case when there is no GNSS error in the reported VRU position, followed by the analysis when GNSS error of $\pm 2m$ is present in the reported VRU position.

5.2.1.1 Action window (for safety) analysis (no GNSS errors)

Time instances for the VRU

- At time = 0 s, the VRU is at its initial position, i.e. 7.1 m to the intersection.
- At time = 2.46 s, the VRU has travelled 17.1 m and is entering the risk zone.
- At time = 4.19 s, the VRU has travelled 29.1 m and is exiting the risk zone.

Note: the distance 29.1 m includes VRU length of 2 m.

Safety conditions for ego vehicle

- The ego vehicle must not enter the risk zone while the VRU is still inside it.
- The ego vehicle ensures a minimum distance of at least 1 m from this risk zone when the VRU exits the risk zone.
- The ego vehicle must enter the risk zone at a reduced speed as the VRU is exiting the risk zone; missing the VRU at high speed is considered unsafe, and the targeted reduced speed is set to 25 km/h in this scenario to match the speed of the VRU.

Braking and reaction parameters

- To reduce speed from 60 km/h to 25 km/h with a deceleration of 4 m/s², the Ego vehicle requires 2.43 s and 28.69 m of braking distance.
- End-to-end transmission plus driver reaction adds 1.1 s and 18.33 m.

Start of action window (for safety)

- Start of the action window is when the ego vehicle and the VRU are 59 m and 7.1 m away from the intersection, respectively (t = 0 s).
  - The ego vehicle will enter the risk zone when the VRU is still inside it, if no action is taken.
- If the ego vehicle receives the first V2X message from the VRU after starting the action window:
  - When the VRU is exiting the risk zone (i.e. at 4.19 s), the ego vehicle is 7.4 m away from the intersection and has already reduced its speed to 25 km/h.

Note that ego would have travelled: 18.33 m (transmission and reaction) + 28.69 (braking) + 4.58 m (cruising at 25 km/h for 0.66 s) = 51.6 m. Thus, distance from intersection is 59-51.6 = 7.4 m.

  - The ego vehicle will reach to 1m from the risk zone at a speed of 25 km/h in 4.45 s, by which time the VRU has already exited the risk zone.

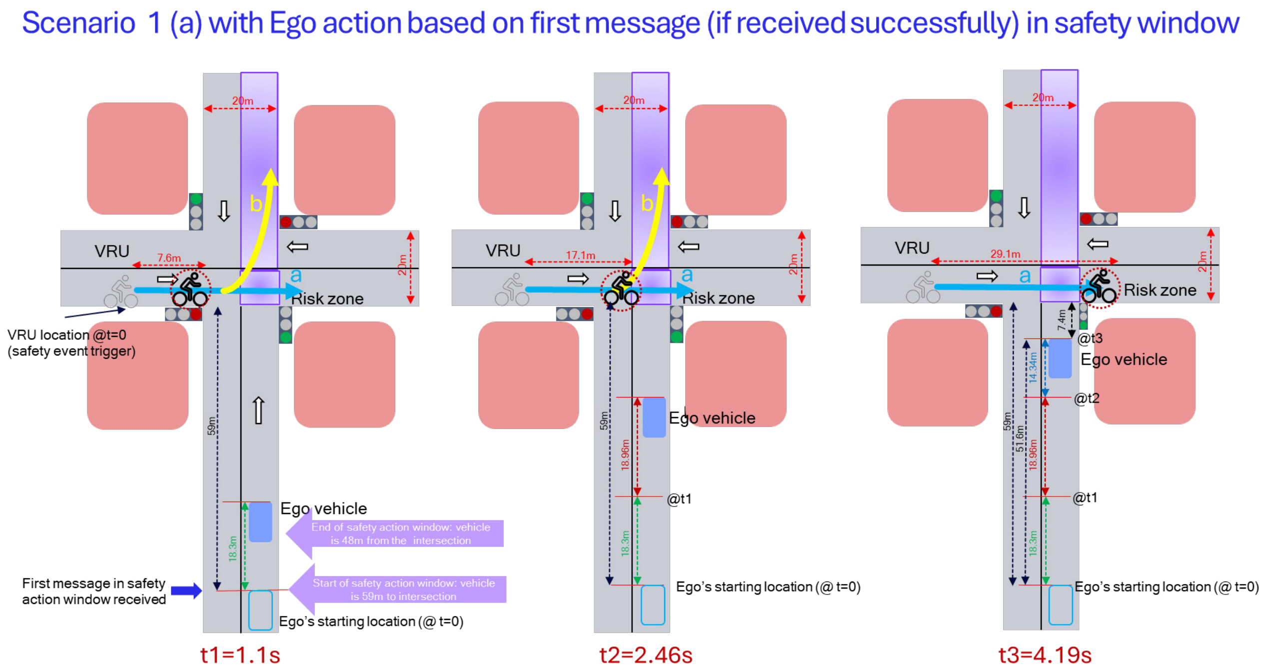
Note the timeline: 0.1 s (transmission) + 1 s (reaction) + 2.43 s (deceleration) + 0.92 s (assuming cruise at 25 km/h up to intersection) = 4.45 s.

End of action window (for safety)

- The last V2X transmission opportunity occurs when the ego vehicle is 48 m from the risk zone (18.33 m during reaction and transmission time + 28.69 m braking distance + 1 m distance margin).
- Thus, the action window duration is the time needed for the Ego vehicle to cover the distance of 11 m (=59-48) at the speed of 60 km/h. This yields an action window duration of 0.66 s.
- Thus, if V2X is successful at the end of the window, the Ego vehicle would be 1 m from the risk zone at 25 km/h, with the following timeline:
  - 0.66 s (window) + 0.1 s (transmission) + 1 s (reaction) + 2.43 s (deceleration) = 4.19 s, by which time the violator is just exiting the risk zone.

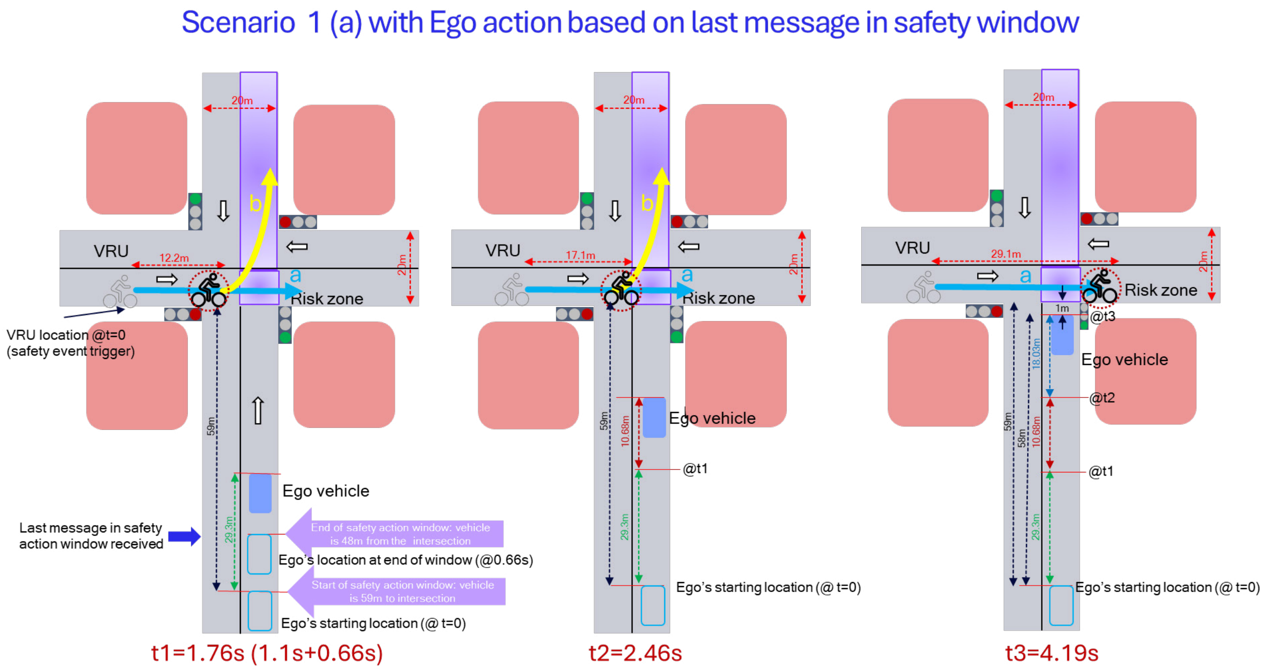
Figure 5 and Figure 6 illustrate the relative location of the VRU and ego vehicle over three time instances when the vehicle can still take action based on the first V2X message (if successful) or the last V2X message within the safety action window, respectively. The first instant (t1) is when the ego starts to decelerate (including 1 s of driver reaction time and 0.1 s of transmission latency). The second time instant (t2) is when the VRU is entering the risk zone, and the third time instant (t3) is when the VRU is exiting the risk zone.

Note that the ego's response and the safety action window for scenario 1b (where the VRU takes a left turn after entering the risk zone) is identical to scenario 1a. Hence, for brevity, we have not included illustrative figures for scenario 1b as the ego's location will remain the same, with the only difference from scenario 1a being that the VRU would have taken a left turn at time t3.



Scenario 1 (a) with Ego action based on first message (if received successfully) in safety window

Figure 5 Scenario 1a showing the ego vehicle and VRU locations over time when the ego acts based on the first message (if received successfully) within the safety action window



Scenario 1 (a) with Ego action based on last message in safety window

Figure 6 Scenario 1a showing the ego vehicle and VRU locations over time when the ego acts based on the last message received within the safety action window

5.2.1.2 Impact of GNSS error in VRU's reported location on action window (for safety)

The analysis so far assumed that the reported location by the VRU matches the 'ground truth' location of the VRU, and the trigger for safety action is when the VRU reports its location to be 7.1 m from the intersection and travelling at 25 km/h. In this section, we consider when an error of $\pm 2m$ is present in the reported VRU location.

GNSS error of -2 m in reported VRU location:

- VRU reported position = 7.1 m, while ground truth position = 5.1 m from the intersection.
- Ego ground truth position (when VRU ground truth position is 5.1 m) is 54.2 m.
- End of action window (for safety)
  - The last V2X transmission opportunity occurs when the ego vehicle is 48 m from the risk zone (18.33 m during reaction and transmission time + 28.69 m braking distance + 1m distance margin).
  - Thus, the action window duration is shortened compared to the case of 0 m GNSS error. The action window is now the time needed for the ego to cover the distance of 6.2 m (54.2-48) at the speed of 60 km/h. This yields an action window duration of 0.37 s.

GNSS error of +2m in reported VRU location:

- VRU reported position = 7.1 m, while ground truth position = 9.1 m from the intersection.
- Ego ground truth position (when VRU ground truth position is 9.1 m) is 63.8 m.
- End of action window (for safety)
  - The last V2X transmission opportunity occurs when the Ego vehicle is 48 m from the risk zone (18.33 m during reaction and transmission time + 28.69 m braking distance + 1 m distance margin).
  - Thus, the action window duration is elongated compared to the case of 0 m GNSS error. The action window is now the time needed for the ego to cover the distance of 15.8 m (63.8-48) at the speed of 60 km/h. This yields an action window duration of 0.95 s.

The following table shows the impact of GNSS error in VRU reported location on the size of the action window (for safety). In the next subsection, we take these action window sizes and quantify the reliability of reception of the V2X message within the safety window for ego to avoid the imminent accident.

GNSS error in VRU reported location	Action window (size in seconds)
-2 m	0.37 s
0 m	0.66 s
+2 m	0.95 s

Table 4 Impact of GNSS error in VRU reported location on the size of the action window (for safety)

5.2.1.3 Reliability in V2X message reception within the action window (for safety)

In this section, we evaluate the reliability in receiving the V2X messages within the action window (as derived in the previous subsection) to enable the ego to receive the message in a timely manner (before the end of the action window) and avoid the imminent accident.

The evaluation is based on LTE-V2X technology in the urban grid scenario specified in 3GPP for V2X simulations [6], focusing specifically on non-line-of-sight (NLOS) propagation conditions. The reliability analysis is based on system-level simulation for three traffic-density levels, defined as low (118 vehicles), medium (1,180 vehicles), and high (2,360 vehicles). The generated vehicular traffic is periodic, consisting of a repeating sequence in which one 300-byte message is followed by four 190-byte messages, as described in [6].

Towards evaluating the reliability of successful reception of at least one V2X message in the action window, Table 5 tabulates the ego-VRU distances and the corresponding packet reception ratio (PRR) at the V2X message opportunities within the action window, from the system-level simulations. Note that the three cases of VRU GNSS errors (-2 m, 0 m, 2 m) result in different action window sizes.

VRU GNSS error	Action window (for safety) [from Table 4]	V2X message opportunities within the action window	Ego-intersection, VRU-intersection, and ego-VRU distances (in m) at the message reception opportunities V2X packet reception ratio (PRR) at the respective ego-VRU distance for low, medium, and high vehicular densities	
-2 m	0.37 s	3	VRU-intersection	[5.1, 4.4, 3.7] m
			Ego-Intersection	[54.2, 52.5, 50.8] m
			Ego-VRU	[62.5, 60.7, 58.9] m
			PRR (low)	[0.998 0.998 0.998]
			PRR (medium)	[0.975 0.980 0.983]
			PRR (high)	[0.947 0.953 0.958]
0 m	0.66 s	6	VRU-Intersection	[7.1, 6.4, 5.7, 5.01, 4.3, 3.6]m
			Ego-Intersection	[59, 57.3, 55.6, 54, 52.3, 50.6]m
			Ego-VRU	[67.7, 65.9, 64.1, 62.3, 60.5, 58.7]m
			PRR (low)	[0.998 0.998 0.998 0.998 0.998 0.998]
			PRR (medium)	[0.962 0.967 0.972 0.977 0.981 0.983]
			PRR (high)	[0.928 0.934 0.941 0.948 0.953 0.958]

2 m	0.95 s	9	VRU-Intersection	[9.1, 8.4, 7.7, 7.0, 6.3, 5.6, 4.9, 4.2, 3.5]m
			Ego-Intersection	[63.8, 62.1, 60.4, 58.8, 57.1, 55.4, 53.8, 52.1, 50.4]m
			Ego-VRU	[72.8, 71.1, 69.2, 67.4, 65.6, 63.8, 62.0, 60.2, 58.4]m
			PRR (low)	[0.997 0.997 0.997 0.997 0.998 0.998 0.998 0.998 0.998]
			PRR (medium)	[0.947 0.952 0.957 0.962 0.968 0.972 0.977 0.981 0.984]
			PRR (high)	[0.908 0.914 0.922 0.929 0.936 0.942 0.947 0.955 0.959]

Table 5 Ego and VRU locations at the V2X message opportunities for varying VRU GNSS errors in the reported location

Based on Table 5, the probability of successfully receiving at least one of the V2X messages in the action window based on which the ego can act and avoid the imminent accident is calculated in Table 6 using the formula $P_{Success} = 1 - \prod_{i=1}^{N}(1 - PRR(i))$ where *N* is the number of V2x messages.

VRU GNSS error	Action window (for safety) [from Table 4]	V2X message opportunities within the action window	**V2X message reception reliability withing action window** (evaluated for low, medium, high vehicular traffic densities)		
			Low	Medium	High
-2 m	0.37 s	3	$1-10^{-8}$	$1-10^{-5}$	$1-10^{-4}$
0 m	0.66 s	6	$1-10^{-16}$	$1-10^{-9}$	$1-10^{-7}$
2 m	0.95 s	9	$1-10^{-23}$	$1-10^{-13}$	$1-10^{-10}$

Table 6 Ego and VRU locations at the V2X message opportunities for varying VRU GNSS errors in the reported location

From Table 6, note that the worst-case reception reliability within the action window is$1-10^{-4}$ (high vehicle density and reduced action window due to negative GNSS error). Hence, it is concluded that for Scenario 1, V2X message can alert the ego vehicle/ driver in a timely manner (with the action window needed based on kinematics of VRU and ego vehicle) to avoid an imminent accident between as the VRU and ego are approaching the intersection.

5.2.2 Scenario 2: Violator vehicle approaching the intersection from the left

In this scenario, the violator vehicle approaches the intersection at a speed of 60 km/h. It is in the rightmost lane, faces a red light, has a length of 5 m, and its GNSS position estimate carries an error radius of approximately 2 m. In this setting, with a hard deceleration capability of 4 m/s², if the violator vehicle is less than 34.7 m from the edge of the intersection, it can no longer come to a complete stop without crossing into the intersection. This triggers a risk assessment and a transmission time window for safety events at the ego vehicle.

Similar to Scenario 1, we define a collision risk zone as a square of width w' whose centre is the intersection point of the trajectories of the violator vehicle and the ego vehicle. Here, we set $w' = \frac{w}{2} = 10m$. The risk zone for vehicle safety evaluation refers to the quadrant of the intersection where the lanes of the violator vehicle and the ego vehicle intersect, represented by a purple square. To ensure safety, the ego vehicle must maintain a minimum distance of at least one metre from this risk zone when the violator vehicle exits it. To avoid a collision, the violator vehicle and the ego vehicle cannot be inside the risk zone at the same time. Further, if the ego vehicle is entering the risk zone at the same time as the violator vehicle is exiting the risk zone, then the ego vehicle should enter the risk zone at a reduced speed.

The ego vehicle is travelling at a speed of 60 km/h toward the intersection. It has a hard deceleration capability of 4 m/s² and is in the rightmost lane. At the time of approach, the ego vehicle has a green light. Its GNSS position estimate carries an error radius of approximately 2 m. The ego vehicle monitors events ahead that may require slowing down or stopping. At a speed of 60 km/h and a deceleration rate of 4 m/s², the braking distance is approximately 36.72 m. Including a driver reaction time of 1 s and a safety action window of 0.74 s (based on the analysis in the following sections), the overall stopping distance is approximately 64 m. Considering a position error of 2 m, the ego vehicle should account for a minimum distance of 66 m. If an upcoming intersection falls within this range, the ego vehicle must remain aware of any activity occurring there. The violator vehicle transmits a safety message every 100 ms, including its position, position accuracy, speed, heading, and length. Using this information and an assumed deceleration profile, the ego vehicle determines that it should alert the driver if the violator vehicle position indicates it is 34.7 m from the intersection and is going at the speed of 60 km/h.

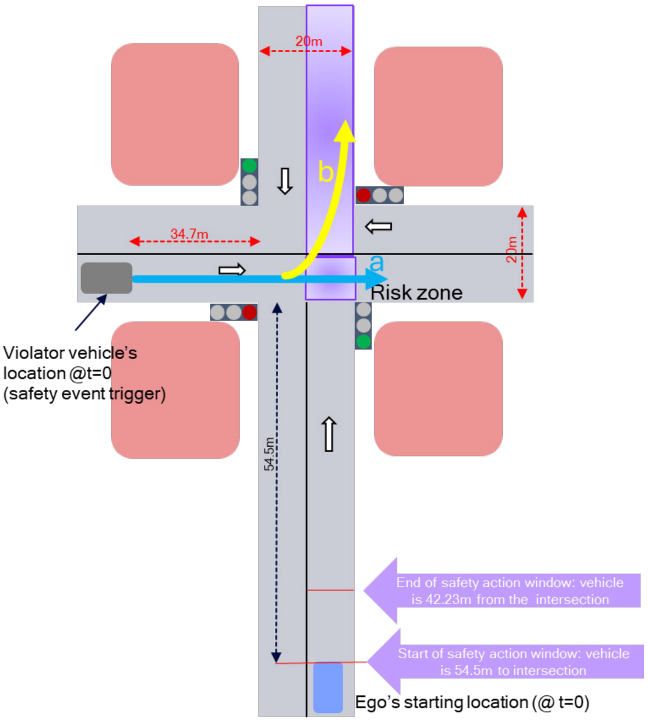


Figure 7 Initial locations for Scenario 2 where violator vehicle approaches intersection from left

In the following analysis, we derive the action window requirements and quantify the success rate of using V2X messages to avoid the imminent safety event. We start with the case when there is no GNSS error in the reported violator vehicle position, followed by the analysis when GNSS error of $\pm 2m$ is present in the reported violator vehicle position.

5.2.2.1 Action window (for safety) analysis (no GNSS errors)

Time instances for the violator vehicle

- At time = 0 s, the violator is at its initial position, i.e. 34.7 m to the intersection.
- At time = 2.68 s, the violator has travelled 44.7 m and is entering the risk zone.
- At time = 3.58 s, the violator has travelled 59.7 m and is exiting the risk zone.

Note: the distance 59.7 m includes vehicle length of 5 m.

Safety conditions for ego vehicle

- The ego vehicle must not enter the risk zone while the violator vehicle is still inside it.
- The ego vehicle ensures a minimum distance of at 1 m from this risk zone when the violator vehicle exits the risk zone.
- The ego vehicle must enter the risk zone at a reduced speed as the violator vehicle is exiting the risk zone. Missing the violator vehicle at high speed is considered unsafe. The target reduced speed is set to 35 km/h in this scenario.

Braking and reaction parameters

- To reduce speed from 60 km/h to 35 km/h with a deceleration of 4 m/s^2, the ego vehicle requires 1.74 s and 22.9 m of braking time and distance, respectively.
- End-to-end transmission plus driver reaction adds 1.1 s and 18.33 m.

Start of action window (for safety)

- Start of the action window is when the ego vehicle and the violator vehicle are 54.5 m and 34.7 m away from the intersection, respectively (t = 0 s).

Note that if no action is taken, then the ego vehicle will enter the risk zone when the violator vehicle is still inside it creating a safety critical event.

- If the ego vehicle receives the first V2X message from the violator after the start of the action window:
  - When the violator vehicle is exiting the risk zone (i.e. at 3.58 s), the ego vehicle is 7.4 m away from the intersection and has already reduced its speed to 35 km/h.

Note that ego would have travelled: 18.33 m (transmission and reaction) + 22.9 m (braking) + 7.19 m (cruising at 35 km/h for 0.74 s) **=** 48.42 m. Thus, distance from intersection is 54.5-48.42 = 6.08 m

End of action window (for safety)

- The last V2X transmission opportunity occurs when the ego vehicle is 42.23 m from the risk zone (18.33 m during reaction and transmission time + 22.9 m braking distance + 1m distance margin).
- Thus, the action window duration is time needed for the ego vehicle to cover the distance of 12.27 m (=54.5-42.23) at the speed of 60 km/h. This yields an action window duration of 0.74 s.
- Thus, if the V2X message is successfully received at the end of the window, the ego vehicle reaches within 1m of the risk zone at 35 km/h, with the following timeline:
    - 0.74 s (window) + 0.1 s (transmission) + 1 s (reaction) + 1.74 s (deceleration) = 3.58 s, by which time the violator is just exiting the risk zone.

Figure 8 and Figure 9 illustrate the relative location of the violator and ego vehicle over three time instances for the case of action being taken by the ego based on the first V2X message (if successful) or the last V2X message within the safety action window, respectively. The first instant (t1) is when the ego starts to decelerate (including 1 s of driver reaction time and 0.1 s of transmission latency). The second time instant (t2) is when the violator vehicle is entering the risk zone, and the third time instant (t3) is when the violator vehicle is exiting the risk zone.

Note that the ego's response and safety action window for scenario 2b (where the violator takes a left turn after entering the risk zone) is identical to scenario 2a. Hence, for brevity, we have not included illustrative figures for scenario 2b as the ego's location will remain the same, and the only difference from scenario 2a being that the violator vehicle would have taken a left turn at time t3.

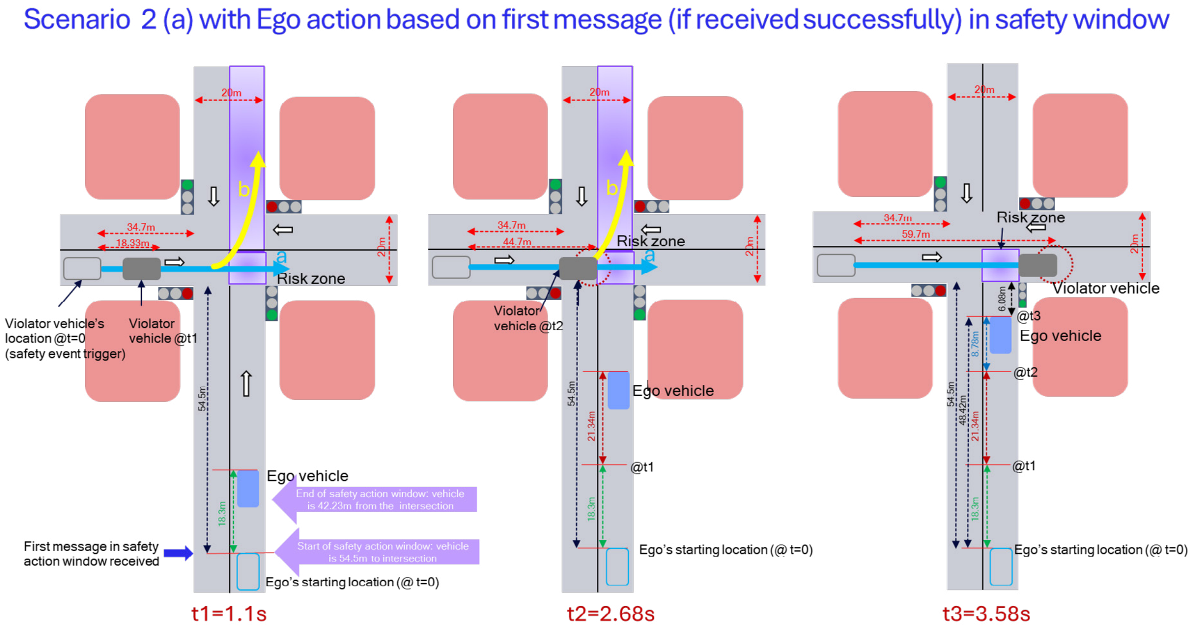


Figure 8 Scenario 2a showing the ego and violator vehicle locations over time when the ego acts based on the first message (if received successfully) within the safety action window

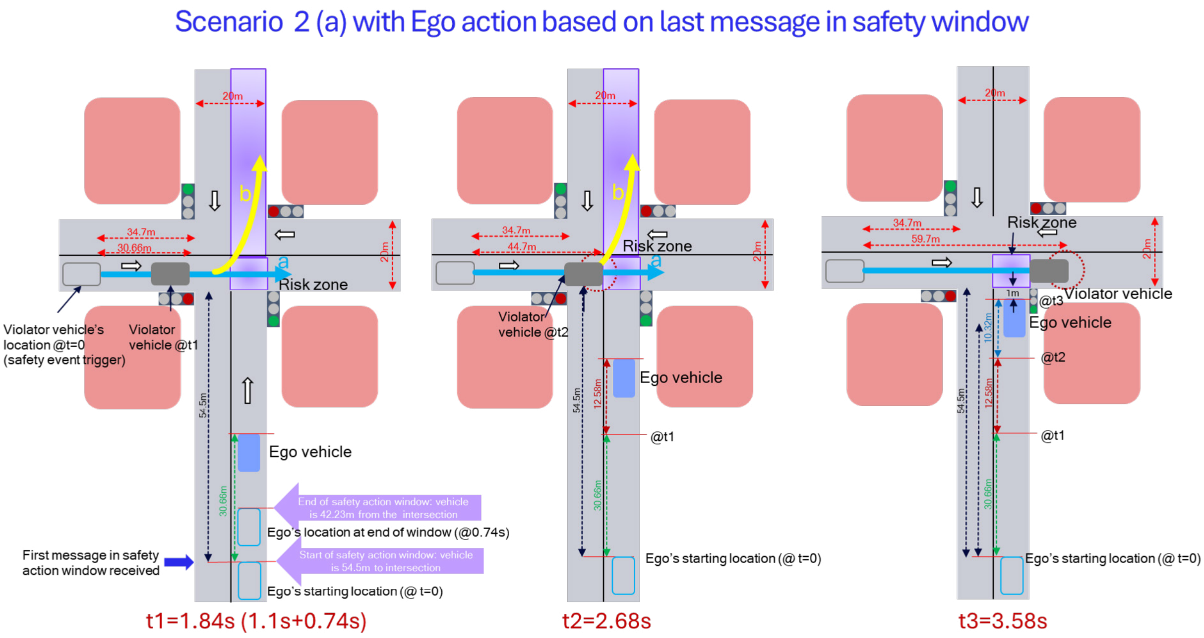


Figure 9 Scenario 2a showing the ego and violator vehicle locations over time when the ego acts based on the last message received within the safety action window

5.2.2.2 Impact of GNSS error in violator vehicle's reported location on action window (for safety)

The analysis so far assumed that the reported location by the violator vehicle matches the 'ground truth' location of the violator vehicle, and the trigger for safety action is when the violator vehicle reports its location to be 34.7 m from the intersection and travelling at 60 km/h. In this section, we consider when there is error of $\pm 2m$ is present in the reported violator vehicle's location.

GNSS error of -2 m in reported violator vehicle's location

- Violator vehicle's reported position = 34.7 m, while ground truth position = 32.7 m from the intersection.
- Ego ground truth position (when violator vehicle ground truth position is 32.7 m) is 52.5 m.
- End of action window (for safety)
  - The last V2X transmission opportunity occurs when the ego vehicle is 42.23 m from the risk zone (18.33 m during reaction and transmission time + 22.9 m braking distance + 1 m distance margin).
  - Thus, the action window is shortened compared to the case of 0 m GNSS error. The action window is now the time needed for the ego to cover the distance of 10.27 m (52.5-42.23) at the speed of 60 km/h. This yields an action window duration of 0.62s.

GNSS error of +2m in reported violator vehicle's location

- Violator vehicle's reported position = 34.7 m, while ground truth position =

36.7 m from the intersection.

- Ego ground truth position (when violator vehicle ground truth position is 36.7 m) is 56.5 m.
- End of action window (for safety)
  - The last V2X transmission opportunity occurs when the ego vehicle is 42.23 m from the risk zone (18.33 m during reaction and transmission time + 22.9 m braking distance + 1m distance margin).
  - Thus, the action window duration is elongated compared to the 0 m GNSS error case. The action window is now the time needed for the ego to cover the distance of 14.27 m (56.5-42.23) at the speed of 60 km/h. This yields an action window duration of 0.86 s.

The following table shows the impact of GNSS error in violator vehicle's reported location on the size of the action window (for safety). In the next subsection, we take these action window sizes and quantify the reliability of V2X message reception within the ego's safety window to avoid an imminent accident.

GNSS error in violator vehicle's reported location	Action window (size in seconds)
-2 m	0.61 s
0 m	0.74 s
+2 m	0.85 s

Table 7 Impact of GNSS error in violator vehicle's reported location on the size of the action window (for safety)

5.2.2.3 Reliability in V2X message reception within the action window (for safety)

In this section, we evaluate the reliability of receiving the V2X messages within the action window (as derived in the previous subsection) to enable the ego to receive the message in a timely manner (before the end of the action window) and avoid an imminent accident.

The evaluation is based on LTE-V2X technology in an urban grid scenario specified in 3GPP for V2X simulations [6], focusing specifically on NLOS propagation conditions. Again, the reliability analysis is based on system-level simulation for three traffic-density levels, defined as low (118 vehicles), medium (1,180 vehicles), and high (2,360 vehicles). The generated vehicular traffic is periodic, consisting of a repeating sequence in which one 300-byte message is followed by four 190-byte messages, as described in [6].

Towards evaluating the reliability of successful reception of at least one V2X message in the action window, Table 8 tabulates the ego-violator distances and the corresponding PRR of the V2X message opportunities within the action window, from the system-level simulations. Note that the three cases of violator GNSS errors (-2 m, 0 m, 2 m) result in different action window sizes.

Violator vehicle GNSS Error	Action window (for safety) [from Table 4]	V2X message opportunities within the action window	Ego-intersection, violator -intersection, and ego-violator distances (in m) at the message reception opportunities V2X PRR at the respective ego-violator distance for low, medium, and high vehicular densities	
-2 m	0.61 s	6	Violator -Intersection	[32.7, 31.0, 29.4, 27.7, 26.0, 24.4] m
			Ego-Intersection	[52.5, 50.8, 49.2, 47.5, 45.8, 44.2] m
			Ego- Violator	[74.7, 72.4, 70.0, 67.7, 65.3, 63.0] m
			PRR (low)	[0.9977, 0.9979, 0.9979, 0.9979, 0.9980, 0.9980]
			PRR (medium)	[0.9408, 0.9549, 0.9549, 0.9549, 0.9698, 0.9698]
			PRR (high)	[0.8990, 0.9192, 0.9192, 0.9192, 0.9382, 0.9382]
0 m	0.74 s	7	Violator-Intersection	[34.7, 33.0, 31.4, 29.7, 28.0, 26.4, 24.7]m
			Ego-Intersection	[54.5, 52.8, 51.2, 49.5, 47.8, 46.2, 44.5]m
			Ego-Violator	[77.5, 75.1, 72.9, 70.5, 68.1, 65.8, 63.5]m
			PRR (low)	[0.9981, 0.9977, 0.9977, 0.9979, 0.9979, 0.9980, 0.9980]
			PRR (medium)	[0.9293, 0.9408, 0.9408, 0.9549, 0.9549, 0.9698, 0.9698]
			PRR (high)	[0.8801, 0.8990, 0.8990, 0.9192, 0.9192, 0.9382, 0.9382]
2 m	0.85 s	8	Violator-Intersection	[36.7, 35.0, 33.4, 31.7, 30.0, 28.4, 26.7, 25.0]m
			Ego-Intersection	[56.5, 54.8, 53.2, 51.5, 49.8, 48.2, 46.5, 44.8, 43.2]m
			Ego-Violator	[80.3, 78.0, 75.6, 73.3, 71.0, 68.6, 66.3, 63.9, 61.6]m
			PRR (low)	[0.9981, 0.9981, 0.9977, 0.9977, 0.9979, 0.9979, 0.9980, 0.9980]
			PRR (medium)	[0.9293, 0.9293, 0.9408, 0.9408, 0.9549, 0.9549, 0.9698, 0.9698]
			PRR (high)	[0.8801, 0.8801, 0.8990, 0.8990, 0.9192, 0.9192, 0.9382, 0.9382]

Table 8 Ego and violator locations at the V2X message opportunities for varying violator GNSS errors in the reported location

Based on the above table, the probability of successfully receiving at least one of the V2X messages in the action window, based on which the ego can act and avoid the imminent accident, is calculated in Table 9 using the following formula $P_{Success} = 1 - \prod_{i=1}^{N}\left(1 - PRR(i)\right)$ where N is the number of V2x messages.

Violator GNSS Error	Action window (for Safety) [from Table 4]	V2X message opportunities within the action window	**V2X message reception reliability withing action window** (evaluated for low, medium, high vehicular traffic densities)		
			Low	Medium	High
-2 m	0.61 s	6	$1-10^{-17}$	$1-10^{-9}$	$1-10^{-7}$
0 m	0.74 s	7	$1-10^{-19}$	$1-10^{-10}$	$1-10^{-8}$
2 m	0.85 s	8	$1-10^{-22}$	$1-10^{-11}$	$1-10^{-9}$

Table 9 Ego and violator locations at the V2X message opportunities for varying violator GNSS errors in the reported location

Note that the worst-case reception reliability within the action window is $1-10^{-7}$ (high vehicle density and reduced action window due to negative GNSS error). Hence, it is concluded that for Scenario 2, a V2X message can alert the ego vehicle/driver in a timely manner (with the action window needed based on the kinematics of the violator and ego vehicle) to avoid an imminent accident as the violator and ego approach the intersection.

5.3 VRU presence awareness – mid-block crossing

5.3.1 Presence awareness using V2N

This section models a scenario in which a driver is alerted to the presence of a pedestrian crossing the road ahead and implements a strategy to enable the VRU to safely cross the road/lane, outlined below, to avoid any potential collision.

The driver is in a typical private car moving at the maximum legal speed in an urban scenario. They receive a VRU presence awareness notification. The driver reduces the vehicle speed such that the pedestrian will have fully and safely crossed the road/lane by the time it reaches the crossing point. A gradual reduction of vehicle speed is intended to avoid causing disruption to any vehicles travelling behind (i.e. heavy braking and potential rear-ending). In the scenario considered here the pedestrian fully crosses the road/lane at a steady speed without stopping. If the pedestrian stops on the road, another use case such as 'emergency collision avoidance' applies, but that scenario is out of scope.

The model uses performance data from measured public mobile networks to estimate the time taken to deliver a VRU presence awareness message over V2N systems. Two possible 'driver reaction' times – quick and delayed – are used to determine how far the vehicle progresses between the time that the message is delivered and the point at which the decision to decelerate is made by the driver. The system cannot know if the driver's reaction will be quick or delayed, the implication of these values will be discussed later in this section. Furthermore, compensation for the positional error due to the VRU's GNSS-enabled device is introduced.

The objective of the model is to determine the distance between the vehicle and pedestrian crossing line/zone at which a VRU presence awareness message should be delivered for the driver to comfortably adapt the vehicle speed and safely navigate the crossing point after the pedestrian has passed. The issue that is then addressed is whether mobile networks are considered 'appropriate' to support VRU presence awareness in this context. The following section outlines the assumptions and model to address this.

5.3.2 Assumptions

- The pedestrian walks perpendicularly across the road/lane, with respect to the vehicle's approach.
- Pedestrian speed = 5 kph (1.4 m/s) (average human walking speed).
- The road/crossing point is 4 m wide (single lane).

Note: The aim of the use case is for the VRU to clear the single lane in which the vehicle is driving; if the road has multiple lanes, it is for other drivers/vehicles to ensure that the VRU safely crosses 'their' lane.

- Car initial speed: 50 km/h (31 mph) = 13.89 m/s. This is considered to be the approximate maximum legal speed for vehicles in urban areas, where much of VRU interaction happens.
- Maximum comfortable vehicle deceleration: -0.3 g = -2.94 m/s². This is the deceleration rate that we assume the driver would apply in a controlled (rather than emergency) scenario.

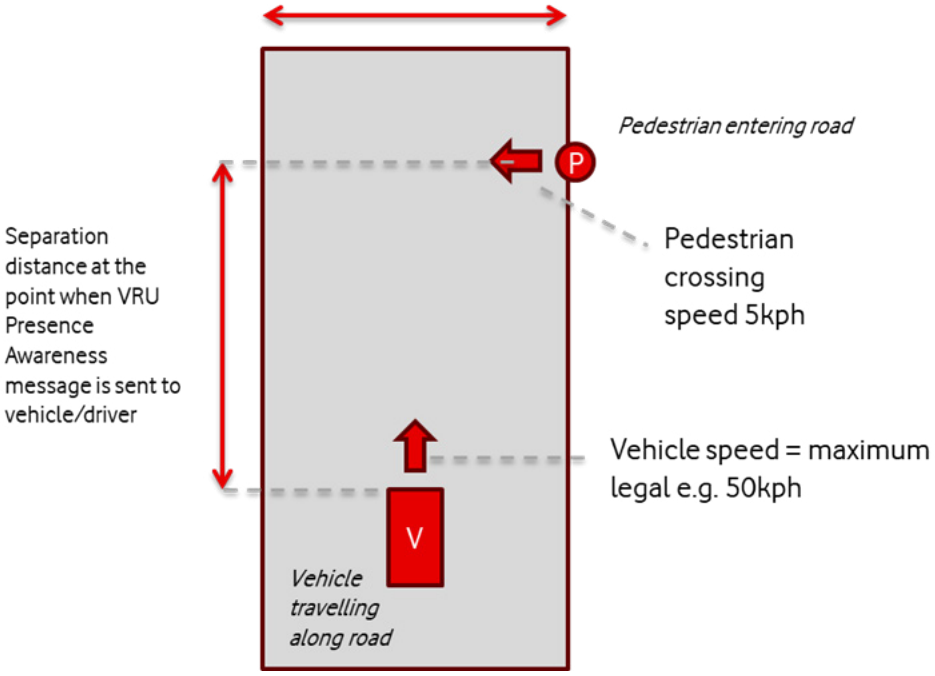


Figure 10 VRU presence awareness scenario description

With the above-listed assumptions, the pedestrian will take 2.86 s to cross the lane in which the vehicle is driving (see Appendix for calculations). To avoid a collision, the front of the approaching car must not reach the crossing line before 2.86 s, so the car must decelerate such that it takes at least 2.86 s to reach that point.

A vehicle decelerating at a constant comfortable rate (-0.3 g) for 2.86 s results in a speed after deceleration of 5.49 m/s (21.2 kph/13.2 mph). The distance covered during the deceleration period is a product of the average speed and the duration which is 27.7 m (see Appendix for calculation). The driver must therefore start to decelerate at a distance of 27.7 m before the crossing, at the latest, to avoid heavy emergency braking. If the car begins to decelerate at a distance greater than this then it could decelerate at a lower, more comfortable rate.

The model must include the time taken (latency) for the VRU presence awareness message to arrive and to be presented to the driver, plus the driver's reaction time. This will add a further distance travelled by the vehicle at the original velocity (50 kph), before deceleration begins. In this case we assume:

- A conservative end-to-end data communication latency and application processing latency = 300 ms.
- Two possible reaction times by the driver
    - 1 s (quick driver reaction)
    - 2.5 s (delayed driver reaction)

In this case, the additional distance travelled by the vehicle during message transmission and reaction time is.

- 1.3 s * 13.89 m/s = 18.1 m
- 2.8 s * 13.89 m/s = 38.9 m

Therefore, the minimum total distance between the vehicle and the VRU's crossing point for which a VRU alert message must be sent in time for the driver to receive it, make the decision to slow down, and then decelerate at the maximum comfortable rate is:

- 27.7 m + 18.1 m = 45.8 m (quick driver reaction)
- 27.72 m + 38.9 m = 66.6 m (delayed driver reaction)

5.3.3 Allowing for GNSS inaccuracy

The VRU presence awareness system's perception of the vulnerable road user's position depends on the accuracy of the GNSS involved. VRU position could be determined by a roadside sensor (e.g. camera, radar or lidar), with relatively high accuracy. However, where the road is not served by a roadside sensor, the role falls to a consumer smartphone or dedicated VRU wearable device. These devices currently have inaccuracies at metre-level in two dimensions. We assume that the GNSS and supporting positioning solutions in the vehicle are relatively accurate and do not significantly affect the analysis.

In the model, the inaccuracy of the GNSS suggests a false position of the VRU at a point within a circle of maximum radius around the VRU's true position. In the diagram below we show an example where the reported position is in the top-left quadrant at the maximum error point. This is the worst-case error for the VRU presence awareness scenario because, firstly, the VRU will be closer to the vehicle than the system believes, thus the vehicle would pass through the crossing point earlier. Secondly, the VRU will need to travel additional distance before beginning to cross the lane, thus taking longer to get to the safe side, so the VRU will still be in the vehicle's path when it reaches the expected crossing point.

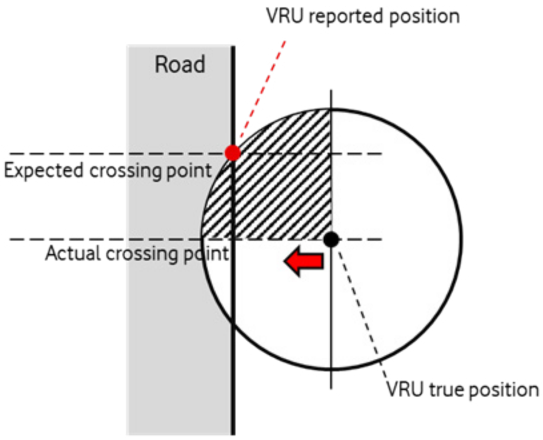


Figure 11 VRU GNSS accuracy

In such a case the receiving system cannot know the true position of the VRU so has to make allowances by changing the distance between the VRU and vehicles targeted by a message alerting the driver to compensate.

If the maximum GNSS error radius is 2 m then the vertical and horizontal errors are both 1.4 m. Because of the 'vertical' error (in the above diagram) the distance between the vehicle and the expected crossing point should be increased to:

- 45.8 m + 1.4 m = 47.2 m (quick driver reaction)
- 66.6 m + 1.4 m = 68.0 m (delayed driver reaction)

Because of the horizontal error, the VRU must first walk 1.4 m to reach the road before beginning to cross. At 5 kph, this takes approximately 1 s, so ideally the vehicle will arrive at the expected crossing line 1 s later than in the previous calculation, after taking this into account.

At 50 kph, the vehicle will travel 13.9 m in 1 s, so the vehicle should be 13.9 m further from the expected crossing point when the message is delivered to the driver:

- 47.2 m + 13.9 m = 61.1 m (quick driver reaction)
- 68.0 m + 13.9 m = 81.9 m (delayed driver reaction)

5.3.4 Discussion

The above example suggests that a VRU presence awareness system, combining real-time VRU and vehicle positions and velocity, should send an alert message to the driver to be presented at a minimum separation distance of 81.9 m, to allow the driver to comfortably decelerate, thus enabling a pedestrian to safely cross a 4 m road/lane. Delayed driver reaction time and VRU positional inaccuracy is accounted for in the result.

The end-to-end network latency used in the model (300 ms) is conservative and does not greatly impact the result, which is mostly determined by the limitations assumed in the scenario (maximum deceleration rate and driver reaction time).

The total time taken for the above ‘ideal, worst-case’ scenario to play out, between alert generation and a vehicle reaching the crossing point (while travelling at a reduced speed of 5.5 m/s) is approximately 6.7 s.

Under the ‘best case’ scenario – where the message is delivered with lower latency and the driver has a faster reaction time or prefers to decelerate more aggressively, and the VRU position estimation is accurate – the VRU will clearly still safely negotiate the crossing in good time.

One question to be considered is whether the delivery of the VRU presence awareness alert at 81.9 m/6.7 s separation might be considered by the driver to be too early, such that it is superfluous or irritating information. Clearly, in the best-case scenario the VRU could have crossed the road/lane well before the vehicle has reached the crossing point (6.7 s – 2.9 s = 3.8 s away). This aspect needs to be evaluated to determine drivers’ responses to alerts delivered in advance. In the event that drivers consider the VRU messaging to be non-valuable then it is possible that the user interface (UI) could be adapted to either delay or gradually escalate the alert, based on the driver’s preference. In such a case it is likely that the V2N performance would be suitable to such adaptations because the accuracy of the reported position of the VRU (taking into account GNSS errors and network latency) is not the most significant factor in the determination of the best point at which to alert the driver.

Even taking into account the above, where it is suggested that C-V2X over Uu is appropriate and reasonable to deliver presence awareness for VRU, it is understood that the business case for including this functionality in vehicles is difficult to make by OEMs, as a standalone service. VRU presence awareness services are unlikely to be implemented resulting from the recent inclusion of V2X technologies in NCAP specifications. As a result, 5GAA has established a Work Item (VRU Awareness and Protection, VRU-AP) to examine the value proposition of VRU safety and awareness services for the VRU ecosystem beyond OEMs, such as micromobility service providers, insurance providers, and fleet operators. This work aims to describe the value exchange mechanism which could encourage the deployment of all required elements used to establish a viable and effective VRU awareness and protection service, and expanding ecosystem. The Work Item is expected to report in Q4 2026.

5.4 High-speed car-to-car rear

This section analyses high-speed car-to-car rear scenarios (described in Section 4.5) under varying assumptions related to driver reaction time, braking deceleration, and relative vehicle speed. Four scenarios are evaluated to determine the required warning distance and associated risk zones for the leading vehicle and for remote vehicles in the surrounding traffic environment.

5.4.1 Scenario Definitions and Common Assumptions

The following scenarios are considered:

- **Scenario 1:** Ego vehicle and leading vehicle at the same speed, fixed non-emergency deceleration, conservative reaction time.
- **Scenario 2:** Ego vehicle and leading vehicle at the same speed, fixed non-emergency deceleration, rapid reaction time.
- **Scenario 3:** Ego vehicle and leading vehicle at the same speed, fixed emergency deceleration, rapid reaction time.
- **Scenario 4:** Ego vehicle at higher speed than the leading vehicle, fixed emergency deceleration, rapid reaction time.

The common assumptions applied across all scenarios include:

- End-to-end (E2E) V2X transmission latency (t_0): 0.1 s.
- Leading-vehicle cut-out time: 2.2 s.
- Distance covered by the leading vehicle during cut-out: 49 m.
- Vehicle length: 5 m.

Reaction time and braking deceleration values vary by scenario, as described below.

5.4.2 Scenario 1: Same speed, non-emergency deceleration, conservative reaction time

In Scenario 1, both the ego vehicle and the leading vehicle travel at 80 km/h (22.2 m/s). A fixed non-emergency deceleration of 4 m/s^2 is assumed, together with a conservative driver reaction time of 2.4s.

The distance components for the ego vehicle are calculated as follows:

- E2E transmission distance (t_0):
  22.2 m/s × 0.1 s = 2.2 m
- Reaction distance (t_1):
  22.2 m/s × 2.4 s = 53.3 m
- Braking distance:
  (22.2 m/s)^2 / (2 × 4 m/s^2) = 61.6 m

The total distance from V2X message reception to a complete stop is therefore 117.1 m. After accounting for the distance covered by the leading vehicle during cut-out, the required initial longitudinal separation between the ego vehicle and the leading vehicle is 68.1 m.

Risk zones:

- Leading-vehicle risk zone: During the cut-out interval (1.1 s), the leading vehicle travels 24.4 m. Including vehicle length, the resulting risk zone length is 29.5 m.
- Remote-vehicle risk zone: Defined as the total stopping distance of the ego vehicle after message reception, resulting in a length of 117.1 m.

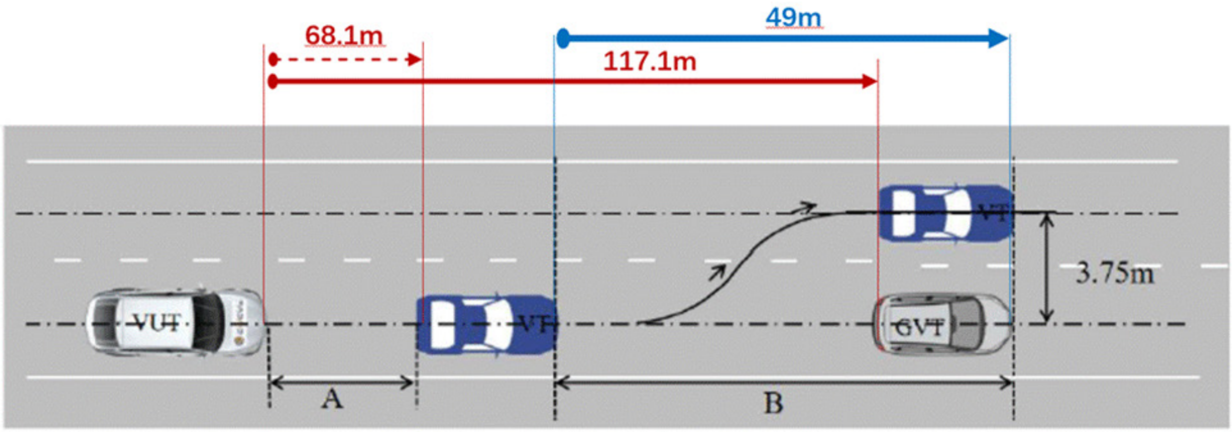


Figure 12 VUT related braking and deceleration distance in CCRH scenario 1

5.4.3 Scenario 2: Same speed, non-emergency deceleration, rapid reaction time

Scenario 2 follows the same assumptions as Scenario 1, except that a rapid driver reaction time of 1.0 s is applied.

With an ego-vehicle speed of 80 km/h and a fixed deceleration of 4 m/s^2:

- Reaction distance (t_1): 22.2 m
- Braking distance: 61.6 m
- Total stopping distance after message reception:
  2.2 + 22.2 + 61.6 = 86.0 m

The corresponding required initial separation between the ego vehicle and the leading vehicle is 37.0 m.

Risk zones:

- Leading-vehicle risk zone: 29.5 m
- Remote-vehicle risk zone: 86.0 m

5.4.4 Scenario 3: Same speed, emergency deceleration, rapid reaction time

In Scenario 3, emergency braking is assumed, with a fixed deceleration of 7 m/s^2 and a rapid reaction time of 1.0 s. Both vehicles travel at 80 km/h. Note that deceleration beyond 4m/s^2 may require ASIL-B qualification [8].

- Braking distance: 35.3 m
- Reaction distance (t_1): 22.2 m
- Total stopping distance after message reception:
  2.2 + 22.2 + 35.3 = 59.7 m

The resulting initial separation between the ego vehicle and the leading vehicle is 10.7 m.

Risk zones:

- Leading-vehicle risk zone: 29.5 m
- Remote-vehicle risk zone: 59.7 m

5.4.5 Scenario 4: Higher ego-vehicle speed, emergency deceleration, rapid reaction time

Scenario 4 considers a higher ego-vehicle speed of 120 km/h (33.3 m/s), while the leading vehicle maintains a speed of approximately 80 km/h. Emergency braking (7 m/s²) and a rapid reaction time of 1.0 s are assumed. Note that deceleration beyond 4m/s² may require ASIL-B qualification [8].

The distance components are:

- E2E transmission distance (t_0): 3.3 m
- Reaction distance (t_1): 33.3 m
- Braking distance: 35.3 m
- Total stopping distance after message reception: 71.9 m

Due to the speed difference, the relative motion between the ego vehicle and the leading vehicle is explicitly evaluated:

- Speed difference: 11.2 m/s
- Time to equalize speeds: 1.6 s
- Distance travelled by ego vehicle during this interval: 44.3 m
- Distance travelled by leading vehicle during this interval: 35.4 m

This results in a minimum relative separation of 8.9 m. Including transmission and reaction distances, the required initial separation between the ego vehicle and the leading vehicle is 45.5 m.

Risk zones:

- Leading-vehicle risk zone: 35.4 m
- Remote-vehicle risk zone: 71.9 m

5.4.6 Discussion

The analysed high-speed car-to-car rear scenarios indicate that the required warning distance and associated risk-zone extent are primarily driven by driver reaction time, braking deceleration capability, and relative speed between the ego vehicle and the leading vehicle. For scenarios with equal vehicle speeds, faster reaction times and emergency braking significantly reduce the required initial separation and the extent of the remote-vehicle risk zone, while conservative reaction assumptions lead to substantially larger affected distances.

When a relative speed difference exists, the closing dynamics between the ego vehicle and the leading vehicle become the dominant factor. In such cases, the distance accumulated during speed equalisation adds to the overall separation requirement, even under rapid reaction and emergency braking conditions. Across all scenarios, the leading-vehicle risk zone is largely determined by the cut-out interval and vehicle length, whereas the remote-vehicle risk zone directly reflects the ego-vehicle stopping distance following V2X message reception.

Overall, the results emphasise the importance of V2X communication in reducing rear-end collision risk by providing the driver with a timely and reliable notification of hazardous situations ahead, thereby enabling earlier reaction and more effective braking responses.

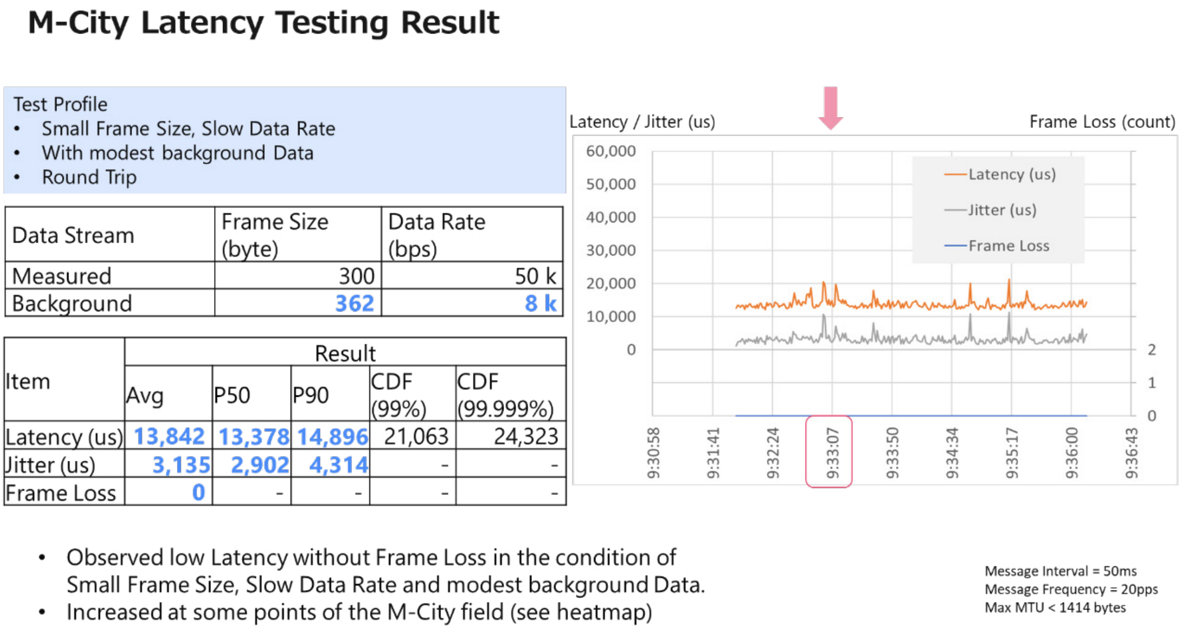
6 Available data sets for V2X

This chapter presents recorded data sets from V2X field trials, including latency and GNSS accuracy measurements from live demonstrations in Detroit, USA and Berlin, Germany, as well as PC5 and multi-access edge computing (MEC) latency measurements from laboratory experiments.

6.1 Data from 5GAA demos and field trials

6.1.1 M-City (Detroit, Michigan, USA)

This set of data was collected by Anritsu during 5GAA VRU demonstrations and showcase activity at M-City (Detroit US). These demonstrations used the Verizon 4G network, together with AWS Wavelength MEC (Detroit location). The packet size was set to 300 bytes, corresponding to the intelligent transport system (ITS) messages used in the demonstrations.



M-City Latency Testing Result

Test Profile
- Small Frame Size, Slow Data Rate
- With modest background Data
- Round Trip

Data Stream	Frame Size (byte)	Data Rate (bps)
Measured	300	50 k
Background	362	8 k

Item	Result				
	Avg	P50	P90	CDF (99%)	CDF (99.999%)
Latency (us)	13,842	13,378	14,896	21,063	24,323
Jitter (us)	3,135	2,902	4,314	-	-
Frame Loss	0	-	-	-	-

- Observed low Latency without Frame Loss in the condition of Small Frame Size, Slow Data Rate and modest background Data.
- Increased at some points of the M-City field (see heatmap)

Message Interval = 50ms
Message Frequency = 20pps
Max MTU < 1414 bytes

Figure 13 M-City latency test results

It is seen that an average round trip time latency of 13.8 ms was recorded, and the 99% percentile was at 21.0 ms.

6.1.2 Berlin MEC inter-operability (Berlin, Germany)

This set of data was collected by Anritsu during the 5GAA demonstrations in Berlin for VRU use cases. The overall connectivity architecture for the demonstrations is shown below. The T-Mobile network was connected to a T-Mobile MEC location in Berlin. One test point was located in the car that was driving around the demonstration route.

The second test point was located inside the T-Mobile MEC. Packets of data were then exchanged between the two test points, and the time of flight for each packet was recorded.

Separate data profiles for uplink and downlink data traffic were configured and time of flight for each direction was then measured simultaneously, using the packet size and rates that correspond to the packet sizes of the ITS messages used for the actual VRU demonstrations being made. The T-Mobile MEC used an external NTP server as timing reference, which was also verified for stability/accuracy.

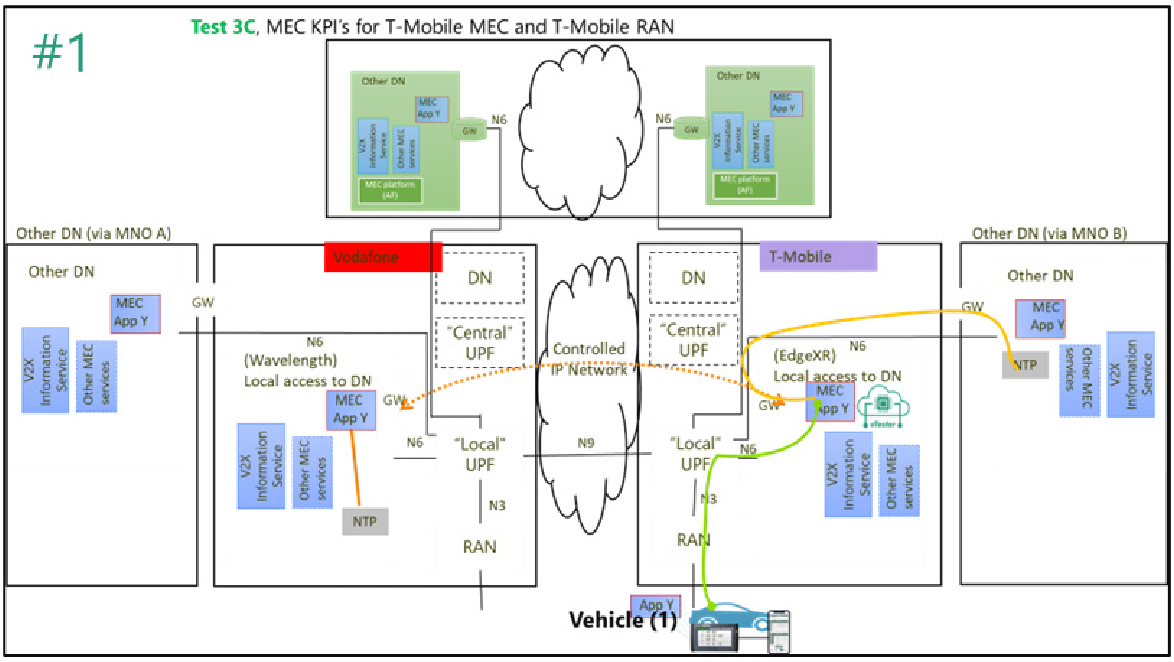
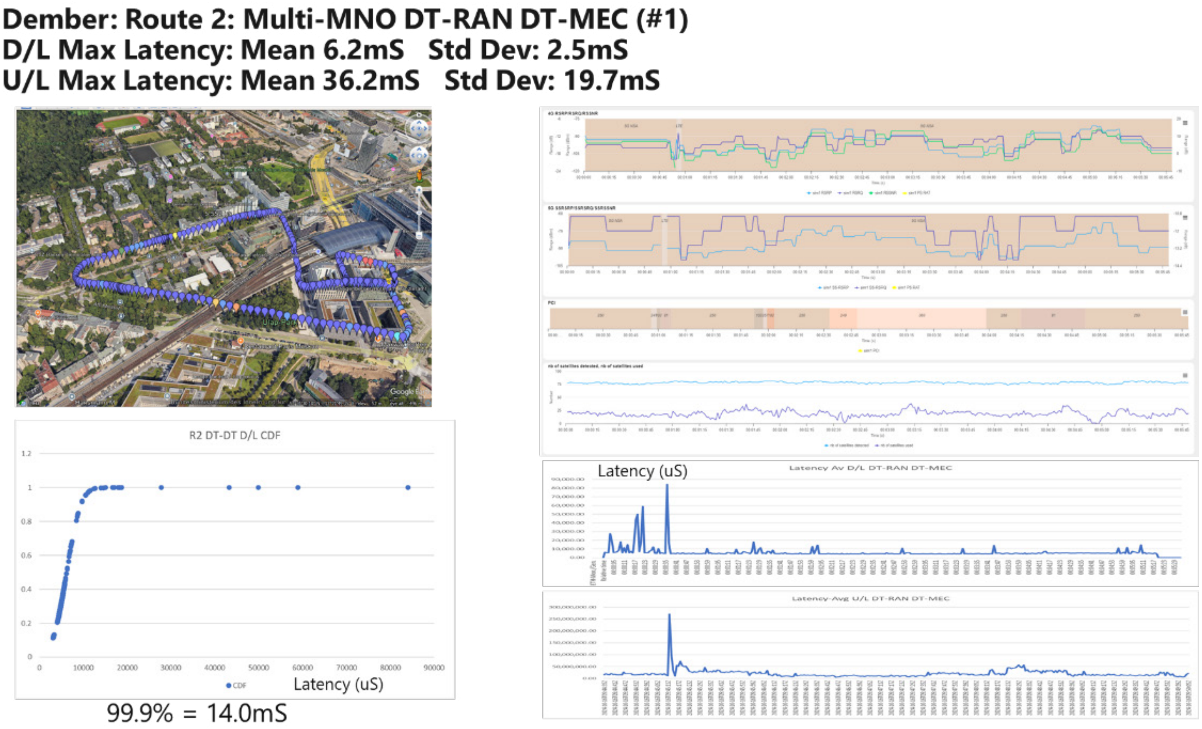


Figure 14 Berlin Demo – MEC architecture



Dember: Route 2: Multi-MNO DT-RAN DT-MEC (#1)
D/L Max Latency: Mean 6.2mS Std Dev: 2.5mS
U/L Max Latency: Mean 36.2mS Std Dev: 19.7mS

99.9% = 14.0mS

Figure 15 Route 2 latency measurements

It was seen that the downlink latency had an average value of 6.2 ms, with the 99.9% percentile at 14.0 ms. The uplink latency had an average value of 36.2 ms.

The logs for the radio conditions show that there was a degradation in 5G received signal strength, leading to a brief handover to 4G and then back to 5G near the start of the drive. A larger latency spike is observed at this time, possibly due to buffering or re-routing of packets during the handover period.

The availability of GNSS (as seen from user equipment or UE on the vehicle dashboard) is also logged and shown in the data. The number of GNSS satellites available (from ephemeris data) and then the number of satellites actually available or used by the smartphone are shown. It is noted that the general GNSS availability in this scenario was low, to the point of being very limited in some locations.

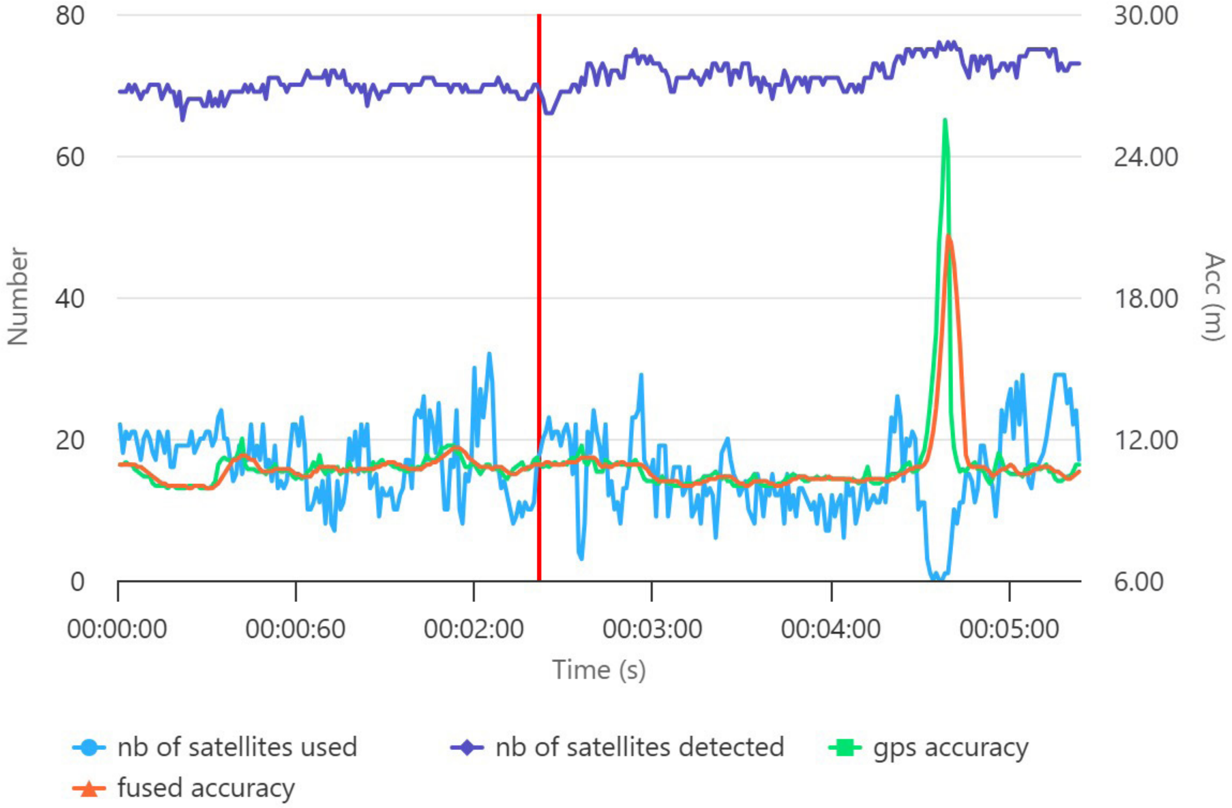


Figure 16 GNSS availability

This second set of data was collected by Anritsu on the Vodafone 4G + 5G network, with AWS Wavelength MEC (Berlin location) during the 5GAA demonstrations in Berlin for VRU use cases. The overall connectivity architecture for the demonstrations is shown below. The Vodafone network was connected to an AWS Wavelength MEC location in Berlin. One test point was located in the car driving around the demonstration route. The second test point was located inside the AWS Wavelength MEC. Packets of data were then exchanged between the two test points, and the time of flight for each packet was recorded. Separate data profiles for uplink and downlink data traffic were configured and time of flight for each direction was then measured simultaneously, using the packet size and rates corresponding to the packet sizes of the ITS messages used for the actual VRU demonstrations being made. The AWS Wavelength MEC used an internal NTP server as a timing reference, which was also verified for stability/accuracy.

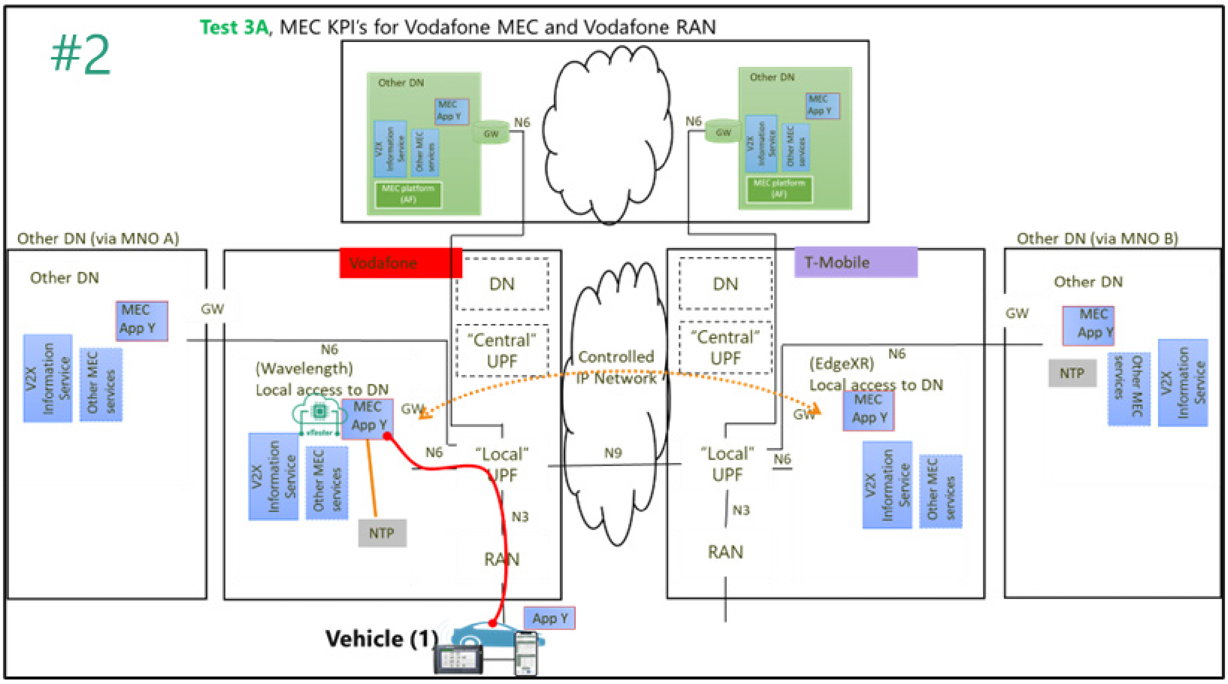
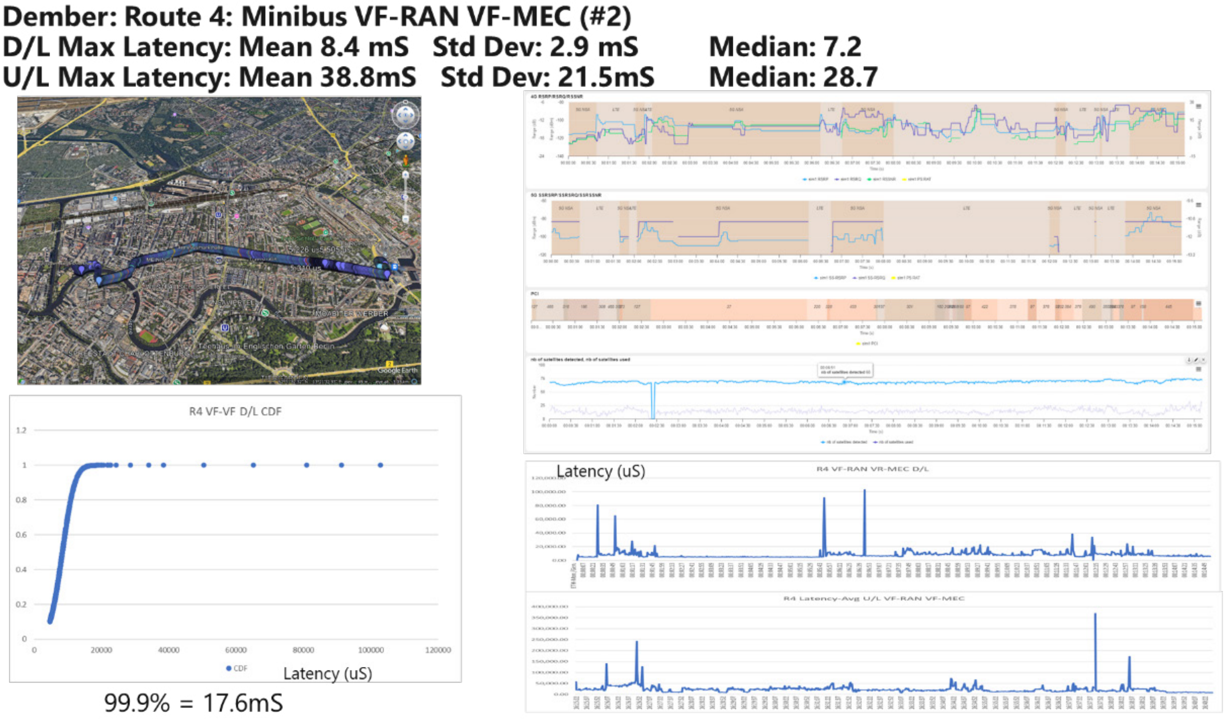


Figure 17 Vodafone MEC and RAN architecture


Dember: Route 4: Minibus VF-RAN VF-MEC (#2)

D/L Max Latency: Mean 8.4 mS Std Dev: 2.9 mS Median: 7.2

U/L Max Latency: Mean 38.8mS Std Dev: 21.5mS Median: 28.7

99.9% = 17.6mS

Figure 18 Route 4 latency measurements

It was seen that the downlink latency had an average value of 8.4 ms, with the 99.9% percentile at 17.6 ms. The uplink latency had an average value of 38.8 ms. The logs on the radio conditions show that the 5G signal strength was low in several areas along the route, and that there were several handovers between 4G and 5G during the drive.

Larger latency spikes can be seen during some of these handovers, possibly due to buffering or re-routing of data packets during the handovers.

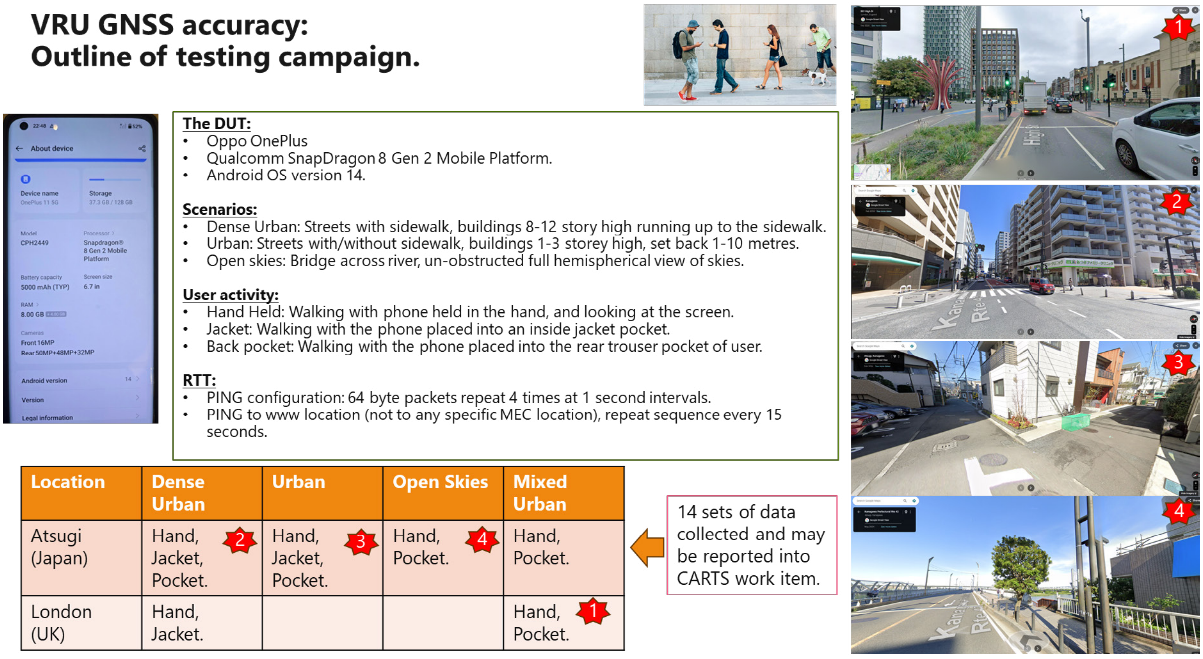
The availability of GNSS (as seen by UE on the vehicle dashboard) is also logged and shown in the data. The number of GNSS satellites available (from ephemeris data) and then the number of satellites actually available or used by the smartphone are shown. It is noted that the general GNSS availability in this scenario was good, with only a few locations reporting limited GNSS availability.

6.1.3 GNSS accuracy for VRU scenarios

These data sets for GNSS accuracy were captured using the reported ‘GNSS accuracy’ and ‘fused accuracy’ functions available for Android OS monitoring. The data sets were captured using standard commercial devices (Oppo OnePlus 11, and Google Pixel 9), unmodified devices, with an application loaded to record the location accuracy data (plus GNSS location, and network related data).

The first sets of data were recorded using Oppo OnePlus 11, at locations in Atsugi (Japan) and London (UK). For each test, the device was placed either in the outstretched hands of the user or the user’s jacket pocket or back pocket. This is to represent three typical scenarios of how a smartphone can been worn or carried by a user. A further set of tests were made in Sacramento (USA) using a Google Pixel 9 device, to compare the relative reported GNSS error from different device types.

The test zones included ‘dense urban’ locations with high-rise buildings on either side, and also some ‘mixed urban’ scenarios with houses, shops, and other smaller buildings close to the user. For reference, ‘open sky’ data sets were also recorded in locations with no buildings or other obstructions, so the device would have full ‘visibility’ of all available GNSS satellites.



VRU GNSS accuracy:
Outline of testing campaign.

About device
Device name: OnePlus 11 5G
Storage: 37.3 GB / 128 GB
Model: CPH2449
Processor: Snapdragon® 8 Gen 2 Mobile Platform
Battery capacity: 5000 mAh (TYP)
Screen size: 6.7 in
RAM: 8.00 GB
Cameras: Front 16MP, Rear 50MP+48MP+32MP
Android version: 14
Version
Legal information

The DUT:
- Oppo OnePlus
- Qualcomm SnapDragon 8 Gen 2 Mobile Platform.
- Android OS version 14.

Scenarios:
- Dense Urban: Streets with sidewalk, buildings 8-12 story high running up to the sidewalk.
- Urban: Streets with/without sidewalk, buildings 1-3 storey high, set back 1-10 metres.
- Open skies: Bridge across river, un-obstructed full hemispherical view of skies.

User activity:
- Hand Held: Walking with phone held in the hand, and looking at the screen.
- Jacket: Walking with the phone placed into an inside jacket pocket.
- Back pocket: Walking with the phone placed into the rear trouser pocket of user.

RTT:
- PING configuration: 64 byte packets repeat 4 times at 1 second intervals.
- PING to www location (not to any specific MEC location), repeat sequence every 15 seconds.

Location	Dense Urban	Urban	Open Skies	Mixed Urban
Atsugi (Japan)	Hand, Jacket, Pocket. 2	Hand, Jacket, Pocket. 3	Hand, Pocket. 4	Hand, Pocket.
London (UK)	Hand, Jacket.			Hand, Pocket. 1

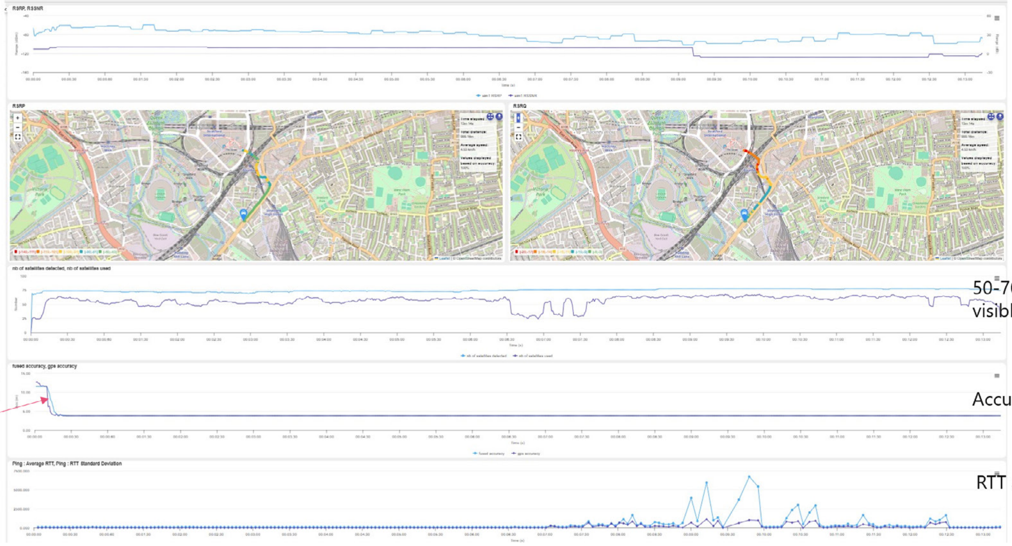
14 sets of data collected and may be reported into CARTS work item.

Figure 19 GNSS accuracy test description

6.1.3.1 London test locations

Using Oppo OnePlus 11 device, we could see a reported GNSS accuracy of 3.8 m when handheld, and between 3.8 m and 15 m when placed in the back pocket. This was for a user walking across a mixed urban environment in central London.

GNSS: London
Mixed Urban – Handheld



Starting indoors and walking out onto street

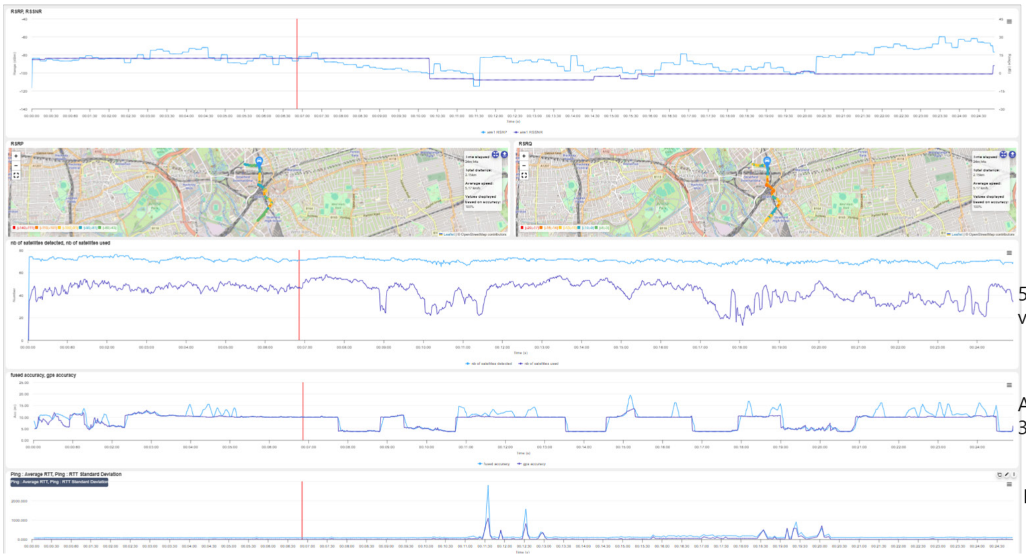
50-70 satellites visible

Accuracy at 3.8m

RTT at 100 mS

Figure 20 GNSS accuracy: London, mixed-urban handheld

GNSS: London
Mixed Urban – Back Pocket



50-70 satellites visible

Accuracy at 3.8 – 13.5m

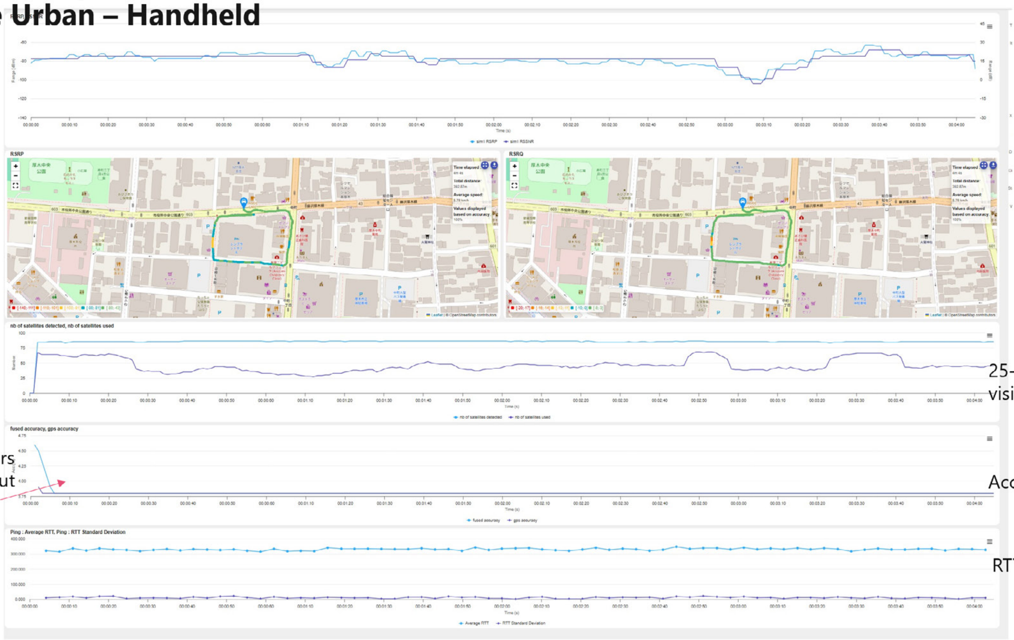
RTT at 100 mS

Figure 21 GNSS accuracy: London, mixed-urban back pocket

6.1.3.2 Atsugi test locations

Using Oppo OnePlus 11 device, we could see a reported GNSS accuracy of 3.8 m when handheld, and between 3.8 m and 10 m when placed in the back pocket. This was for a user walking across a dense urban environment in Atsugi.

GNSS: Atsugi
Dense Urban – Handheld



25-70 satellites visible

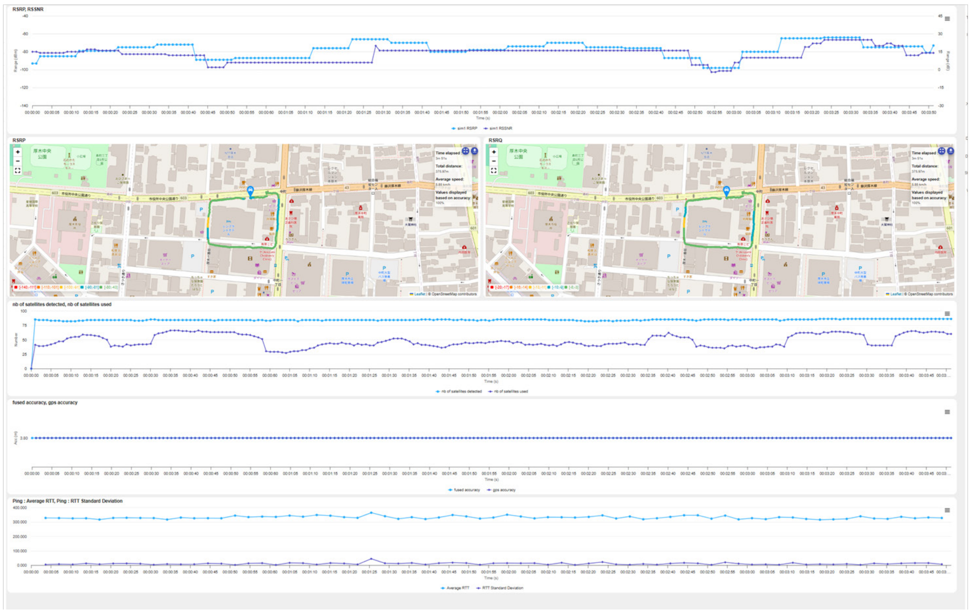
Starting indoors and walking out onto street

Accuracy at 3.8m

RTT at 320 mS

Figure 22 GNSS accuracy: Atsugi, dense-urban handheld

GNSS: Atsugi
Dense Urban – Jacket



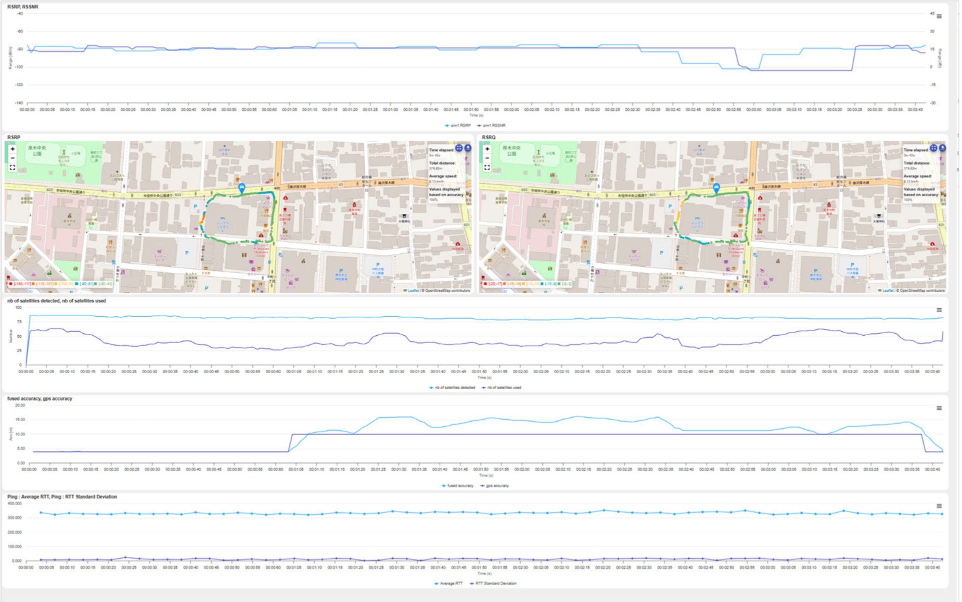
25-70 satellites visible

Accuracy at 3.8m

RTT at 320 mS

Figure 23 GNSS accuracy: Atsugi, dense-urban jacket

GNSS: Atsugi
Dense Urban – Back pocket



25-70 satellites visible

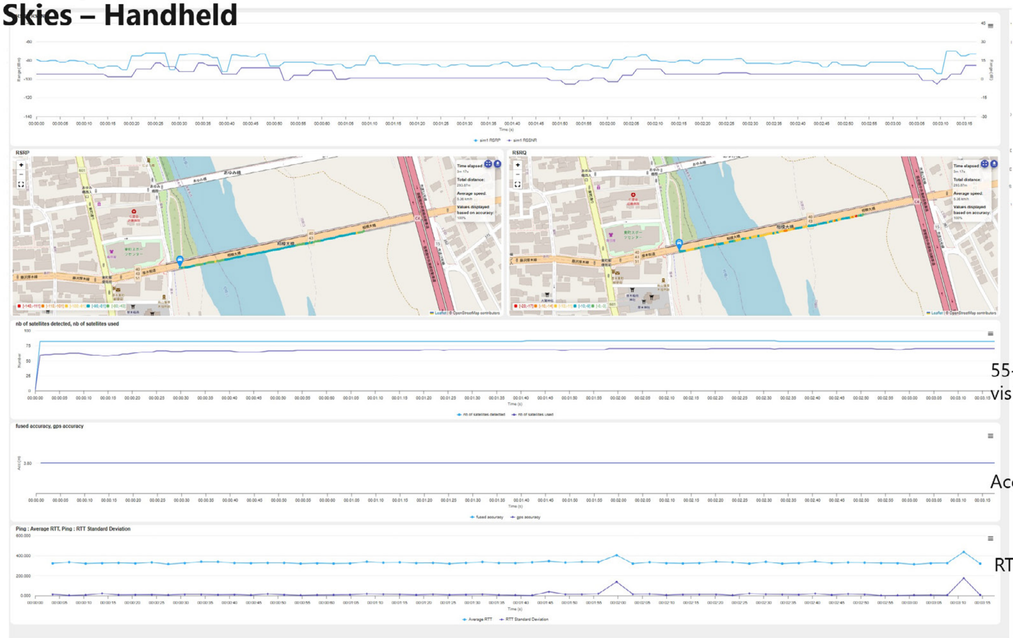
Accuracy at 3.8 to 10.0m

RTT at 320 mS

Figure 24 GNSS accuracy: Atsugi, dense-urban back pocket

The testing was also repeated in an 'open skies' environment, with no GNSS blockage. GNSS reported accuracy was 3.8 m when handheld, and 3.8-10.0 m in the back pocket. This open-sky scenario represents the 'best case' where the device has maximum GNSS accuracy and shows the minimum possible reported errors in terms of a specific type of device in a real-world scenario.

GNSS: Atsugi
Open Skies – Handheld



55-70 satellites visible

Accuracy at 3.8m

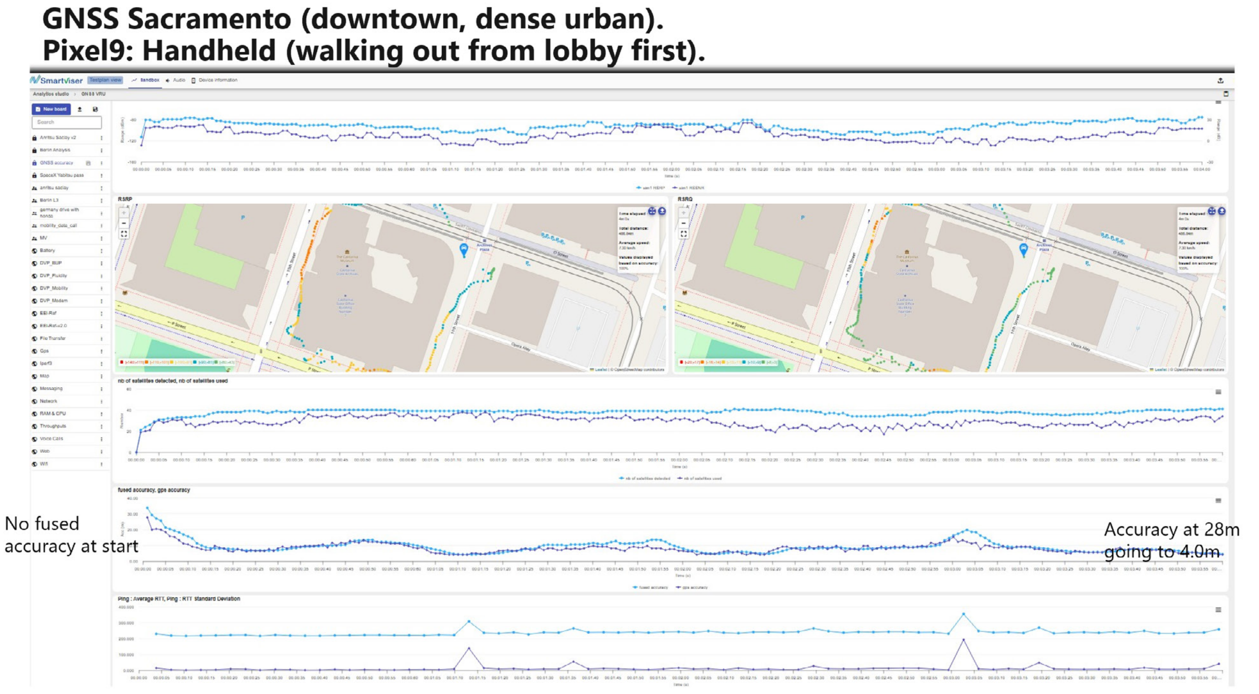
RTT at 320 mS

Figure 25 GNSS accuracy: Atsugi, open skies, handheld

6.1.3.3 Sacramento (USA) test results

For the testing in Sacramento, a Google Pixel 9 device was used, to provide an alternative data set to that of Oppo OnePlus 11. The same type of data acquisition and logging method were used as previously, and the same user positions (handheld, jacket pocket, back pocket) were applied.

In these dense urban (downtown) scenarios, the reported GNSS accuracy was between 28 m (when first walking out from a building onto the sidewalk) to 4.0 m when walking along the sidewalk. For the 'back pocket' test results, the initial accuracy reported was 2.5 m when walking out of the building, then going up to 20 m when walking along the sidewalk. This very good accuracy when first leaving the building is suspected to be due to previously cached location information prior to exiting the building.



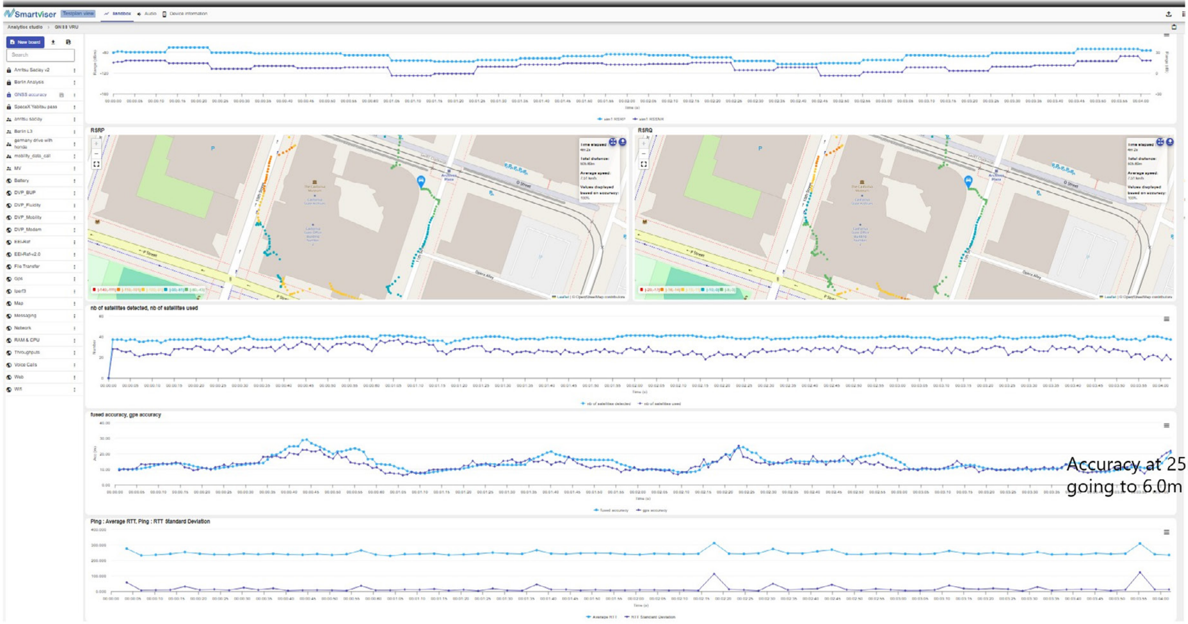
GNSS Sacramento (downtown, dense urban).
Pixel9: Handheld (walking out from lobby first).

No fused accuracy at start

Accuracy at 28m going to 4.0m

Figure 26 GNSS accuracy: Sacramento, dense-urban handheld

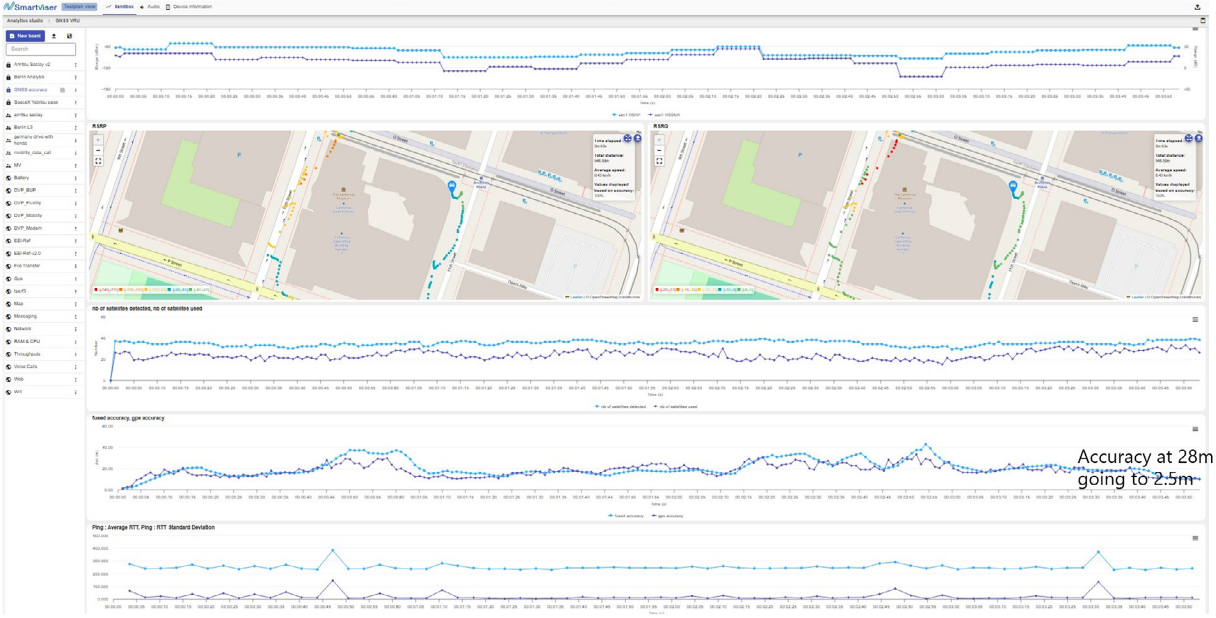
GNSS Sacramento (downtown, dense urban).
Pixel9: Jacket pocket.



Accuracy at 25m
going to 6.0m

Figure 27 GNSS accuracy: Sacramento, dense-urban jacket

GNSS Sacramento (downtown, dense urban).
Pixel9: Back pocket (walking out from lobby first).

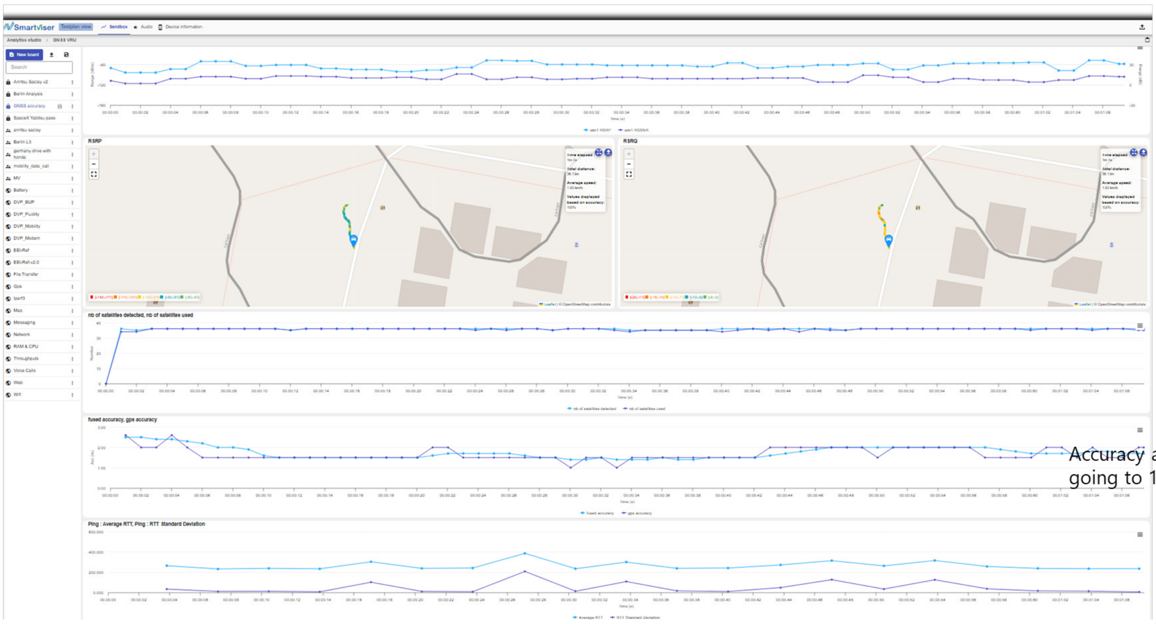


Accuracy at 28m
going to 2.5m

Figure 28 GNSS accuracy: Sacramento, dense-urban back pocket

For the Google Pixel 9 in open skies scenarios, we could see a reported GNSS error of 1 m in the best case (handheld). This verified that under ideal conditions the device was able to report an estimated error of 1.0 m. It was still clear that a user with the device in a jacket pocket or back pocket would degrade reported GNSS accuracy even under ideal ‘clear skies’ conditions.

GNSS Sacramento (Open Skies, demo location). Pixel9: Hand held.



Accuracy at 2.5m going to 1.0m

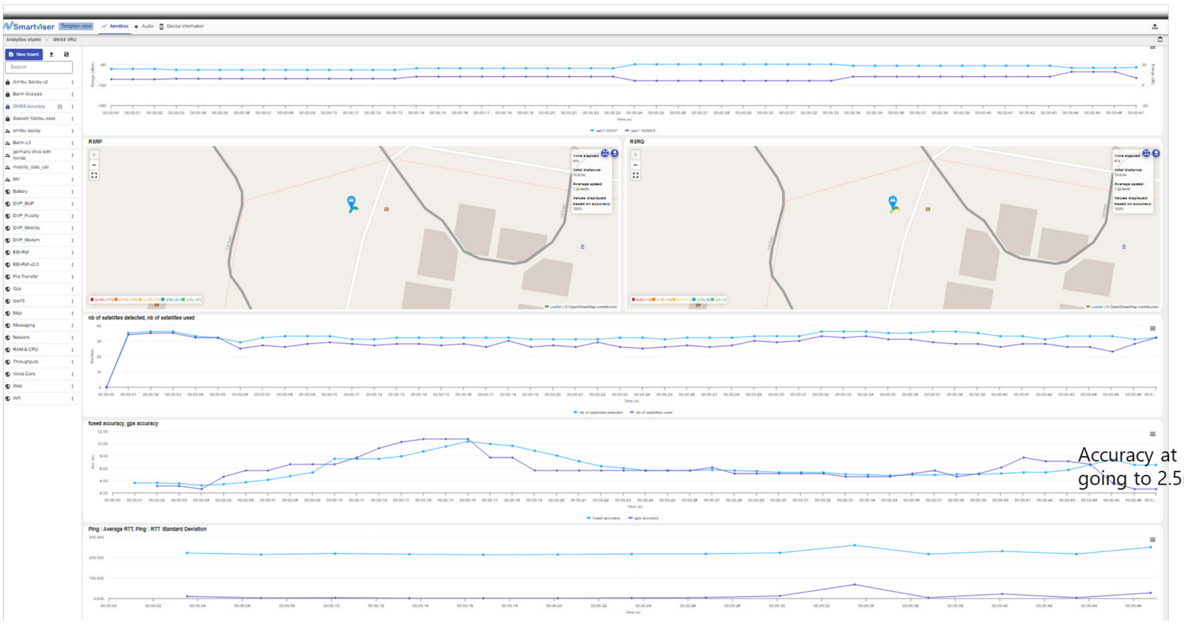
Figure 29 GNSS accuracy: Sacramento, open skies handheld

GNSS Sacramento (Open Skies, demo location). Pixel9: Jacket pocket.

Accuracy at 5m going to 2.0m

Figure 30 GNSS accuracy: Sacramento, open skies jacket

GNSS Sacramento (Open Skies, demo location).
Pixel9: Back pocket.



Accuracy at 10m
going to 2.5m

Figure 31 GNSS accuracy: Sacramento, open skies back pocket

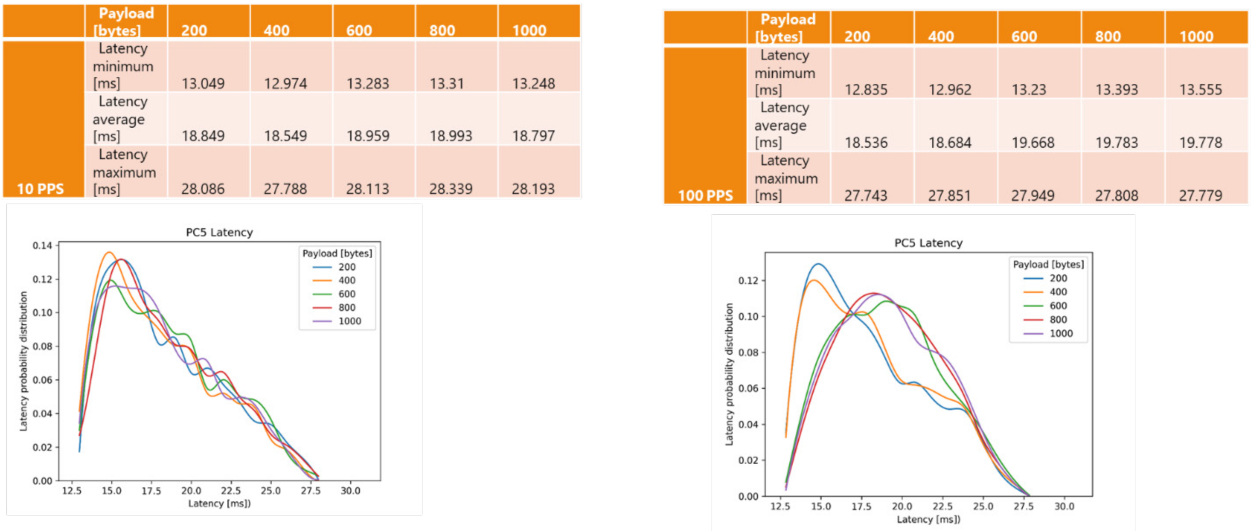
6.2 Other 5GAA data sets

Drawing on wider data sources (publications or member contributions), this section makes use of other relevant data from 5GAA, not specifically covered by the demo and trials activities described in Section 6.1.

6.2.1 PC5 latency under laboratory conditions.

The following set of data from Anritsu shows an evaluation of PC5 latency using the same methodology and equipment as the MEC latency testing in Sections 6.1.1 and 6.1.2. The test configuration used two sets of PC5 radios, one for transmitting and one for receiving, so the total one-way latency is measured. Reference test packets were sent to the transmit board, and then recovered from the receive board, and the time of flight of each packet was recorded.

This analysis focused on the PC5 latency evaluation reading only the PC5 layer (no ITS stack) to give equivalent data as V2N data sets. Laboratory conditions (RF cable connection) were used as an ideal radio link condition, with an unloaded PC5 link (no other PC5 users on the channel), to isolate the inherent latency (due to the PC5 design and protocols of the air interface) as the measurand.



	Payload [bytes]	200	400	600	800	1000
10 PPS	Latency minimum [ms]	13.049	12.974	13.283	13.31	13.248
	Latency average [ms]	18.849	18.549	18.959	18.993	18.797
	Latency maximum [ms]	28.086	27.788	28.113	28.339	28.193

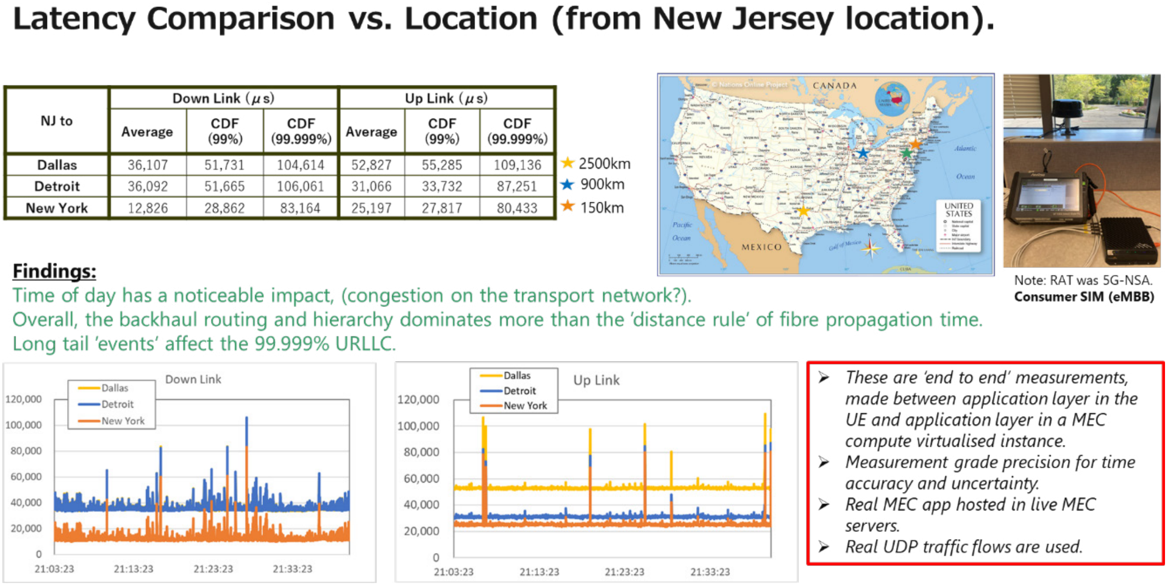
	Payload [bytes]	200	400	600	800	1000
100 PPS	Latency minimum [ms]	12.835	12.962	13.23	13.393	13.555
	Latency average [ms]	18.536	18.684	19.668	19.783	19.778
	Latency maximum [ms]	27.743	27.851	27.949	27.808	27.779

Figure 32 PC5 latency (lab)

In the first set of measurements, the rate is set to 10 packets per second (PPS) corresponding to 100 ms intervals. With this configuration, the PC5 link shows an average latency of 18 ms, with a robust lower bound of 13 ms and upper bound of 28 ms.

In the second set of measurements, the packet rate is set to 100 PPS corresponding to 10 ms intervals. With this configuration, the PC5 link shows an average latency of 19 ms, with a robust lower bound of 13 ms and upper bound of 28 ms. It is noted that as the packet size is increased the latency distribution changes, with larger packet sizes tending to a higher average latency (around 20 ms). However, the same lower and upper bounds of latency are still maintained under these conditions.

6.2.2 MEC versus Central Cloud latency



Latency Comparison vs. Location (from New Jersey location).

NJ to	Down Link (μs)			Up Link (μs)			
	Average	CDF (99%)	CDF (99.999%)	Average	CDF (99%)	CDF (99.999%)	
Dallas	36,107	51,731	104,614	52,827	55,285	109,136	★ 2500km
Detroit	36,092	51,665	106,061	31,066	33,732	87,251	★ 900km
New York	12,826	28,862	83,164	25,197	27,817	80,433	★ 150km

Note: RAT was 5G-NSA.
Consumer SIM (eMBB)

Findings:
Time of day has a noticeable impact, (congestion on the transport network?).
Overall, the backhaul routing and hierarchy dominates more than the 'distance rule' of fibre propagation time.
Long tail 'events' affect the 99.999% URLLC.

- *These are 'end to end' measurements, made between application layer in the UE and application layer in a MEC compute virtualised instance.*
- *Measurement grade precision for time accuracy and uncertainty.*
- *Real MEC app hosted in live MEC servers.*
- *Real UDP traffic flows are used.*

Figure 33 MEC latency comparison

This data was captured by Anritsu during the 5GAA MEC4AUTO activity, using live field trials, to compare latency across different MEC locations. The UE was located in New Jersey and connected to the Verizon 5G network. Test probes were then installed at the AWS Wavelength MEC locations in New York (150 km), Dallas (2,500 km), and Detroit (900 km). Separate uplink and downlink traffic flows were created for each location, and the time of flight of each packet in each data flow was recorded. All of the traffic flows were simultaneous, so any effects from radio conditions or the Verizon 5G network were common to all data flow locations. Latency spikes that are common to all three locations can be seen in both downlink and uplink, which indicate delays due to the 5G network. The average values show clearly the different latency performance due to the different locations. For downlink, the Dallas and Detroit locations had almost the same average latency despite the physical location being much further away. This indicates that the latency delay is not only a function of distance, but the actual routing and transport network between the UE and the MEC location. A misalignment between distance and latency is seen in the uplink, which indicates that the routing and transport network on the uplink has a different configuration. Such effects may be due to the traffic load in different directions across the transport network, and corresponding buffering/congestion management within switches/routers in the transport network.

6.3 Analysis and key findings from the data sets

6.3.1 Discussion of KPI's chosen

The main KPI considered is the combination of latency and reliability. The latency term is normally expressed in time units (e.g. milliseconds or ms), but the chosen level of reliability is shown by the threshold of latency that is chosen. Although the 'average' latency may be an attractive term to use, it is preferred to state latency with a given reliability (such as 99% of packets received within this time frame). By expressing the latency at a given time bound (where it is related to the requirements of the use case) then the 'reliability' of the service to meet this latency bound can be expressed, or conversely the latency performance to meet the reliability bound can be expressed. To make this statistical analysis relevant, there does need to be enough samples of data captured such that the confidence bound for the KPI can be assured. For the 5GAA trials (Sections 6.1 and 6.2), the related packet size and rates considered in the data sets were those used in the actual demonstrated use cases.

6.3.2 Discussion on the values and findings from the data sets; typical values, distribution analysis of values, etc.

The V2N (network mode) data presented from M-City and Berlin shows downlink latency with ranges of 6-8 ms (average) and uplink latency ranges of 34-38 ms (average), and it is seen that the 'long tail' of latencies (e.g. 99.9%) can extend out to over twice these values. For the PC5 (direct mode) it is seen that the latencies are contained within a range of 13-28 ms, with no 'long tail' effects. However, this PC5 testing was done without loading on the radio link, and radio congestion may result in transmission of lower priority packets in a later 10 ms frame.

The MEC-Cloud data showed that going from 150 km distance to 2,500 km distance from UE to cloud location gave an increase in downlink data from 13 ms to 36 ms, and between 900 km and 2,500 km distance latency figures could be more similar. This is presumed to be due to the switching/routing infrastructure dominating the latency value far more than the pure distance (time of flight) for the longer reaches.

For GNSS reported accuracy, there were two main effects seen. Firstly, under ideal ‘open skies’ conditions we could see differences between the two types of devices used in these tests (1.0 m versus 3.8 m in the best cases). The second effect was that the reported GNSS accuracy was heavily affected by where the user placed the smartphone during testing. In the ‘handheld’ location we can see the best results, but when the smartphone is placed into a jacket pocket or back pocket then the reported GNSS accuracy can be significantly degraded.

7 End notes and conclusion

The CARTS Work Item was instigated in 5GAA to evaluate and present evidence for appropriate inclusion of C-V2X technologies in use cases beyond ‘Day 1’ awareness ITS, such as collision avoidance for direct, PC5-based systems, and VRU awareness for mobile network-based Uu systems. While confidence in the usefulness of C-V2X has not been lacking in 5GAA, a dedicated Technical Report with use-case-specific analysis supporting deployment of C-V2X was considered to be sufficient justification for the Work Item.

For each use case, a model of the dynamic relationships between the various actors has been developed with agreed values for system parameters (e.g. driver reaction time, transmission latency, GNSS error, etc.) applied to the models. The aim of the modelling exercise is to demonstrate that C-V2X systems can deliver the information required to support the driver’s (and in one case, ADAS) response sufficiently well to support the use cases’ service objectives. During the CARTS exercise, additional considerations which could be expected to influence the performance of the use case service (i.e. the above-mentioned parameter values) were identified and their effects discussed. The integration of C-V2X is modelled as a multi-layered framework, where direct (PC5) and network-assisted (Uu) communications serve as complementary functional components. Each mode addresses distinct operational conditions and information exchange requirements, and their combined use enables broader situational awareness. The two communication modes function in tandem with ADAS and onboard sensing systems – such as radar, lidar, and vision sensors, to form a comprehensive perception profile. While autonomous sensors provide high-resolution local detection, C-V2X extends the operational horizon through non-line-of-sight awareness and coordinated data exchange. This collaborative architecture ensures that each system augments the others, enhancing overall reliability without implying the displacement of existing sensor technologies.

7.1 CARTS use cases summary

- The **soft intersection approach use case** investigates the effectiveness of C-V2X technologies in enhancing safety and comfort, where vehicles approach intersections when the traffic light is about to turn red. Findings indicate that information received from intersection controllers can reliably help to engage in a comfortable soft braking procedure until full stop. Overall, the integration of V2X in soft intersection approaches shows promise in supporting accidental traffic light violation while employing a ‘comfortable deceleration’ even before onboard sensors can detect the signal shift. The time window for which high certainty of the V2X SPAT information is needed, is as low as 3 s in an urban environment (50 km/h). However, it is left to the vehicle manufacturers to evaluate the user acceptance related to automated soft deceleration (e.g. maximum acceptable soft deceleration while yellow/red light is not confirmed by onboard sensors).

- In the **intersection safety scenario**, we consider both VRU (25 km/h) to ego vehicle (60 km/h) and violator vehicle (60 km/h) to ego vehicle (60 km/h) scenarios. The ego vehicle has the green light and right of way while the cyclist or other vehicle is running the red light or stop sign. The VRU messages transmitted by the violating cyclist is received by the ego vehicle and the driver is alerted in time to be able to react to the impending collision, to prevent an accident by reducing its speed appropriately. We also show the reliability of the reception of the messages based on multiple transmissions via the 3GPP urban grid simulation assumptions. The results presented above show that reliability based on our urban intersection assumptions is higher for PC5, which makes a strong case for using it in urban intersection safety scenarios.
- In the **VRU presence awareness scenario**, a pedestrian VRU is crossing a road/lane at a mid-block location. The pedestrian is equipped with a smartphone and installed app, which is generating VRU presence data for the scenario. A vehicle receiving the VRU's data over the mobile network is approaching the VRU at the maximum legal speed. In this use case the driver is alerted to the presence of the VRU ahead and encouraged to manage their vehicle's speed down as they approach the crossing point so the VRU can fully and safely cross without stopping before the vehicle arrives. The result of the analysis is that typical Uu transmission characteristics can be considered suitable to support VRU presence awareness in urban and suburban scenarios (where the maximum speed is approximately 50 km/h), although potentially inaccurate GNSS positioning by the smartphone and worst-case driver response times can render the solution less effective. This means the presence awareness warning may need to be given at such an early stage in the scenario that the driver may not consider the initial information as reliable or valuable (i.e. in compensating for unknowns or possible inaccuracies in the data the vehicle-to-VRU distance is considered extreme or unrealistic by the driver, undermining the system's perceived utility).
- The **high-speed car-to-car rear scenario** is Based on high-speed car-to-car rear scenarios inspired by C-NCAP 2024 standards, our evaluations demonstrate the effectiveness of PC5 direct communication during sudden cut-out manoeuvres. The analysis tested various highway speeds and following distances where a leading vehicle unexpectedly changes lanes, revealing a remote vehicle ahead. The findings confirm that under both emergency and non-emergency braking assumptions, the required deceleration distance consistently falls well within the PC5 direct communication range, ensuring adequate response time and effectively mitigating collision risks within the identified safety zones.

Evidence about current uncertainties related to some smartphone models (in terms of GNSS and fused position accuracy) was presented, showing variability between smartphones but also how the smartphone is carried or worn by a person. The smartphones were seen to experience little degradation of GNSS location accuracy when in dense urban (e.g. urban canyon) scenarios, compared to suburban or 'open skies' conditions.

Data is presented in the Work Item to show the end-to-end and one-way latency measured in various scenarios. For 'network mode' Uu, there are several data sets for 4G and 5G networks that are including MEC, showing mean latency (50% of all packets) of 7-15 ms, and 99.9% of all packets at 14-18 ms for downlink data. For the uplink, latency is seen to be significantly increased (due to 3GPP scheduling protocols) and having an average latency in the range of 35-38 ms, and a much higher value for 99.9% of all packets (e.g. 55-60 ma). These values were all captured in live commercial networks, using regular consumer SIM card subscriptions, and utilising local MEC as the data end point. For the 'direct mode' PC5, it is seen that the E2E one-way latency averaged 18-19 ms, with 100% of packets arriving within a robust bound of 13-28 ms for an un-congested radio channel. This data matches expected differences that coming from different access layer protocols used by Uu and PC5 modes of transmission in 3GPP, excluding any application layer protocols (e.g. C-ITS, SAE, etc).

Overall, the study concludes that both PC5 and Uu are appropriate enablers for the use cases under study, with each interface offering complementary characteristics depending on the application context. Deployments making effective use of one or both interfaces can enable timely and reliable communication for safety-relevant scenarios and have the potential to contribute to improved accident and crash outcomes, taking into account the technical, operational, and system-level aspects discussed in this report.

7.2 Next steps and follow-up suggestions

A critical factor in the commercialisation of V2X-enabled safety services is their integration into NCAP protocols, which provide the necessary regulatory framework and incentive for industry-wide implementation. Consequently, the use cases analysed in this document are mapped against the following China and Euro NCAP roadmaps to identify the path from technical concept to standardised safety rating.

7.2.1 China NCAP

The CN-NCAP 2024 protocol introduced V2V-based Forward Collision Warning (FCW) for high-speed scenarios leveraging direct V2X communication, with further tightening of the requirements planned for 2027. Relevant scenarios include:

- Highway Stationary Vehicle Warning (CCRH) : See high-speed car-to-car rear scenario in section 5.4.
- High-Occlusion Intersection Collision Warning (SCPO): See violator vehicle approaching the intersection from the right in Section 5.2; CN-NCAP 2027 tightens the scenario by exchanging the parking vehicle with a concrete wall (blind ego-sensors).

To align with Euro NCAP requirements for V2X-triggered interventions, the current CN-NCAP FCW-based scenarios would need to be extended beyond warning-only functionality. In particular, the introduction of qualified mitigation (QM) braking would be required to meet Euro NCAP 2029 expectations.

The CN-NCAP 2024 also introduces a traffic signal recognition (TSR) and early warning test that evaluates whether a vehicle can detect a red traffic light and warn the driver in time when approaching an intersection. The soft intersection approach gives an example of a more comfortable and risk-adverse manoeuvre which requires I2V SPAT information. The proposed use case could be a test candidate in future NCAP test involving TSR.

7.2.2 Euro NCAP

In parallel, the increasing accident rate involving bicycles in both urban and rural environments is driving greater focus on VRU-related scenarios. As a result, Euro NCAP scenarios, such as Car-to-Bicyclist Nearside Adult Obstructed (CBNAO), are being considered as candidates for future protocol extensions (e.g. intersection safety, Section 5.2). For rural use cases in particular, both NCAP protocols and OEM implementations should consider additional V2X-enabled traffic participants beyond emergency vehicles, starting from Euro NCAP 2026.

Pedestrian protection is currently addressed through the Car-to-Pedestrian Manoeuvring Forward scenario, which primarily relies on ego-vehicle sensors and assumes no line-of-sight obstruction. Currently, infrastructure-based or ‘connected’ VRUs are not within the scope of the Euro NCAP 2026 protocol.

Potential study items include:

- Investigation of multi-technology integration strategies, covering Uu, PC5, and onboard sensing, with the objective of identifying best practices and implementation guidelines for NCAP-relevant use cases.
- The path to deployment for the pedestrian VRU presence awareness use case is less clear than others covered here and is not referred to in NCAP plans. 5GAA has established a Work Item to study the possible paths to market for VRU safety and awareness services called ‘VRU Awareness and Protection: Value Creation and Capture’, which is scheduled for completion and publication in Q4 2026.

8 References

[1] LI Guo-fa, OUYANG De-lin, WU Hao, et al. Critical Technologies and Development Trends of Intelligent Perception in Complex Scenarios for High-level Autonomous Driving. China Journal of Highway and Transport, 2025, 38 (X): 000-000.

[2] Yuxiao Zhang, Alexander Carballo, Hanting Yang, et al. Perception and sensing for autonomous vehicles under adverse weather conditions: A survey. ISPRS Journal of Photogrammetry and Remote Sensing, 2023, 196: 146-177.

[3] Shizhe Zang, Ming Ding, David Smith, et al. The impact of adverse weather conditions on autonomous vehicles: How rain, snow, fog, and hail affect the performance of a self-driving car. IEEE Vehicular Technology Magazine, 2019, 14(2): 103-111.

[4] Ziye Qin; Ang Ji; Zhanbo Sun, et al. Game Theoretic Application to Intersection Management: A Literature Review. IEEE Transactions on Intelligent Vehicles, vol. 10, no. 4, pp. 2589 - 2607, Apr. 2025, DOI: 10.1109/TIV.2024.3379986

[5] ISO 26684:2015 Intelligent transport systems (ITS) — Cooperative intersection signal information and violation warning systems (CIWS) — Performance requirements and test procedures

[6] 3GPP TR 36 885. “Study on LTE-based V2X Services (Release-14)”.

[7] 5GAA Conclusions and Recommendations for Communications Service Providers Supporting Road Operator Priorities and Expectations

[8] 5GAA Safety Treatment in Connected and Automated Driving Functions Report

The 5G Automotive Association (5GAA) is a global, cross-industry organisation of over 100 members, including leading global automakers, Tier-1 suppliers, mobile operators, semiconductor companies, and test equipment vendors.
5GAA members work together to develop end-to-end solutions for future mobility and transport services.
5GAA is committed to helping define and develop the next generation of connected mobility, automated vehicles, and intelligent transport solutions based on C-V2X.
For more information, please visit https://5gaa.org

5GAA
Automotive Association