ROADVIEW

Robust Automated Driving in Extreme Weather

Project No. 101069576

Deliverable 5.3

SW on Collaborative Perception Solutions – First report

WP5 – Robust perception system

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Partner short names

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VTT	VTT Technical Research Centre of Finland
CRF	Canon Research Centre France

Abbreviations

API	Application Programming Interface
C2C-CC	Car-to-Car Communication Consortium
C-ACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CAV	Connected Automated Vehicles
C-ITS	Cooperative Intelligent Transport Systems
CPM	Collective Perception Message
CPS	Collective Perception Service
D	Deliverable
DCNN	Deep Conventional Neural Network
EC	European Commission
ENU	East North Up
EU	European Union
ETSI	European Telecommunication Standard Institute
GAN	Generative Adversarial Network
HEU	Horizon Europe
I2V	Infrastructure to Vehicle
IVIM	In Vehicle Information Message
LiDAR	Light Detection and Ranging
M	Month
MAP	Map data
MCM	Manoeuvre Cooperation Message
MQTT	Message Queue Telemetry Transport
MRM	Minimum Risk Manoeuvre
MS	Milestone
NTP	Network Time Protocol
OBU	On Board Unit

ODD	Operational Design Domain
POC	Perceived Object Container
PRC	Perception Region Container
QoS	Quality of Service
RGB	Red Green Blue
ROS	Robot Operating System
RSU	Road Side Unit
RWM	Road Weather Message
SAE	Society of Automotive Engineers
SIC	Sensor Information Container
SPAT	Signal Phase and Timing
SW	Software
VAM	Vulnerable Road User Awareness Message
VRU	Vulnerable Road User
WP	Work Package
V2X	Vehicle-to-Everything
XAI	eXplainable Artificial Intelligence

Executive summary

Objectives

Collaborative Perception Solutions target to improve the vehicle perception by sharing information provided from roadside infrastructure systems or from other connected vehicles using V2X communication protocols.

One of the objectives of this deliverable is to identify the benefits and the limitations of C-ITS (Cooperative-Intelligent Transport System) services and related V2X communication protocols to assist automated driving functions in case of harsh weather conditions and complex conditions (e.g. presence of Vulnerable Road Users, VRU).

With the help of this deliverable, we aim to define enhancement of V2X messages and the software architecture of the collaborative perception solution integrating infrastructure-based perception system to generate additional data to be received by the vehicle about weather conditions and perceived objects by the roadside sensors.

Methodology and implementation

First, the approach was to make a review of the Cooperative Intelligent Transport Systems (C-ITS) services relevant to the ROADVIEW targeted environment conditions and use cases defined in D2.1 and D2.2 and to identify their benefits and limitations.

Second, by referring to the ROADVIEW architecture and requirements defined in D2.3 and D2.4 we have studied an architecture to set-up a collaborative perception solution integrating infrastructure-based perception system to extend the ROADVIEW use cases when the autonomous vehicle is in the communication range of such an infrastructure-based system.

Outcomes

As a first outcome C-ITS services selected for Robust Perception Solutions (WP5) and Control and Decision-Making System (WP6) are:

C-ITS Service	Benefits and enhancements for ROADVIEW
Collective Perception Service (ETSI TS 103 324)	The collective perception service allows to share local sensor information and perceived object information using Collective Perception Message, CPM. In task 5.2, we will develop CPM considering the sensor Operation Design Domain, ODD and the quality of the perception based on the weather conditions.
Road Weather Service (SAE J2945-3)	The road weather service allows to share weather information collected from weather sensors using Road Weather Message, RWM. This message will be enhanced to share the roadside weather type estimation developed in task 5.2 and the vehicle on-board visibility estimation and slipperiness estimation developed in task 5.3.
Manoeuvre Cooperation Service (ETSI TR 103 578)	The manoeuvre cooperation service allows cooperation between autonomous vehicles in case of trajectory conflicts using Manoeuvre Cooperation Message, MCM. This message will be enhanced with weather-aware driving advice in the scope of task 6.3.

Table 1: Relevant C-ITS services with plan to implement and evaluate in ROADVIEW

As a second outcome, we have proposed a software architecture for the Collaborative Perception Solutions developed in WP5. This architecture integrates an infrastructure-based perception system having the following main features:

- A weather estimation module based on machine learning from roadside camera images,
- A sensor fusion module to detect and track objects such as vehicles or vulnerable road users from roadside sensors,
- A vehicle-to-everything, V2X collaborative road weather service and perception service using RWMs to share the weather conditions and CPMs to share perceived objects with quality information based on the sensor ODD.

Next steps

Remaining functions to be further considered in the next steps of task 5.2 are:

- Global fusion between the roadside local data and the received data from V2X,
- Sharing of the VRU detection from the FGI LiDAR in artic weather conditions using collective perception,
- Study of congestion-aware collective perception.

The solutions will be tested using WP3 pre-recorded datasets first. Then a roadside perception system is planned to be installed in Finland at a road intersection to gather additional datasets for the weather estimation and to test the roadside sensor fusion for the detection of vehicles and vulnerable road users. This system will be used to evaluate the Collective Perception Solutions in the harsh weather conditions in Lapland somewhere between December 2024 and February 2025. The evaluation of the solutions will be reported in the next deliverable of task 5.2 scheduled in M36.

1 Introduction

This deliverable is a first report on the software on Collaborative Perception Solutions.

The ROADVIEW Collaborative Perception Solutions target to provide additional robustness to the vehicle perception system by sharing information provided from roadside infrastructure systems or from other connected vehicles.

In the context of ROADVIEW project, we focus on complex environment (including the presence Vulnerable Road Users VRUs) and harsh weather traffic conditions which have major impact on the safety and operations of Connected and Automated Vehicles (CAVs). Weather affects not only the vehicle performance but also the roadway infrastructure, thereby increases the risk of collision and traffic scenario variations.

The embedded in-vehicle perception or roadside-sensor perception systems might be affected by the harsh weather conditions. A first component of the Collaborative Perception Solutions is providing an evaluation of the weather conditions. A second component is a roadside sensor fusion system taking into account the weather conditions to evaluate the quality of the information about the perceived objects. A third component is a Cooperative Intelligence Transport Systems (C-ITS) service using V2X to share the weather conditions and the perceived objects from the infrastructure-based system to vehicles.

The first part of this report will study the benefits and limitations of relevant C-ITS services to share information on the perceived environment in complex conditions as defined in D2.1 and the use cases defined in D2.2.

The second part of this report will show the architecture of the infrastructure-based perception system compatible with ROADVIEW vehicle system architecture defined in D2.3 and answering to the requirements defined in D2.4.

In the conclusion part of this report, we will discuss about the next steps and additional features to be considered for the Collaborative Perception Solutions.

2 Benefits and Limitations of C-ITS services

In this section we will study the benefits and limitations of relevant C-ITS services for ROADVIEW targeted environment conditions defined in D2.1 and use cases defined in D2.2.

Cooperative Intelligence Transport Systems (C-ITS) are using C-ITS services for the collaboration between vehicles and infrastructure-based systems aiming at improving road safety, energy saving and traffic efficiency on the roads. The term V2X, which stands for vehicle-to-everything covers the various components of a cooperative communication system with communication from vehicle-to-vehicle (V2V), from vehicle-to-infrastructure (V2I) or from infrastructure-to-vehicle (I2V) or from vehicle-to-pedestrian (V2P).

C-ITS protocols are defined by various standardisation bodies such as ETSI (European Telecommunication Standard Institute) in Europe or SAE (Society of Automotive Engineers) in the United States. Other organisations such as CAR 2 CAR Communication Consortium (C2C-CC), 5GAA or C-ROADS Platform are key players to promote the deployment of the C-ITS services by defining some profiles on top of the specifications defined by ETSI to ensure interoperability of cooperative systems.

In the section 2.1, we will first give an overview of a cooperative ITS system and ITS station architecture. In the section 2.2, we will review the state-of-the-art of C-ITS services that could be relevant for ROADVIEW. Last in the section 2.3, we will discuss how to enhance some of the V2X messages to address complex traffic situation and harsh weather conditions.

2.1 Cooperative ITS system and ITS Station Architecture Overview

A cooperative ITS system is composed of different types of ITS stations:

V-ITS-S	Vehicle ITS station	An ITS station on-board of a vehicle. The term On-Board Unit, OBU is also used to designate the hardware equipment hosting a V-ITS-S.
P-ITS-S	Personal ITS station	An ITS station held by a pedestrian or bicyclist such as an ITS application hosted on a smartphone.
R-ITS-S	Roadside ITS station	An ITS station installed at the roadside. The term Road Side Unit, RSU is used to designate the hardware equipment host a R-ITS-S.
C-ITS-S	Central ITS station	A central ITS station can provide information about traffic conditions and can monitor the information about the local traffic situation.

Table 2: Cooperative ITS station types

The next figure shows an example of cooperative ITS system with the various ITS station types and with the presence of road users not connected through ITS stations:

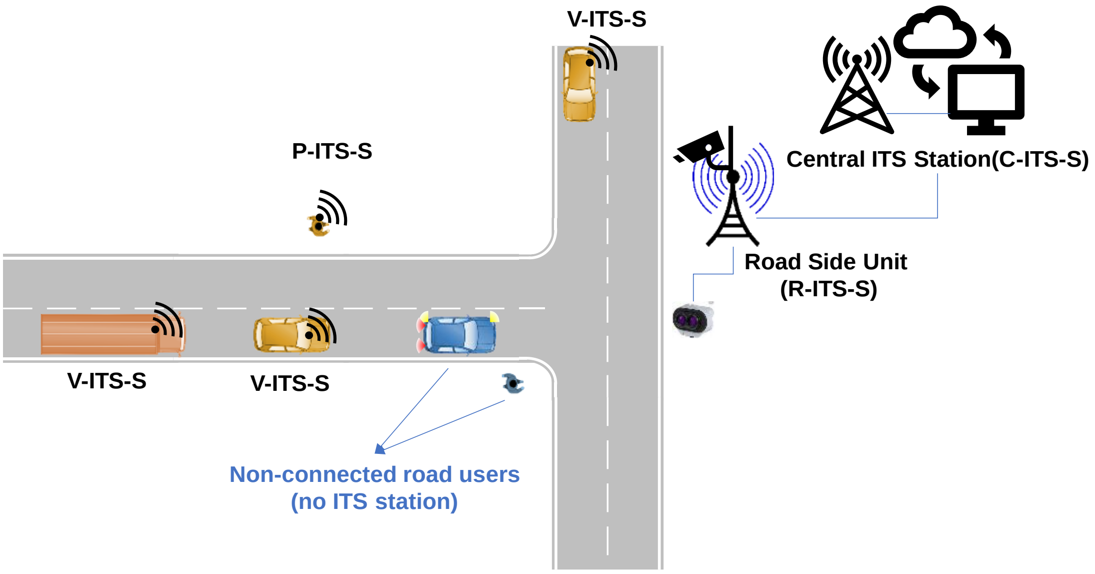

Figure 1: C-ITS System Overview

The next figure shows an ITS station architecture as defined by ETSI (ETSI EN 302 665, 2010) .

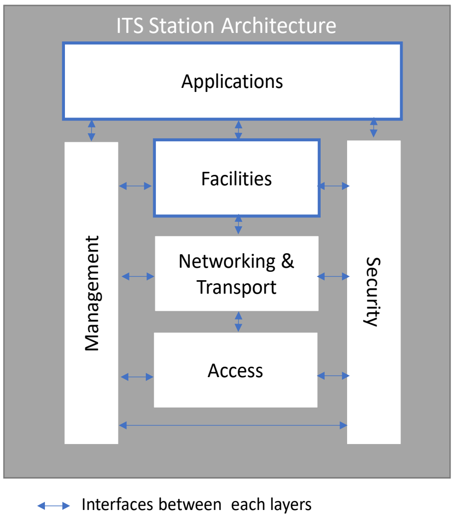

Figure 2: ITS Station Reference Architecture

In the scope of ROADVIEW, we will focus on the higher layers “Applications” and “Facilities”.

2.1.1 ITS applications

The top layer of an ITS station architecture is for the ITS applications generally grouped into “Road safety”, “Traffic efficiency” and “Other Applications”. An example of ITS application (ETSI TR 102 638, 2009) is Cooperative Adaptive Cruise Control where a subject vehicle can dynamically adapt its time gap to a target vehicle using continuous communication between both vehicles applying V2X as an additional real-time input to longitudinal control.

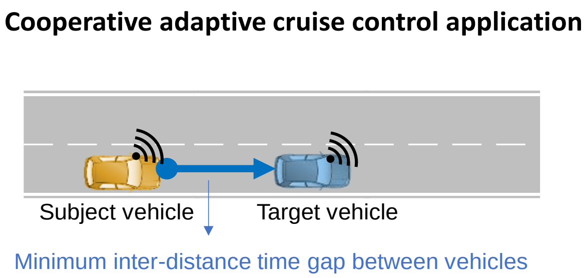

Figure 3: ITS Application example – Cooperative Adaptive Cruise Control (C-ACC) use case

2.1.2 ITS facilities and V2X messages

The ITS facilities layer defines a set of basic services to be used by the applications.

An example of basic service is the “Cooperative Awareness Service” (ETSI TS 103 900, 2023). Connected vehicles are generating radio-beacon messages named Cooperative Awareness Messages, CAMs, that are broadcasted to other ITS stations to indicates their current state. Typically, CAM can be used by the C-ACC applications illustrated in Figure 3.

In the section 2.2 we will review in more details relevant C-ITS service and corresponding V2X messages.

2.1.3 Other layers and entities

The ITS facilities layer is designed to be technology-agnostic for the access layer. The access layers define the various possible radio communication interfaces for ITS-G5, Wi-Fi, Cellular, etc.

The networking & transport layer contains functionality from the OSI network and transport layers (e.g. ITS-specific such as GeoNetworking, TCP, UDP, IPv6 or other protocols).

Last, there are two cross-layer entities: management and security. Security is in charge of checking the validity of the messages. Management entity is in charge of cross-layer parts such as the management of multi-channel operations.

Various studies are comparing ITS-G5 (IEEE802.11p) short-range radio technology for direct communication and cellular-V2X. Experimentations in Finland related to the communication in real-time of weather measurements were done using cellular-based network (LTE, 5G) and ITS-G5 (Tahir, Leviäkangas, & Katz, 2022) (Tahir, Maenpaa, Sukuvaara, & Leviakangas, 2021). Their conclusion was that all those radio technologies fulfilled the minimum requirements of the ITS-road weather and traffic platform to offer reliable communication for enhanced road traffic safety.

For ROADVIEW demonstrations, we will rely on LTE, 4G or 5G connectivity as available in each demonstration vehicle (WP8) and test locations. However, the enhanced V2X messages proposed in ROADVIEW could be deployed also on ITS-G5 radio technology.

2.2 Relevant C-ITS services and V2X Messages

In this section we will focus on C-ITS services defined at the facilities layer relevant to ROADVIEW use cases.

In term of implementation, a first release of C-ITS services is already deployed in Europe by some car manufacturers and road operators to provide basic awareness services with some danger notifications services.

A second release is planned to be deployed from 2025 as the interoperability test specifications will be prepared in 2024. This second release will provide extension of the first release with additional service to share the perception environment to extend the global situation awareness. This is totally in the scope of the ROADVIEW robust perception system developed in WP5.

A third release will address more largely autonomous vehicles and will be studied in the scope of the ROADVIEW control and decision-making system developed in WP6.

2.2.1 Basic awareness services

A first set of basic awareness services allows vehicles or VRUs to provide information about their current state.

2.2.1.1 Cooperative Awareness Message (CAM)

The Cooperative Awareness Message, CAM standardised by ETSI ITS (ETSI TS 103 900), is a vehicle radio beacon message containing the ego-vehicle position, speed, heading, driving direction (forward or backward), vehicle length and width, longitudinal acceleration, curvature and yaw rate.

This information can be used by other vehicles and the road infrastructure to know where the ego-vehicle is and where its heads to.

Typically, CAM are broadcasted by each vehicle in its vicinity with a frequency of 1 to 10 Hz, depending on the vehicle velocity or change of direction.

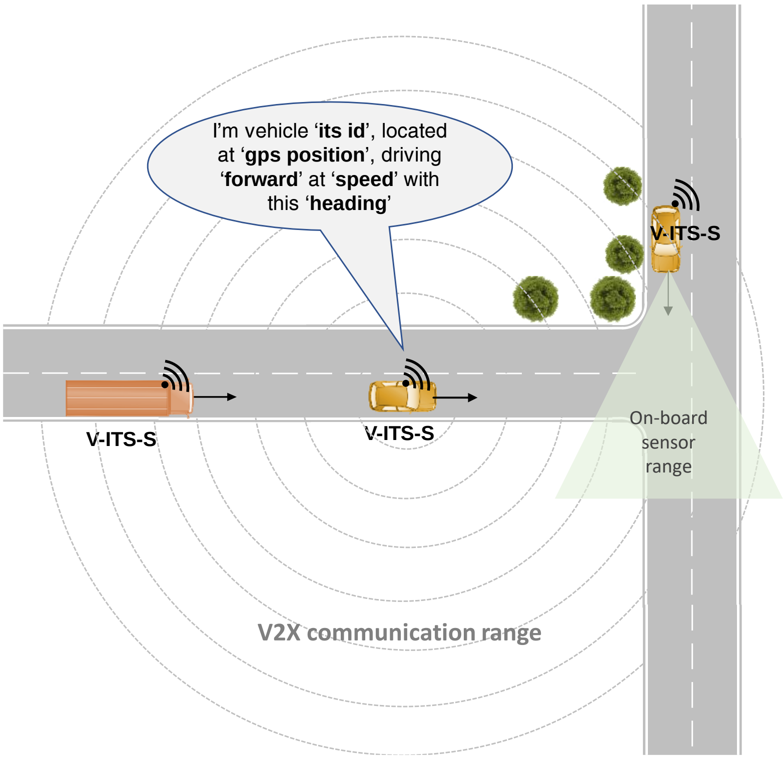

Figure 4: Example of use of Cooperative Awareness Message, CAM

CAM	Cooperative Awareness Service
BENEFITS	V2X communication range is higher than the sensor perception range especially in case of low visibility. CAM Release 1 service is already deployed in Europe.
LIMITATIONS	Not all vehicles are connected and able to generate CAM.
PLAN TO USE IN ROADVIEW	No plan to use directly. In the scope of WP6, the autonomous vehicle will share its current state and short-term planned trajectory using Manoeuvre Coordination Message, MCM. The Vehicle Manoeuvre information will contain similar information present in CAM (position, speed and heading) with additional description of the vehicle intention.

Table 3: Benefits and limitations of C-ITS Cooperative Awareness Service (CAM)

2.2.1.2 Vulnerable Road User (VRU) Awareness Message (VAM)

Similar to CAM, VRU Awareness Message, VAM, is intended to be used by Vulnerable Road Users to indicate their ego-position and speed and is also standardised by ETSI ITS (ETSI TS 103 300-3). Various profiles of VRU are considered such as pedestrian, bicyclist, motorcyclist or animal.

In urban area, complex situation with many pedestrians or many bicyclists may lead to a high number of VAMs. A VRU Clustering function is enabling to have a single VRU (VRU Cluster Leader) that emits a VAM representing all the VRUs of the cluster.

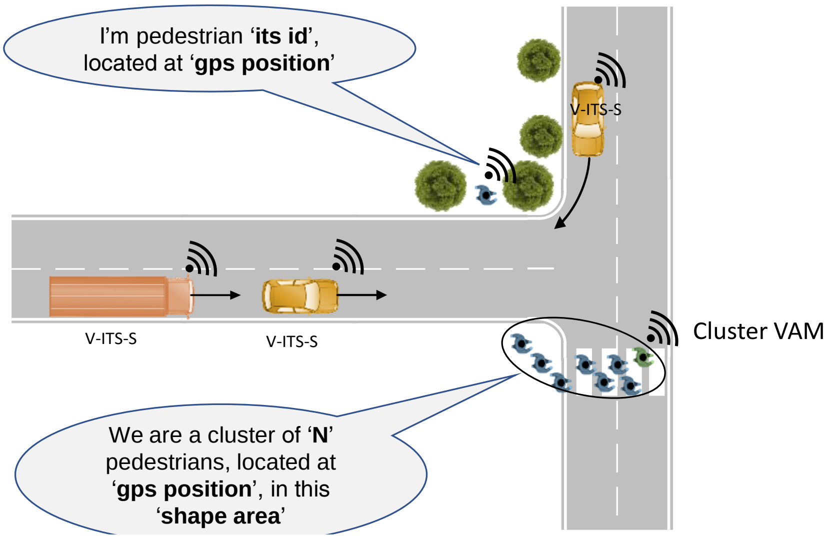

Figure 5: Example of use of VRU Awareness Message, VAM

VAM	**VRU Awareness Service**
BENEFITS	As for CAM, V2X communication range is higher than the sensor perception range especially in case of low visibility. VRUs can be difficult to recognise in harsh weather condition due to their small size or possibly occluded behind a vehicle. Grouping of VRUs in a VAM Cluster reduces the radio channel usage in case of urban area with the presence of many ITS stations.
LIMITATIONS	VAM service is not yet deployed, it is part of ITS release 2. As for vehicles, not all VRUs will be equipped with an ITS station.
PLAN TO USE IN ROADVIEW	No plan to use VAM during ROADVIEW demonstrations. However, VAM is part of the recommended C-ITS service to be included in Collaborative Perception Solutions.

Table 4: Benefits and limitations of C-ITS VRU Awareness Service (VAM)

2.2.2 Infrastructure services

Infrastructure to vehicle (I2V) services defined by ETSI ITS (ETSI TS 103 301) can provide:

- Information for the traffic light using Signal Phase and Timing, SPAT message
- Information on the road and lane topology using MAP (map data) message
- Information on the road signs (static or variable road signs) or road works using Infrastructure to Vehicle Information Message (IVIM).

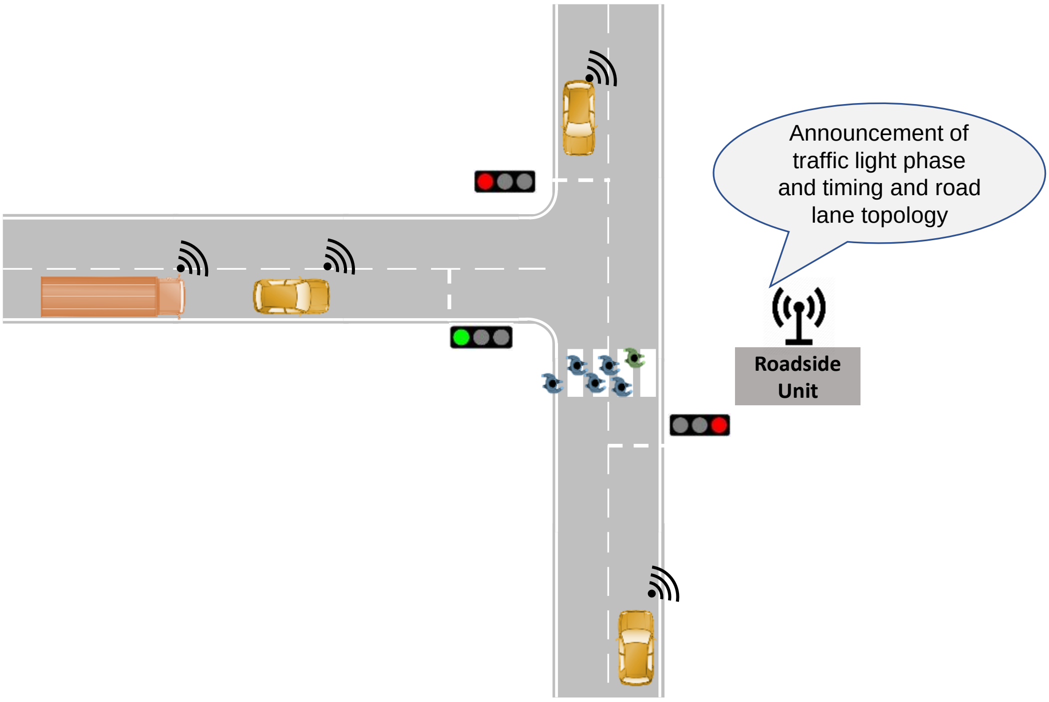

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Figure 6: SPAT/MAP message use case

IV2	**Infrastructure to vehicle (I2V) services**
BENEFITS	In case of harsh weather conditions, automated driving recognition may be affected (Yoneda, Suganuma, Yanase, & Aldibaja, 2019). For example, in case of sunlight traffic light recognition may be difficult, thus getting the traffic light phase and timing through an infrastructure to vehicle (I2V) message could overcome this issue. In case of snow, the road surface is recovered and the lane lines are no more visible. I2V message could be sent by the infrastructure to provide the road geometry to connected vehicles. Infrastructure-based messages (IVIM, SPAT/MAP) are already deployed by road operators or cities (part of ITS Release 1).
LIMITATIONS	Lack of deployment in rural areas.
PLAN TO USE IN ROADVIEW	No plan to use I2V messages during the ROADVIEW demonstrations. However, such messages are relevant for the harsh weather conditions. In the scope of WP6, we plan to use weather-aware speed advice from the infrastructure to the vehicle but using Manoeuvre Coordination Message, MCMs rather than IVIM or SPAT messages.

Table 5: Benefits and limitations of Infrastructure to vehicle, I2V such as IVIM or SPAT/MAP messages

2.2.3 Collective Perception Service

The Collective Perception Service allows to share the sensor detections between vehicle and infrastructure to help/warn vehicles. The Collective Perception Message, CPM, may be broadcasted by vehicles or road side units equipped with sensors such as cameras, LiDAR, radar, etc.

As CAM, the CPM are broadcasted to other road users in the vicinity at a frequency of 1 Hz to 10 Hz depending on dynamics or the type of the perceived objects reported in the CPM.

CPM enables to extend the field of view of other nearby vehicles. This is very useful at intersection or in case of occlusion.

In the context of ROADVIEW, in case of harsh weather conditions such as fog, vehicles will have limited visibility. By using CPM vehicles and roadside units can extend each other their situation awareness. For the protection of VRUs, CPM is also very interesting to share the position of detected pedestrians that may be occluded to the other vehicles.

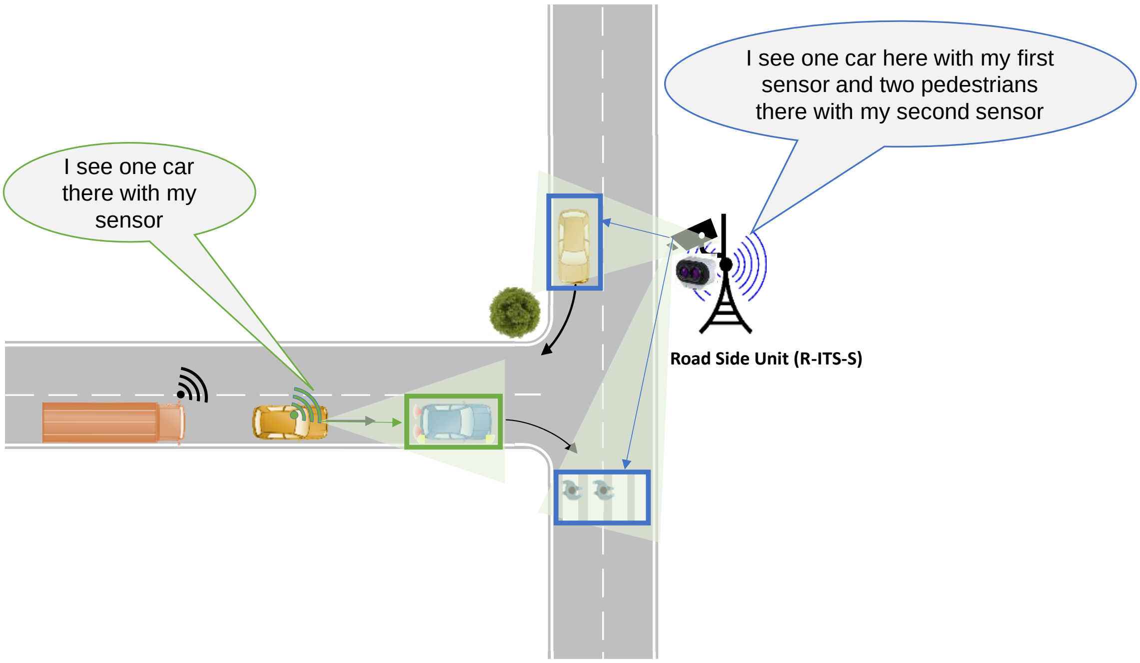


Figure 7: Example of use of Collective Perception Message

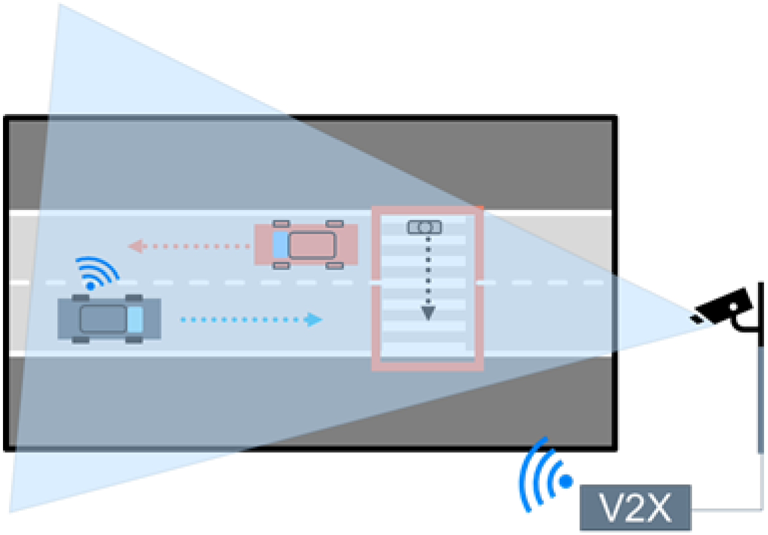
CPM	Collective Perception Service
BENEFITS	Collective Perception Message, CPM, enables to share information about non-connected road users detected by on-board or roadside sensors. CPM is an essential C-ITS service to extend the field of view of ITS stations and to provide awareness included the non-connected road users.
LIMITATIONS	Collective perception service is not yet deployed. Quality of the information contained in CPMs may be altered by the perception conditions especially in the case of harsh weather conditions.
PLAN TO USE IN ROADVIEW	In WP5, CPM will be an essential feature to integrate the infrastructure-based perception system with the on-board perception system. Especially we plan to include the quality information based on the sensor ODD in case of harsh weather conditions. Example of use case extracted from D2.2 where CPM will be demonstrated to extend the perception of the autonomous vehicle is shown here:  **Figure 8: Infrastructure-based Based Solution Scenario to show VRU protection**

Table 6: Benefits and limitations of C-ITS Collective Perception Service (CPM)

2.2.4 Manoeuvre Coordination Service

Another relevant C-ITS service that is being standardised by ETSI is the Manoeuvre Coordination Service (ETSI TR 103 578) . This service can be used between vehicles or between the infrastructure and vehicles to coordinate a manoeuvre. Example of manoeuvre could be lane merging on a highway. This type of service is very relevant for automated driving. In case of trajectory conflict between automated vehicles, the Manoeuvre Coordination Messages, MCM, can be used for agreement seeking between the vehicles. Prescriptive mode is also envisaged for the infrastructure or authorities to request some trajectories to the vehicles (e.g. emergency vehicle use case). In rural area or urban area, this service can be used for left-turn assistance in uncontrolled intersections. In highway, this service can be used for lane merging.

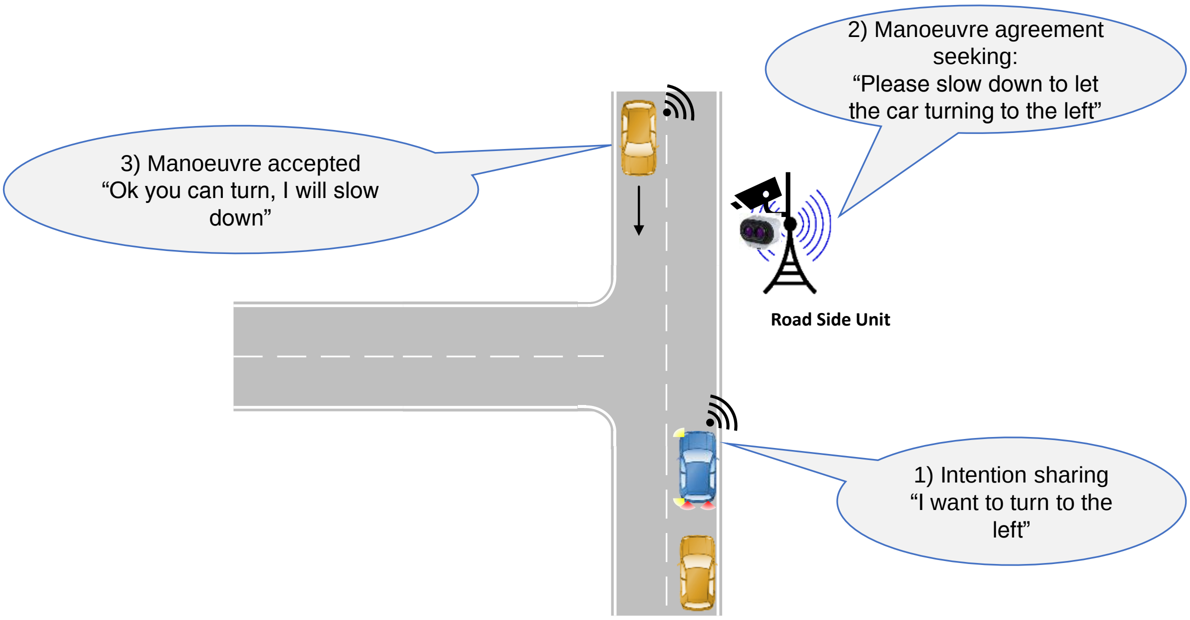


Figure 9: Example of left turn assistance using Manoeuvre Coordination Service

MCM	Manoeuvre Coordination Service
BENEFITS	Manoeuvre Coordination service is an essential feature to enable automated vehicles to manage conflict of trajectories by agreement seeking or even by prescription from an infrastructure-based system. MCM should be a key marker for ITS Release 3, whereas CPM should be a key marker for ITS Release 2.
LIMITATIONS	Impact of the weather conditions to coordinate vehicles is not yet studied and should be addressed to extend the ODD of automated vehicles in case of harsh weather conditions. MCM deployment plan is not yet well defined. It is expected to be a key marker of ITS Release 3, while CPM is expected to be a key marker of ITS Release 2.
PLAN TO USE IN ROADVIEW	For the control and decision-making system (WP6) we plan to use MCM: - For the vehicle side to indicate its short-term trajectory (vehicle manoeuvre) - For the infrastructure to provide some weather-aware speed or lane change advice or to trigger a Minimum Risk Manoeuvre (MRM) request to the autonomous vehicle based on the weather conditions. More details about it will be described in D6.3.

Table 7: Benefits and limitations of C-ITS Manoeuvre Coordination Service (MCM)

2.2.5 Danger notification service

The Decentralised Environment Notification service (ETSI TS 103 831) allows to generate warning messages triggered by an event.

Decentralised Environmental Notification Message (DENM) is event-triggered and warns about hazardous locations. This message can be forwarded from vehicle-to-vehicle in the relevance area of the message.

DENM can be emitted by a vehicle ITS station or by a roadside ITS station. Examples of warning causes are listed here:

- Collision risk
- Accident
- Road works
- Adverse weather conditions
- Stationary vehicle
- Traffic jam
- …

DENM warns the vehicles or the roadside units about risks, but it is not suggesting any manoeuvre or action to mitigate the risk.

DENM comprises information about the event position, the relevance or awareness area and is emitted regularly as long as the event is applicable.

DENM includes the cause and/or sub-cause code to categorise the warning. Depending on the warning type additional information in optional message container can be added.

In the context of ROADVIEW, the DENM for adverse weather conditions is of interest. As DENM is a warning message it should be emitted only in case of high risk otherwise too many messages maybe considered as false alarm or congest the radio communication channel as DENM has highest priority than other messages.

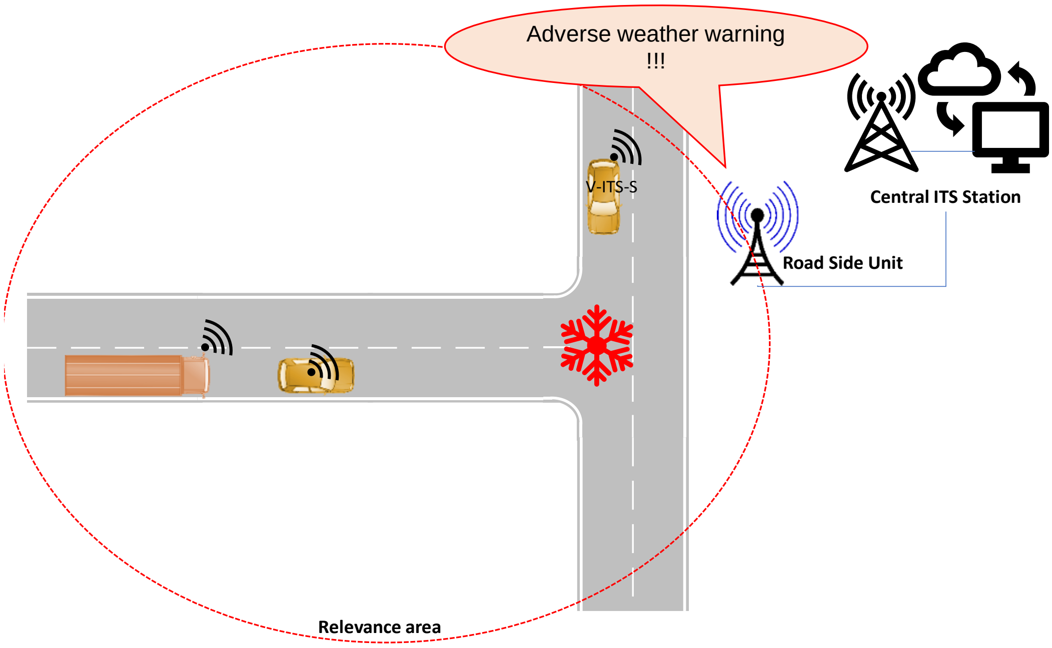


Figure 10: Example of DENM for adverse weather conditions

Here is a summary of possible DENM adverse weather conditions cause values related to ROADVIEW environment conditions defined in ROADVIEW deliverable D2.1:

DENM Cause Value	Sub Cause Value
Visibility	unavailable(0), fog(1), smoke(2), heavySnowfall(3), heavyRain(4), heavyHail(5) lowSunGlare(6), sandstorms(7), swarmsOfInsects(8)
Precipitation	unavailable(0), heavyRain(1), heavySnowfall(2), softHail (3)
Traction loss	unavailable(0) heavyFrostOnRoad(1), fuelOnRoad(2), mudOnRoad(3) snowOnRoad(4), iceOnRoad(5), blackIceOnRoad(6) oilOnRoad(7),looseChippings(8),instantBlackIce(9),roadsSalted (10)

Table 8: summary of DENM cause codes related to weather conditions

Various organisations such as the CAR-2-CAR Communication Consortium for the vehicle side and C-ROADS platform for the infrastructure side, have defined what are the triggering conditions to generate a DENM in case of adverse weather conditions (CAR 2 CAR Communication Consortium, Basic System Profile, 2023) (C-ROADS Platform, 2021).

For example, C2C-CC basic system profile for adverse weather is focusing on three use cases for fog, precipitation and traction loss. The profile specifies a relevance distance of 1000 m and a validity duration of 300 s in urban area or 600 s or type of areas. DENM warning message is also repeated every 1 s while the event is present.

When the weather conditions are not considered as adverse there is no message generated.

DENM	**Decentralised Environmental Notification Service**
BENEFITS	DENM warning release 1 has been already deployed by some road operators in Europe. Warning cause code are existing for some of adverse weather conditions
LIMITATIONS	DENM warning is only triggered in case of adverse weather conditions. ROADVIEW targets to sharing the weather estimations not only in case of harsh weather conditions is also one of objective in the ROADVIEW. Not all connected vehicles or infrastructure systems will have the same weather measurement sensors or algorithms. Determination of the current road weather conditions are also necessary to determine if the vehicle or the infrastructure sensors are in their ODD
PLAN TO USE IN ROADVIEW	No plan to use DENM during the ROADVIEW demonstration. However, the trigger to generate a DENM warning for adverse weather conditions could be done using the weather estimation developed in ROADVIEW task 5.2 and 5.3.

Table 9: Benefits and limitations of C-ITS Decentralised Environmental Notification Service

2.2.6 Road Weather Service

SAE has defined requirements for road weather applications (SAE J2945-3) that specifies a road weather message that can be used to collect data about weather between various vehicles or roadside units for weather applications. Message Data elements are described in SAE (V2X Communications Message Set Dictionary) (SAE J2735).

Contrary to the DENM warning, the RWM is broadcasted periodically with repetition rate between one to two times per second. This message can be used to describe a current weather situation at a location point. It comprises the following information:

- Reference time of the weather situation data
- Location of the collecting ITS station (vehicle or road side unit)
    - Geographical location
    - Direction or travel or heading in the case of vehicle
- Weather situation data: can be comprise a set of values among:
    - air temperature
    - atmosphere
    - wind
    - humidity
    - dewpoint
    - pavement
    - visibility
    - cloud situation
    - precipitation situation
    - solar radiation

The weather situation data contains data elements derived from the National Transportation Communications for ITS Protocol Environmental Sensor Station (ESS) Interface Protocol, (NTCIP 1204, 2022). The NTCIP 1204 is also referring to some international codes defined by the World Meteorological Organisation ((WMO Manual on Codes, 2022).

In the table below, we provide an extract of NTCIP elements that can be included in the SAE RWM that are relevant to the ROADVIEW weather estimates and to the ROADVIEW environment conditions defined in deliverable D2.1.

Ntcip element	Code
Visibility	Visibility range in one tenth of meter
Visibility situation code	other (1), unknown (2), clear (3), fogNotPatchy (4), patchyFog (5), blowingSnow (6), smoke (7), seaSpray (8), vehicleSpray (9), blowingDustOrSand (10), sunGlare (11), swarmsOfInsects (12)
Precipitation situation code	other (1), unknown (2), noPrecipitation (3), unidentifiedSlight (4), unidentifiedModerate (5), unidentifiedHeavy (6), snowSlight (7), snowModerate (8), snowHeavy (9), rainSlight (10), rainModerate (11), rainHeavy (12), frozenPrecipitationSlight (13), frozenPrecipitationModerate (14), frozenPrecipitationHeavy (15)
Pavement surface status	other (1), error (2) dry (3), moist (4), chemicallyMoist(5), wet (6), chemicallyWet (7), standingWater (8), frost (9), slush (10), snow (11), ice (12), noReport (13)
Mobile friction	Integer value between 0 and 101 as the measured coefficient of friction in percent. 101 value indicate an error condition of a missing value

Table 10: extract of SAE RWM data element for weather conditions

In Europe, ETSI has not yet defined an equivalent of the SAE Road Weather Message. In ROADVIEW project, we will use an approach similar to SAE RWM to share the weather estimation between the vehicles and the infrastructure-based system. However, DENM warning could be anyway triggered in addition of the RWM to alert road users in case of adverse weather conditions.

RWM	**Road Weather Service**
BENEFITS	Road Weather Message can be used to shared weather conditions between connected vehicles and roadside units.
LIMITATIONS	Current version of the SAE RWM is more targeting the sharing of weather sensor measurements. In Europe there is no specification so far of a similar service to share weather conditions apart from the DENM warning.
PLAN TO USE IN ROADVIEW	Road Weather Message concept will be adapted to ROADVIEW weather estimators developed in task 5.2 for the roadside and task 5.3 for the vehicle side. Please refer to section 2.3 for the proposed enhancement.

Table 11: Benefits and limitations of C-ITS Road Weather Service

2.3 Summary relevant C-ITS services

C2C-CC have reviewed in a white paper (CAR 2 CAR Communication Consortium, 2023) the research and development projects in Europe in connected automated driving. They have identified that important common technologies for automated driving are cooperative perception, trajectory or intention sharing.

In ROADVIEW project, we plan to address cooperative perception in WP5 using Collective Perception service identified as a key marker of ETSI ITS release 2 to extend the global situation awareness. In WP6, we also plan to address trajectory or intention sharing using Manoeuvre Coordination service identified as a key marker of ETSI ITS release 3 for autonomous driving. Regarding the weather-related aspects, they are not yet addressed. We plan to extend the road weather service specified by SAE.

The next table summarises the relevant C-ITS services plan to be implemented and evaluated in ROADVIEW.

C-ITS Service	**V2X Message**	**Related standards**	**Purpose and adaption for ROADVIEW**
Collective Perception Service	CPM	ETSI TS 103 324	This service allows to share local sensor information and perceived object information using CPMs. In task 5.2, we will develop and evaluate CPM taking into account the sensor ODD and the quality of the perception based on the weather conditions.
Road Weather Service	RWM	SAE J2945-3	This service allows to share weather information collected from weather sensors using RWMs. This message will be enhanced by CRF to share the roadside weather type estimation developed by CE (task 5.2) and the vehicle on-board visibility estimation developed by VTT and slipperiness estimation developed by FGI (task 5.3).
Manoeuvre Cooperation Service	MCM	ETSI TR 103 578	This service allows cooperation between autonomous vehicles in case of trajectory conflicts. This message will be adapted with some weather-aware manoeuvre requests and responses in the scope of task 6.3.

Table 12: Relevant C-ITS services planned to be evaluated and demonstrated in ROADVIEW

Other relevant C-ITS services that will not be implemented nor evaluated in ROADVIEW are recalled in the next table. Except VAM, other C-ITS services are already deployed in ITS Release 1 and their benefits are already well-studied.

C-ITS Service	V2X Message	Related standards	Purpose and adaption for ROADVIEW
Cooperative Awareness Service	CAM	ETSI TS 103 900	This service allows the ego-vehicle to disseminate its current state (position, speed, heading).
VRU Awareness Service	VAM	ETSI TS 103 300	Similar to the CAM, allows a VRU equipped with a C-ITS station to disseminate its current state.
Decentralised Environment Notification Service	DENM	ETSI TS 103 831	This service allows the notification of dangerous situation on the road.
Infrastructure Service	IVIM MAP SPAT	ETSI 103 301	This service allows to inform about the road and lane topology, about the traffic light signal phase and timing or to provide road signs to connected vehicles.

Table 13: Other relevant C-ITS services

3 ROADVIEW Collaborative Perception Solutions

In this second part of this deliverable, we will describe the various elements of the ROADVIEW collaborative perception solutions and the software architecture.

ROADVIEW collaborative perception solutions consist in exchanging information about locally perceived data between different traffic participants using V2X to increase their awareness of the local environment. The system is composed of ITS stations on-board of vehicles (also called On Board Unit, OBU) and will also integrate infrastructure-based perception system (also called Road Side Unit, RSU). Such roadside system is providing additional capacities to the collaborative perception system thanks to:

- wider field of view, different perspectives (higher position of the sensors),
- stationary, precise positioning systems,
- higher processing power to perform analysis.

3.1 Architecture Overview

The ROADVIEW infrastructure-based perception system uses various types of stationary sensors (RGB camera, LiDAR, RADAR) to analyse the situation and will exchange information about the local perceived environment with V2X connected vehicles using Road Weather and Collective Perception Services previously described in section 2.2.3

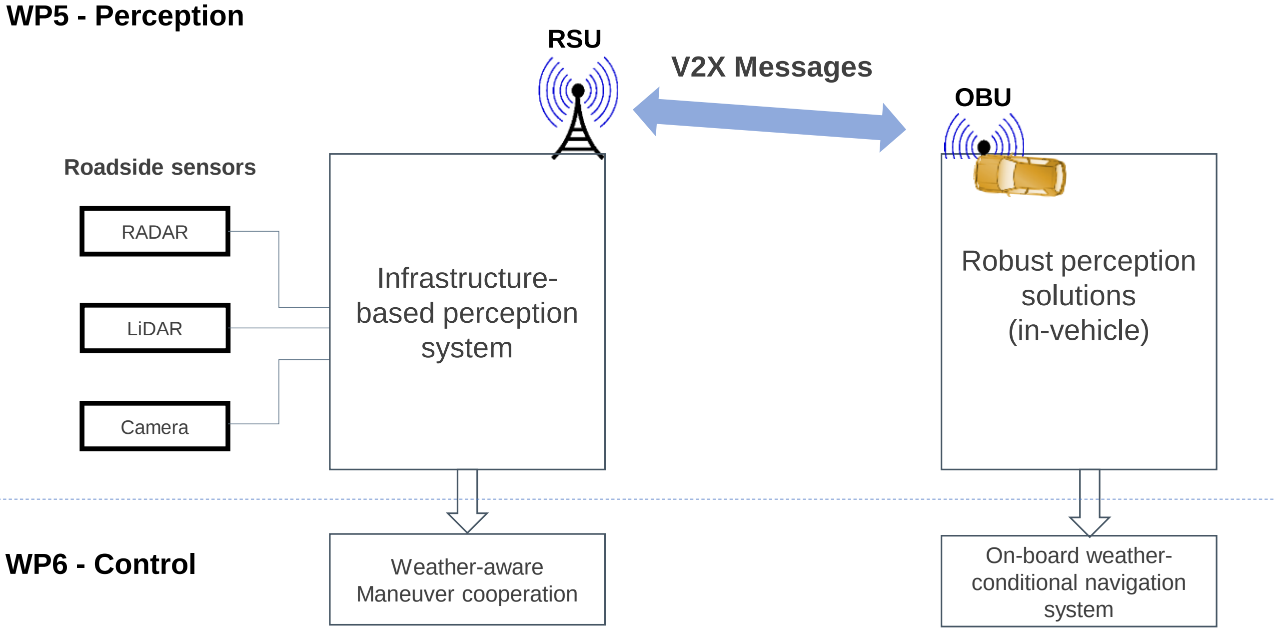


Figure 11: Collaborative Perception Solution Overview

The information from the perception systems (WP5) are used as input for the control and decision-making systems (WP6). The automated vehicle should be able to make safe decisions based on the sensor information, either local or remote. In case of harsh weather conditions, the quality of the sensor measurements might be affected.

First, to evaluate the ODDs of the sensors based on the weather conditions, the Collaborative Perception Solutions include a Collaborative Road Weather Service that will be further described in section 3.2.

Second, in section 3.3 we will describe the architecture of the infrastructure-based perception system for the roadside sensor fusion taking into account the sensor ODDs.

Then in section 3.4 we will describe the collaborative perception solution integrating the infrastructure-based perception system. The quality of the reported information using V2X messages is crucial for a reliable sensor fusion, traffic analysis and decision-making system and shall comprise information about the sensor ODD and the impact on their predictions.

Last, in section 3.5 we will describe the architecture of the C-ITS services for the generation and reception of V2X messages.

3.1.1 Position of V2X infrastructure system in ROADVIEW reference architecture

The next figure shows the positioning of the infrastructure-based perception system in the ROADVIEW reference architecture defined in D2.3.

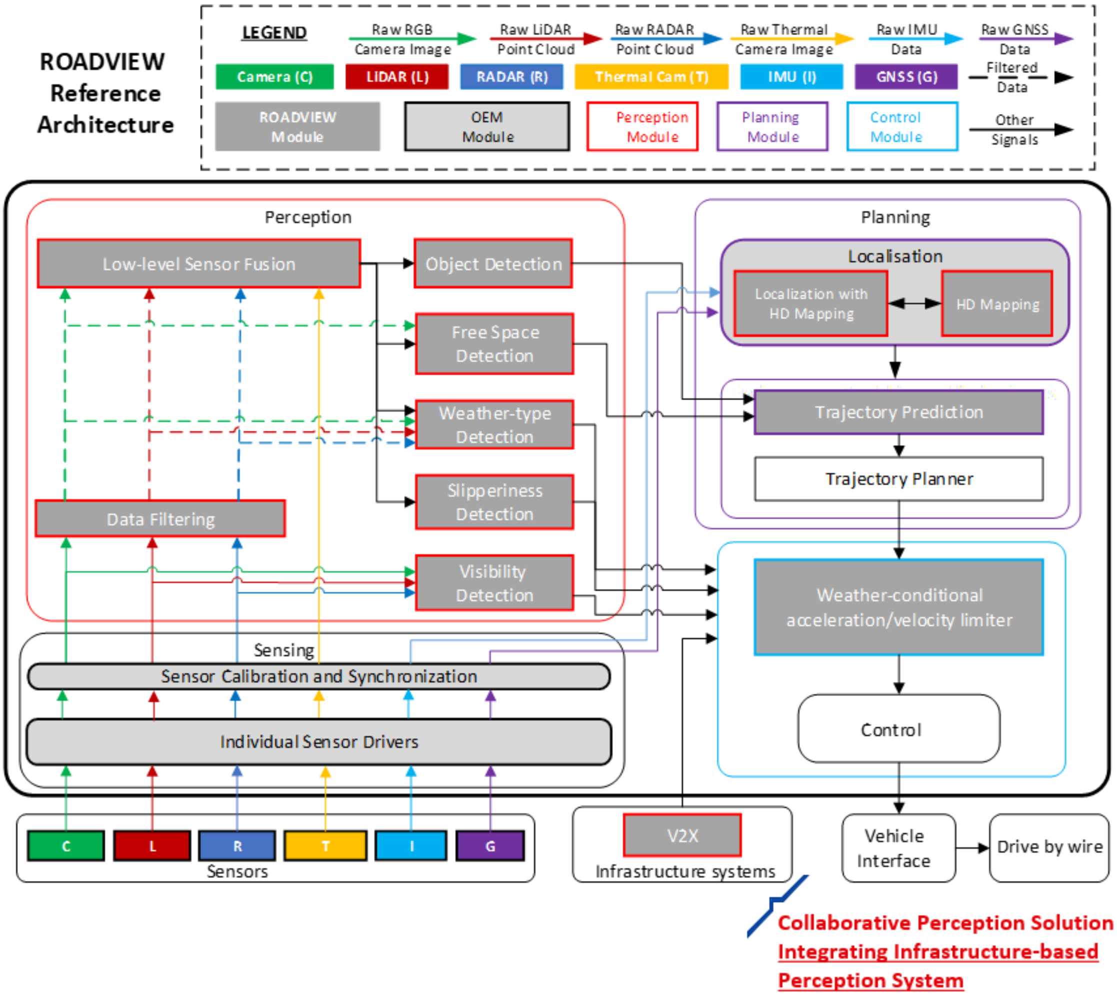


Figure 12: Integration of infrastructure-based perception system in the ROADVIEW reference architecture

The integration of the V2X part in each demonstration vehicle can be slightly different as illustrated in the various demonstration vehicle architectures provided in D2.3.

The V2X data from the infrastructure-based perception system can be fused with the on-board perceived data in the late fusion algorithms to increase the situation awareness usually included in the environment model or the local dynamic map of the connected autonomous vehicles. The next figure shows the reference architecture of demo 4 (FORD vehicle) (D2.3):

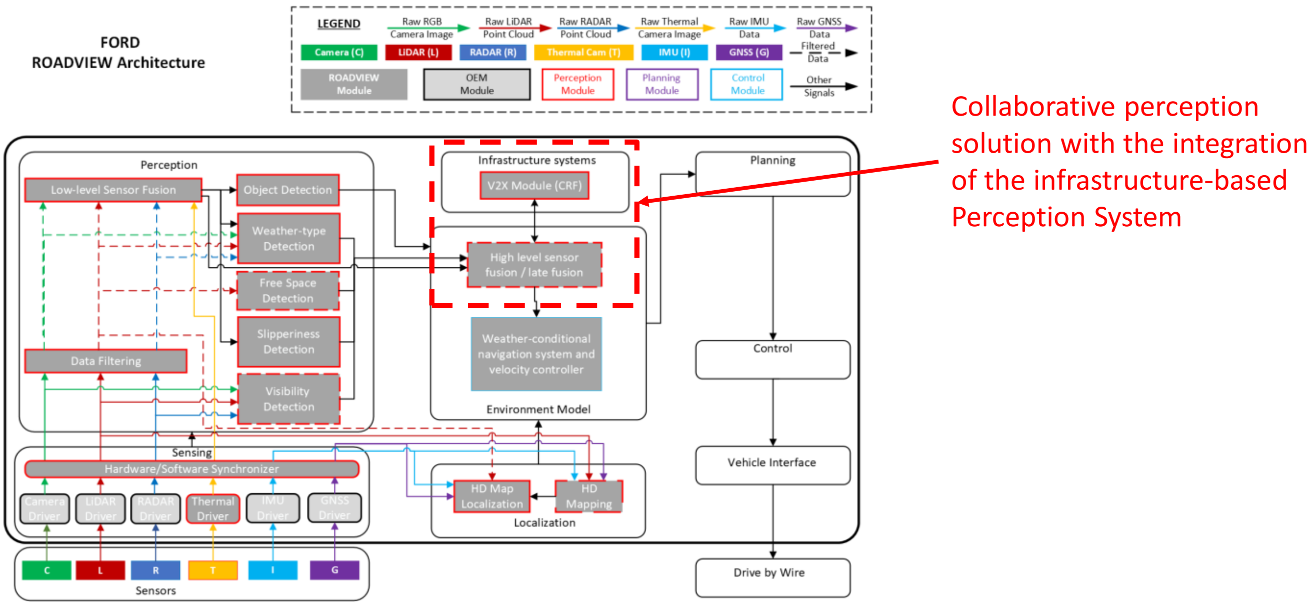


Figure 13: Integration of infrastructure-based perception system in the ROADVIEW demo 4 architecture

3.1.2 Physical architecture of the infrastructure-based perception system

In the next steps of task 5.2, the roadside system is planned to be installed in the Lapland to evaluate the collective perception solutions in harsh weather conditions. The next figure illustrates an overview of the equipment to be installed. RGB camera and LiDAR are planned to be mounted on the pole as roadside sensors. For RADAR sensor type, tests will be done only using pre-recorded datasets from WP3.

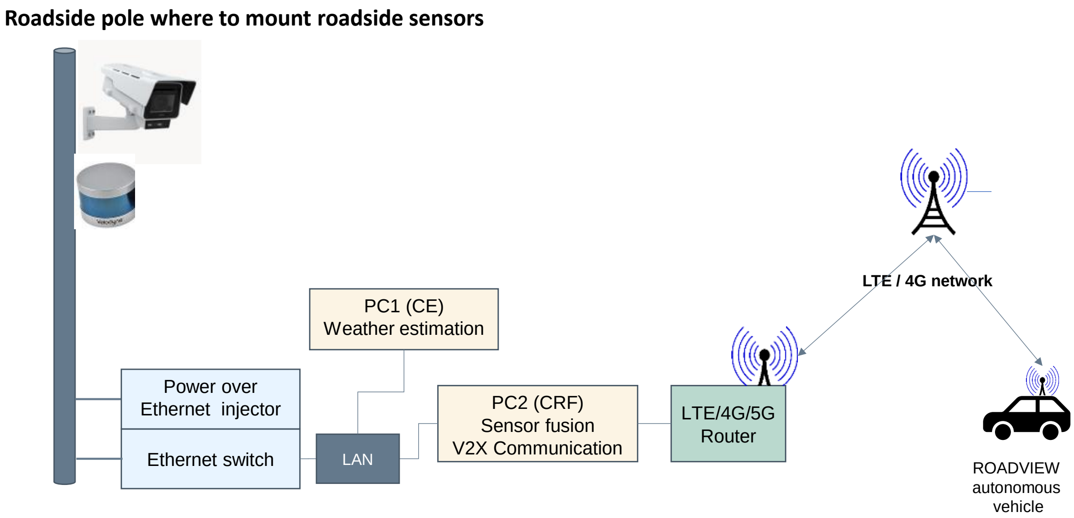


Figure 14: Physical set-up of the roadside perception system

3.1.3 Functional architecture

In the next figure we illustrate the main functions of the collaborative perception solutions.

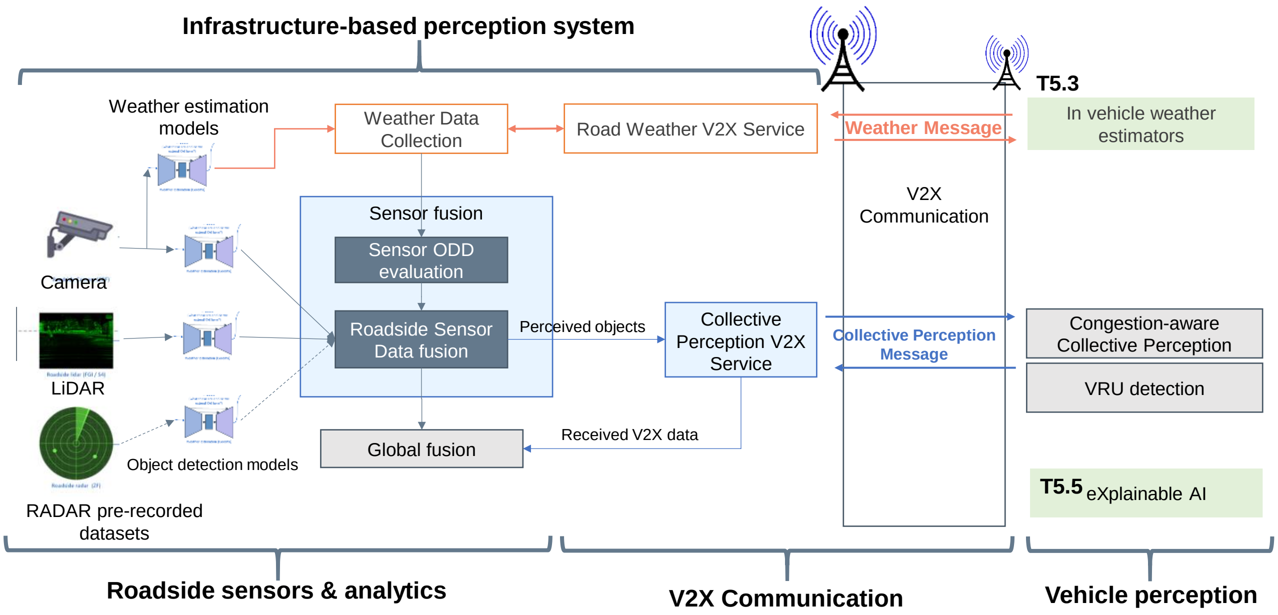


Figure 15: Collaborative Perception Solutions Overview

First, to evaluate the ODDs of the sensors based on the weather conditions, the Collaborative Perception Solutions include a Collaborative Road Weather Service that will be further described in section 3.2. This road weather service will also integrate the in-vehicle weather estimators developed in task 5.3.

Second, in section 3.3 we will describe the architecture of the infrastructure-based perception system for the roadside sensor fusion taking into account the sensor ODDs.

Then in section 3.4 we will describe the collaborative perception solution integrating the infrastructure-based perception system. The quality of the reported information using V2X messages is crucial for a reliable sensor fusion, traffic analysis and decision-making system. CPM V2X messages shall comprise information about the sensor ODD and the impact on their predictions as specified in the requirements of eXplainable AI in task 5.5.

Last, in section 3.5 we will describe the architecture of the V2X communication part to generate and receive V2X messages for the relevant C-ITS services to be used in ROADVIEW.

Remaining functions to be further considered in the next steps of task 5.2 are:

- Global fusion between the local data and the received data from V2X,
- Sharing of the VRU detection from the FGI LiDAR in artic weather conditions using collective perception,
- Study of congestion-aware collective perception.

3.2 Collaborative Road Weather Service

The Collaborative Road Weather Service will share the estimations about the weather conditions provided by several ROADVIEW modules:

- Weather type estimation from roadside camera images developed in this task 5.2 by CE (see section 3.2.1),
- On-board weather estimation for visibility (VTT) and for road slipperiness (FGI) will be developed in task 5.3.

The information about the weather estimations will be shared using enhanced V2X Road Weather Message described in section 3.2.2.

3.2.1 Weather type estimation from roadside sensors

The camera-based perception system will be based on a machine learning mechanism. A review of the literature has identified three possible approaches: classical classification methods (Machine Learning based algorithms e.g. Deep Conventional Neural Networks, DCNNs), methods using attention mechanisms (Transformers DCNNs), and the indirect use of Generative Adversarial Networks (specific DCNNs GANs). The first method envisaged is based on the use of standard classification mechanisms, such as DCNNs, applied to input images with the type of weather encountered as output. This type of approach has already been successfully used to detect rain, fog and clear weather (Dahmane, et al., 2021) (Ibrahim, Haworth, & Cheng, 2019) (Xia, Xuan, Tan, & Xing, 2020). The main drawback of these approaches is that scene's change (change of camera location) can lead to a drop in the detection rate due to the well-known domain bias. In fact, this more recent type of classification method takes better account of low-level aspects in images (contours, contrasts, colors, textures, etc.). The attention-based methods will probably improve the results obtained with conventional methods (Li & Luo, 2023). The third approach we are looking at is the roundabout use of GANs (Park, Efros, Zhang, & Zhu, 2020) (Zaher, 2020) (Zhu, Park, Isola, & Efros, 2017). A GAN comprises two neural networks: the first is used to change the style of an image (e.g. from a clear-weather image to the same image in the rain), while the second acts as a discriminator. The discriminator's role is to tell whether the image presented to it is a real image or not. In WP3, GANs will be used to simulate weather on images. It will therefore be proposed to reuse the discriminator obtained for image classification in this task. This innovative method will be put to the test against conventional methods.

The software architecture will be the same whatever the method used. A specific computer (with a graphics card) will be installed in parallel with the CRF machine managing the V2X messages as shown in Figure 14. The camera, the CRF machine and the Cerema weather detection machine will all be on the same network. The Cerema machine will retrieve an image from the CRF surveillance camera every second. For each image, it will apply the weather detection method, followed by temporal filtering. This will send the type of weather detected, with an associated confidence index, to the CRF machine at least once a minute. This will be sent over the network in TCP server/client mode.

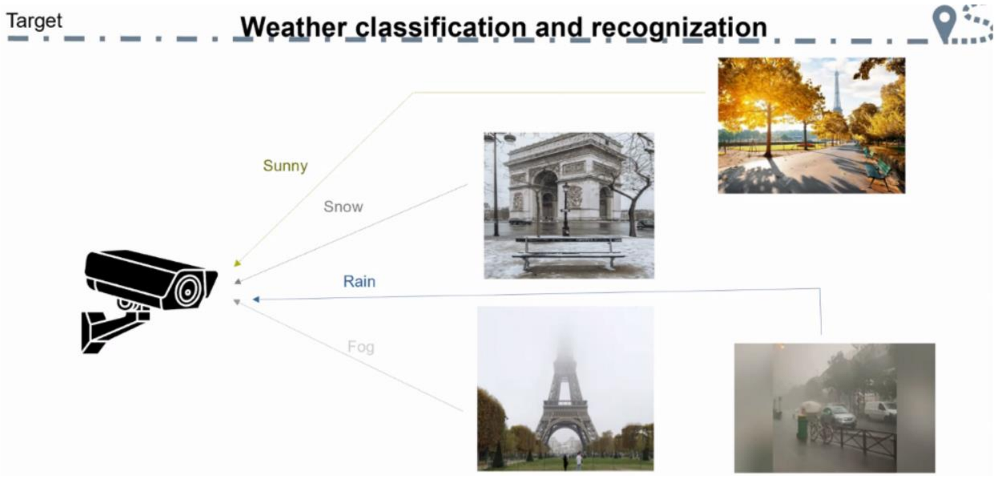


Figure 16: Weather type classification from RGB camera image

3.2.2 Road Weather Message (RWM)

The ROADVIEW road weather message (RWM) is used to share weather condition estimates from the various ROADVIEW modules developed either in Task 5.2 or Task 5.3. Using RWM, other road users that may not have such weather estimation system can then benefit of more precise weather information.

The next figure shows an example of the message sequence and the message content overview.

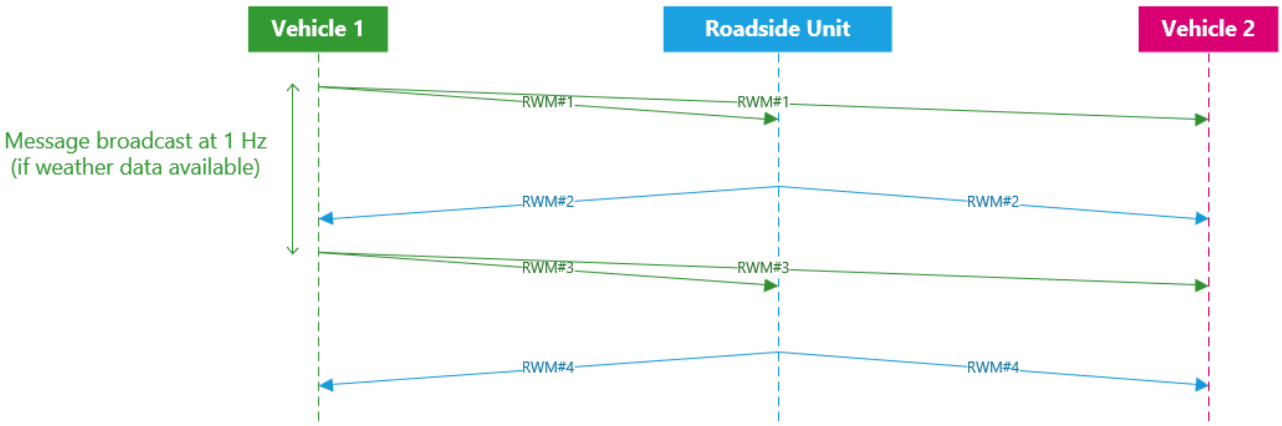


Figure 17: Road Weather Message sequence diagram

Either a vehicle or a roadside unit can generate a road weather message when local weather data are available. This message is broadcasted at a frequency of 1 Hz to take into account the mobility aspect of the ITS stations generating or receiving the RWM.

For example, the roadside unit may obtain information on the local weather estimation from the module described in the section 3.2.3.1 at a certain frequency (e.g. once every minute). The same information will then be repeated at 1 Hz so that new vehicles driving in the monitored area can obtain this local weather estimation.

The next figure shows the RWM data structure.

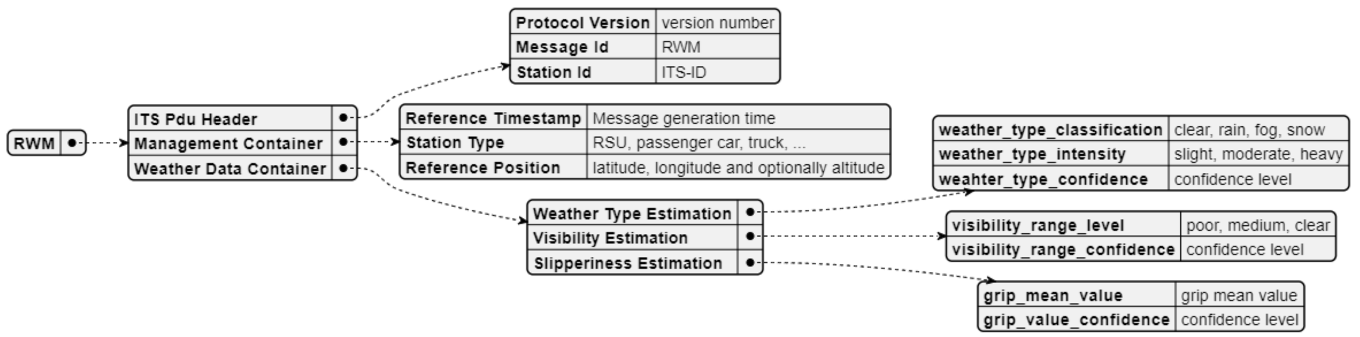


Figure 18: Road Weather Message sequence diagram

The RWM first contains a header part common to all ITS messages (ITS PDU Header), then a management container describing the ITS station generating the RWM and last a weather data container.

Depending on the availability of weather data at the RWM transmitted, the weather data container of the RWM can contain one or more type of weather data information obtained from the ROADVIEW weather estimators. At the vehicle side, the road weather message will typically contain either the visibility or the slipperiness estimation or both from Task 5.3. At the roadside, the road weather message will contain the weather type estimation developed by CE in Task 5.2 (See section 3.2.1).

3.2.2.1 ITS PDU Header

The header part of the message is common all C-ITS messages. It shall contain:

- Protocol version id: identifying the version of the ITS protocol.
- Message id: identifying the message type. Here id that will indicate a Road Weather Message (RWM).
- Station id: identifying the station generating the message using ITS pseudonym (ITS-ID).

3.2.2.2 RWM Payload

3.2.2.2.1 Reference time

The message shall contain a reference time according to ITS timestamp. ITS timestamp is a value in milliseconds since the ITS Epoch. The ITS epoch is 00:00:00.000 UTC, 1 January 2004.

3.2.2.2.2 Basic container

The basic container is a general container for usage in various types of messages with:

- Station type: type of the station generating the message such as:
  - Unknown (0)
  - Passenger Car (5)
  - Light Truck (7)
  - Heavy Truck (8)
  - Roadside unit (15)
- Reference position: latitude, longitude, and optionally the altitude of the station generating the message at the reference time

3.2.2.2.3 Weather estimation container

The weather estimation container is the one that will contain the estimation obtained from the various ROADVIEW weather estimation modules.

After the analysis of the visibility situation and precipitation situation codes of SAE Road Weather Message or DENM for adverse weather conditions, the following issues are noticed for the expected used in ROADVIEW:

- the RWM precipitation situation codes are combining the situation type and the intensity level (e.g. rainHeavy), there is no code to just indicate the precipitation type (e.g. rain). With the current weather message, if a weather estimation module is not able to indicate the intensity level, it cannot just indicate the weather type.
- the RWM visibility situation code has no indication of the visibility level; there is another visibility range value provided as a distance.
- DENM adverse weather message for visibility is also mixing the precipitation situation.
- for the road surface or traction loss, there is a mobile friction value that could be used to provide the slipperiness estimated in ROADVIEW.

So, as an enhancement of V2X RWM for ROADVIEW we propose:

- to rename the precipitation situation to weather type classification for all the weather situations in the scope of ROADVIEW ODD defined in D2.1 (rain, fog, snow) and to add an optional intensity level information (see section 3.2.2.2.3.1).
- for the visibility estimator, to indicate the visibility range level (see section 3.2.2.2.3.2).
- for the slipperiness estimation, to indicate the grip mean value (see section 3.2.2.2.3.3).

The ROADVIEW weather estimations are using Artificial Intelligence. As specified by Task 5.5 (eXplainable AI requirements), the weather information is used by the WP6 decision-making and control for decisions that may affect the safety. The level of uncertainty of the provided information shall be assessed. A certain threshold on the confidence level values can be set at the transmitter side to avoid sending estimations with a high-level of uncertainty.

3.2.2.2.3.1 Weather type estimation

Weather type estimation will be feed with data obtained from the weather type estimation modules from CE (see section 3.2.1).

Data element	Value
Weather type classification	Unavailable (0) Clear (1) Rain (2) Fog (3) Snow (4) Unidentified precipitation (5)
Weather type intensity	Unavailable (0) Slight (1) Moderate (2) Heavy (3)
Weather type confidence	Confidence level value between 0 (no confidence) and 100 (full confidence) Unavailable (101)

Table 14: Weather type estimation data elements

As difference from SAE RWM, we separate the weather type classification and the intensity part. Some weather estimation models might be able to class the weather type but may not have the intensity level determination part. We have kept the unidentified precipitation case when difference between rain, snow or fog is difficult to determine.

3.2.2.2.3.2 Visibility estimation

Visibility estimation will be feed with data obtained from the visibility estimation module from VTT developed in Task 5.3. The data elements described here may be updated later from the work done in task 5.3.

Data element	Value
Visibility range level	Unavailable (0) Poor (1) Medium (2) High (3)
Visibility range level confidence	Confidence level value between 0 (no confidence) and 100 (full confidence) Unavailable (101)

Table 15: Visibility estimation data elements

3.2.2.2.3.3 Slipperiness estimation

Slipperiness estimation will be feed with data obtained from the slipperiness estimation from FGI developed in Task 5.3. The data elements described here may be updated later from the work done in task 5.3.

Data element	Value
Grip mean value	Value between 0 (no grip) and 100 (full grip) Unavailable (101)
Grip value confidence	Confidence level value between 0 (no confidence) and 100 (full confidence) Unavailable (101)

Table 16: Slipperiness estimation data elements

3.2.3 Software architecture of collaborative road weather service

The next figure illustrates the ROADVIEW high-level architecture for weather estimation collaborative solution. This solution will be developed also in Task 5.3 for the on-board vehicle weather estimators whereas in Task 5.2 we will focus on the infrastructure-based system.

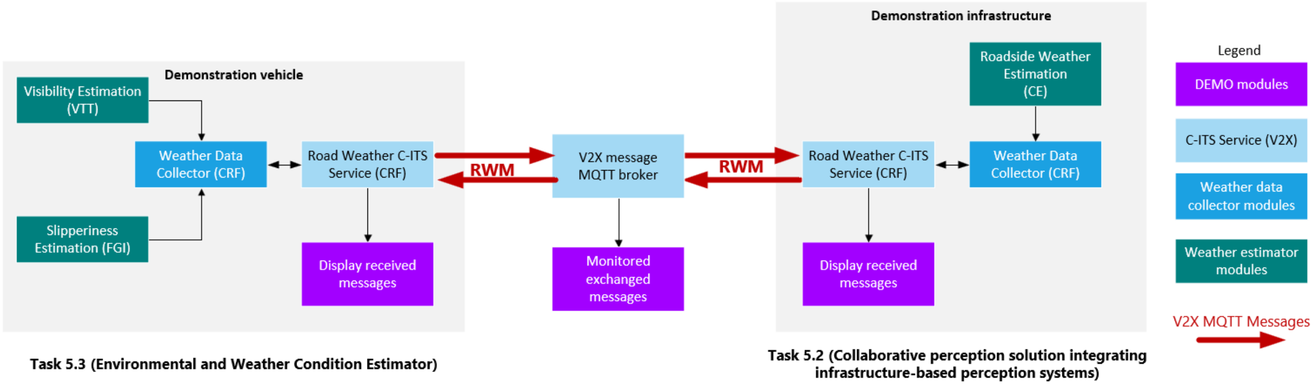


Figure 19: Architecture related to weather estimation and collaborative perception solution

3.2.3.1 Weather Estimation Modules

Weather estimation modules provide local weather estimations on the vehicle side for the visibility estimate and the slipperiness estimate and on the roadside for the weather type classification.

At the vehicle side, the visibility and slipperiness estimates are published to ROS topics according to the ROS API defined in the ROADVIEW deliverable D2.3.

At the roadside unit, the weather type estimations can be obtained through a TCP socket with the computer machine running the weather estimation models.

3.2.3.2 Weather Data Collector Module

Weather data collector module is updating the weather situation based on the various local weather estimations.

It is also able to collect the global weather estimations received on the RWMs from other ITS stations (from vehicles or from a roadside unit).

Collected weather data might be used by other modules of ROADVIEW project.

For instance, in task 5.2, the weather conditions are used by the roadside sensor fusion module to evaluate if the sensor is in its ODD.

Another example, related to the weather-aware decision control making system in WP6, is the use of the slipperiness or the visibility estimation information to provide weather-aware driving advice in Task 6.3

3.2.3.3 Road Weather C-ITS Service

The Road Weather C-ITS Service module is in charge of generating and receiving Road Weather Message (RWM) on top of a V2X communication system.

The V2X communication system is using cellular network connectivity and a MQTT (Message Queuing Telemetry Transport) broker to exchange the V2X messages between vehicles and roadside units ITS stations.

For demonstration and evaluation purpose, the exchanged road weather messages can be monitored by subscribing to the MQTT broker related topic (e.g. ‘v2x/rwm’). We could also have some local display of the received message on the vehicle or on the roadside unit.

The RWM generation is done each second when weather estimation is available. The validity time of the weather estimation may vary according to each type of estimation. For example, the weather type classification can be considered as valid during 600 s as for the DENM adverse weather warnings.

The RWM reception is filtering the messages based on their reference position. Based on the ROADVIEW requirements D2.4, the considered relevant distance is set to 500 meters. During the evaluation of the collaborative perception solutions, the value could be adjusted to the target use cases.

3.3 Infrastructure-based perception system

3.3.1 Impact of harsh weather conditions on infrastructure-based perception system

As explained in D2.1 (Definitions of the complex environment conditions), harsh weather conditions for rain, fog or snow have impact on sensor performance. Having multiple sensor types should then increase the robustness of the perception system.

For the roadside sensors, we are considering three types of sensors:

- Video camera: good for the object type recognition
- LiDAR: good distance evaluation
- 4D RADAR: good for the speed evaluation

Each sensor might be impacted differently by each type of harsh weather conditions. As human eyes, video camera is impacted by poor visibility conditions due to heavy rain or fog or falling snow.

Getting the information about the local weather conditions is thus very important to provide reliable information for the confidence level in the perceived objects by the roadside sensors.

Stationary roadside cameras are fixed on a pole to have an elevated view of the situation to limit the number of occlusions (as illustrated in Figure 20). The camera can be equipped with some cover with a cap and even with windshield wiper (such as Axis Q1656-LE camera model). Thanks to such accessories, the video camera is less impacted by the rain or snow droplets.

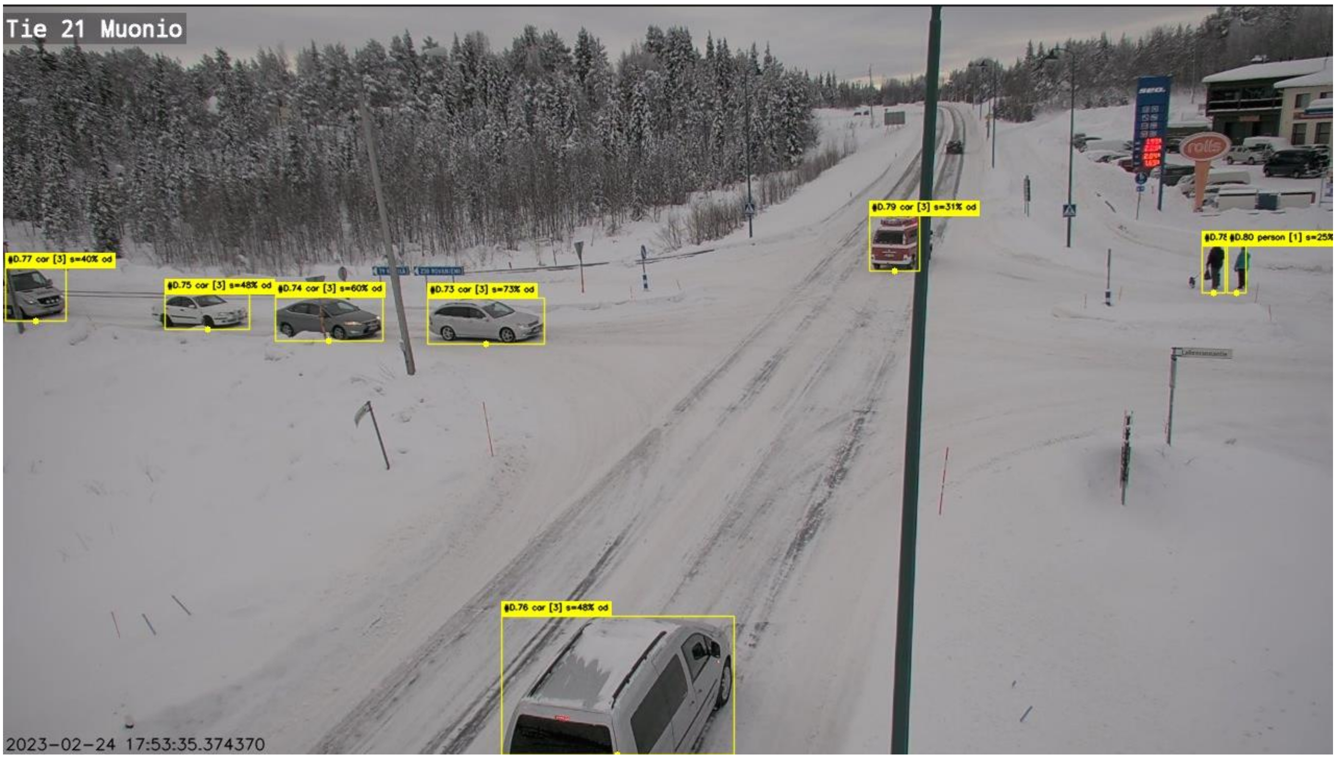


Figure 20: Illustration of object detection in Lapland using a roadside camera

The set-up of the roadside sensors will depend on each demonstration test site. The goal is to have a common area covered by the various sensor types to be able to do some sensor fusion based on the list of objects and their characteristics as perceived by each sensor.

3.3.2 Main modules of the infrastructure-based perception system

The next figure shows the main modules of the infrastructure-based perception system.

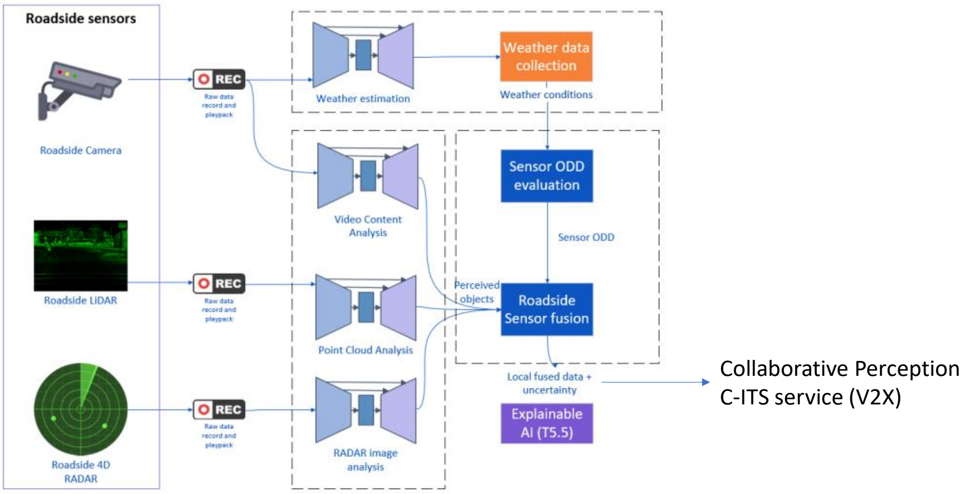


Figure 21: Infrastructure-based perception system

For each roadside sensor there is an analytic module used to detect presence of objects such as vehicles or VRUs (pedestrian, bicycles). Additionally, the camera roadside sensor is also used to estimate the weather condition type as described in section 3.2.1.

As shown in Figure 21 the roadside sensor fusion algorithm will use as input the estimated weather conditions to evaluate the sensor ODD.

The output of the roadside sensor fusion algorithm will provide the local fused data as a list of objects with their attributes (such as the object type, its position, its speed and an identifier to track the object in the time).

Task 5.5 is providing requirements related to Explainable Artificial Intelligence (XAI). AI modules providing information to decision-making modules shall indicate a level of uncertainty on their results.

More specifically, the roadside sensor fusion module will provide a confidence level in the local fused data based on the evaluation of the sensor ODD.

The local fused data outputs are shared with other traffic participants using V2X Collective Perception Service as further described in the section 3.4.

Sending of data with a high level of uncertainty over the V2X should be avoided (not to consume too much bandwidth, trust in the data). Impact of false positive or false negative shall be evaluated. For instance, a false positive indicating the presence of the VRU might slow down the vehicle and has low impact on the safety, while the reverse of not indicating the presence of a VRU that is actually present has impact on the safety.

3.3.3 Tests with pre-recorded datasets

To start testing the analytic modules of the infrastructure-based perception system with various weather conditions, we will use datasets with stationary sensors recorded in WP3 containing various target types (car, pedestrian or bicyclist). As example, in the next figures, we show a car detection and a pedestrian detection located at 56 m from the stationary sensors using video analytics and point cloud analytics module.

Figure 22: Example of car detection at 56 m distance, with rain

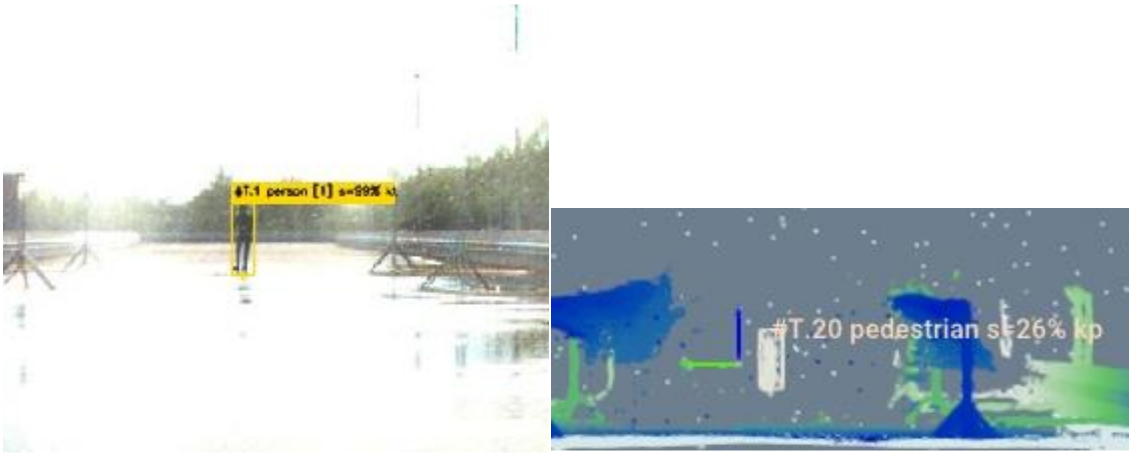


Figure 23: Example of pedestrian detection at 56 m distance, with rain

In the next steps of task 5.2, additional tests will be performed using pre-recorded datasets of WP3 and real-time sensor data capture using the roadside system described in section 3.1.2.

3.4 Collaborative Perception Solution integrating infrastructure-based perception system

The collaborative perception solution consists in sharing the local perceived data with the connected ITS stations in the same area (either vehicles or road side units) using V2X.

As described in section 3.2, weather estimations will be broadcasted over V2X using Road Weather Message, RWM.

Perceived environment from the infrastructure-based perception system will be broadcasted over V2X using Collective Perception Message, CPM.

In the next steps of task 5.2, we will first provide CPM generated from the roadside system with the perceived objects from the roadside sensor. In a second time, VRU detected from FGI vehicle could be shared in CPM using the collective perception service to a second vehicle or to the roadside unit during the evaluation of the solutions in the Lapland.

3.4.1 Collective Perception Message (CPM)

The next figure shows the general structure of Collective Perception Message (ETSI TS 103 324, 2023)..

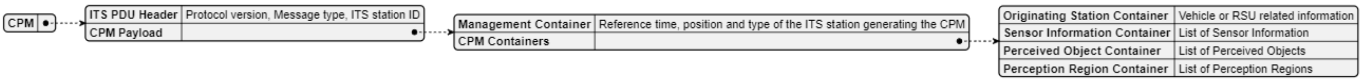


Figure 24: High-level format of CPM

In the next sections we will highlight the main information of CPM that are of interest for the ROADVIEW Collaborative Perception Solution.

3.4.1.1 ITS PDU Header

The header part of the message is common all C-ITS messages. It shall contain:

- **Protocol version id**: identifying the version of the ITS protocol.
- **Message id**: identifying the message type. Here id that will indicate a Collective Perception Message (CPM).
- **Station id**: identifying the station generating the message using ITS pseudonym (ITS-ID).

3.4.1.2 CPM Payload

3.4.1.2.1 Management Container

The management container includes the information about the ITS station generating the CPM:

- **Reference position**: latitude, longitude, and optionally the altitude of the station generating the message at the reference time.
- **Reference time**: message reference time according to ITS timestamp. ITS timestamp is a value in milliseconds since the ITS Epoch. The ITS epoch is 00:00:00.000 UTC, 1 January 2004.

3.4.1.2.2 CPM Containers

Three types of containers can be included in a CPM.

3.4.1.2.2.1 Originating Station Container

If the originating station is a vehicle, then this container shall contain the vehicle orientation (orientationAngle).

If the originating station is an RSU, then this container can optionally contain a reference to MAP infrastructure-to-vehicle message (see section 2.2.2)

3.4.1.2.2.2 Sensor Information Container

The Sensor Information Container (SIC) lists the information about the sensors used to perceived objects or perception regions reported in CPM.

Mandatory elements to describe a sensor are:

- **Sensor identifier**: represents the sensor or data fusion system identifier.
- **Sensor type**: represents the sensor type. For ROADVIEW relevant sensor types are:
    - The value `1` is for 'radar'
    - The value `2` is for 'lidar'
    - The value `3` is for 'monovideo'
    - The value `8` is for sensor data fusion

Other fields are optional but for ROADVIEW infrastructure-based system we plan to set them as they can be used to reflect the impact of the weather conditions:

- **Perception Region Shape**: the perception region of the sensors. Can be defined by a polygon shape. Other shape types are possible (rectangular, circular, elliptical, or radial shapes).
    - The perception region shape is described from a reference point or from the reference position contained in the management container.

- **Perception Region Confidence**: the isotropic perception region confidence that can be assumed for the entire perception region of the sensor as a percentage level (range 1-100, value 101 is used to indicate that the confidence level is unavailable).
  The perception region confidence can vary depending on the weather conditions or due to the presence of some occlusion.
  In case of deviation of the perception region confidence in a sub-region, the Perception Region Container can be used to indicate it.
- **Shadowing Applies**: if the flag for shadowing applies is set to false it means this region can't be used with a ray-tracing algorithm to compute shadowed regions on the receiver side of the CPM. In the case of the infrastructure-based perception system this flag will be set to false.

3.4.1.2.2.3 Perception Region Container

The Perception Region Container is filled with the list of perception regions with their state. The maximum number of perception regions that can be included in a CPM is 8. For each perception region reported in the perceptionRegionContainer shall contain:

- **Measurement Delta Time**: time difference in milliseconds between the CPM reference time provided in the management container and the time of measurement of the perception region state.
- **Perception Region Confidence**: is used to represent the perception confidence in the region as a percentage level (range 1-100, value 101 is used to indicate that the confidence level is unavailable).
- **Perception Region Shape**: specifies the region as a polygon. Please refer to it in Sensor Information Container as both use the same fields. It is possible to have a sub-region included in a larger region. But no partial overlapping of regions is possible.
- **Shadowing Applies**: same definition as for SIC.

Other optional information provided for a perception region are:

- **Sensor Id List**: lists the identifiers of the sensor(s) as defined in the SIC used to perceive the region state.
- **Number Of Perceived Objects**: the number of perceived objects contained in the region specified in the component perceptionRegionShape. Range value is between 0 and 255 objects. When a region is free of objects, the 0 value can be used to indicate a free space.
- **Perceived Object Ids**: the list of identifiers of the objects specified in the Perceived Object Container that are contained in the region specified in the component perceptionRegionShape.

3.4.1.2.2.4 Perceived Object Container

The Perceived Object Container (POC) contains the total number of perceived objects and lists the perceived objects and their attributes.

The next figure shows the coordinate system used to describe the object position from the reference position indicated in Management Container.

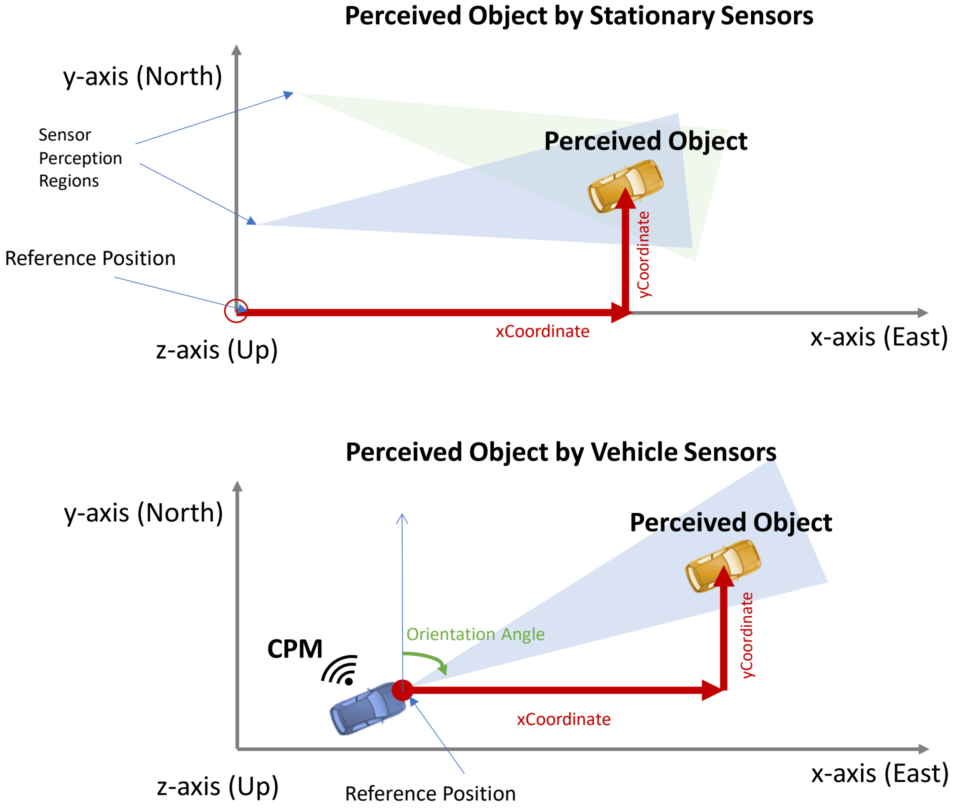


Figure 25: ENU coordinate system used in CPM

Mandatory elements are:

- **Object identifier**: a unique identifier at the level of the originating ITS station associated to the object to track it along it is perceived by its sensors or sensor fusion system.
- **Measurement delta time**: the time difference in milliseconds between the reference time provided in the management container and the measurement time of the object. Negative values are indicated that the perceived object state refers to a point in time before the CPM reference time.
- **Position**: position of the geometric centre of the objects bounding box within the pre-defined coordinate system. The Figure 25 shows the East North Up, ENU, coordinate system used to indicate the x, y, and optionally z cartesian coordinates of the perceived object. A confidence value can be optionally added as the estimated absolute accuracy of a position coordinate with a default confidence level of 95%.

Other optional elements that will be considered in ROADVIEW are:

- **Velocity**: velocity vector
- **Object Age**: indicates the age of the detected and described object in milliseconds. In the standard, a maximum value of 1500 is set. When an object is perceived since more than 1.5 seconds the object age keeps the value 1500.
- **Object Perception Quality**: scalar-value indication of the overall information quality of the perceived object. The value shall be set to:
  - 0: if there is no confidence in detected object, e.g. for "ghost"-objects or if confidence could not be computed,
  - n (n > 0 and n < 15): for the applicable confidence value,

- 15: if there is full confidence in the detected Object.

The object characteristics contributing to the perception quality of an object first detected at time t=0, where t represents discrete time instants, are:

- objectAge (optionally provided in the CPM),
- sensor or system specific detection confidence at time t (between 0 for no confidence and 1 for high confidence),
- binary detection success at time t (0: if not detected, 1: if detected)

- **Sensor Id List**: refers to the sensor(s) used to perceive the objects. In case of data fusion, first the identifier of fusion sensor type (value 8) shall be listed first, followed by the list of sensors used by the fusion.
- **Classification**: specifies the class of detected object with its confidence level (here the confidence level if the confidence in the class type). The objects classes considered in ROADVIEW are vehicles and VRUs.

Object Type	objectClass
person	vru.pedestrian
bicycle	vru.cyclist
car	vehicle.passengerCar
motorcycle	vehicle.motorcycles
bus	vehicle.bus
truck	vehicle.lightTruck

3.4.2 Sensor perception and perceived object quality

The quality measurements on the shared environment models are crucial for a reliable sensor fusion, traffic analysis, and decision-making system. The quality of the reported information to other traffic participants using CPM, shall take into account the ODDs of the sensors and the impact on their predictions. The quality of information is shared with road users to evaluate the limitations caused by the difficult perception conditions.

Through CPM, it is possible to report various elements for the quality of information:

- Sensor perception region confidence per sensor in the SIC,
- Perception region confidence if any deviation from the SIC in the PRC,
- Object Perception Quality and its classification confidence in the POC.

3.4.3 Collective Perception C-ITS Service

The Collective Perception C-ITS Service module is in charge of generating and receiving Collective Perception Message (CPM) on top of a V2X communication system. The V2X communication system is using cellular network connectivity and a MQTT (Message Queuing Telemetry Transport) broker to exchange the V2X messages between vehicles and roadside units ITS stations. For demonstration and evaluation purpose, the exchanged collective perception messages can be monitored by subscribing to the MQTT broker related topics (e.g. 'v2x/cpm').

A new CPM generation event is done every 100 milliseconds to check if there are updates of the sensor information and the object states to be done.

As for the RWM, the relevance distance to receive and analyse CPM is set to 500 m around the current position as defined in D2.4.

3.5 V2X Communication Architecture

As described in the section 2.3, the relevant C-ITS services planned to be implemented for ROADVIEW WP5 and WP6 are reminded in the next table:

Service	Message	Based on	Vehicle		Infrastructure		Purpose
			Tx	Rx	Tx	Rx	
Road Weather	RWM	SAE J2945	✔	✔	✔	✔	Share results from ROADVIEW weather estimators (weather type, slipperiness, visibility)
Collective Perception	CPM	ETSI TS 103 324	✔	✔	✔	✔	Share perceived objects (vehicles, VRUs) with perception quality based on the sensor ODD
Manoeuvre Coordination	MCM	ETSI TR 103 578	✔	✔	✔	✔	Share autonomous vehicle current state and intention (short-term trajectory) (WP6) Weather-aware driving advice from the infrastructure-based system (e.g., speed, triggering Minimum Risk Manoeuvre) (WP6)

Table 17: Overview of selected C-ITS service

3.5.1 V2X Communication using MQTT protocol over a cellular network

The Message Queuing Telemetry Transport, MQTT, protocol is a lightweight publish-subscribe messaging protocol designed for constrained devices and low-bandwidth, high-latency, or unreliable networks.

MQTT is recognised of interest to be used for V2X communications on top of cellular network connection. In the literature review we has found a study (Reiher, et al., 2022) presenting multiple solutions that allow connected agents running the Robot Operating System (ROS) to exchange data using MQTT protocol. Their work integrates methods to assess the connection quality in the form of various key performance indicators in real-time. They compare a variety of approaches that provide the connectivity necessary for the exemplary use case of edge-cloud LiDAR object detection in a 5G network. They show that the mean latency between the availability of vehicle-based sensor measurements and the reception of a corresponding object list from the edge-cloud is below 100 ms with 5G network.

As shown in the Figure 26, in ROADVIEW we plan to use LTE/4G or 5G cellular network depending on available cellular network in the demonstration test site to connect the infrastructure-based system with the ROADVIEW autonomous vehicle. The connection between the publisher and the subscriber is handled through a MQTT broker. In the various ROADVIEW demonstrations, only one roadside unit will be installed. This roadside unit might include the MQTT broker function inside or the MQTT broker might be remote in the cloud.

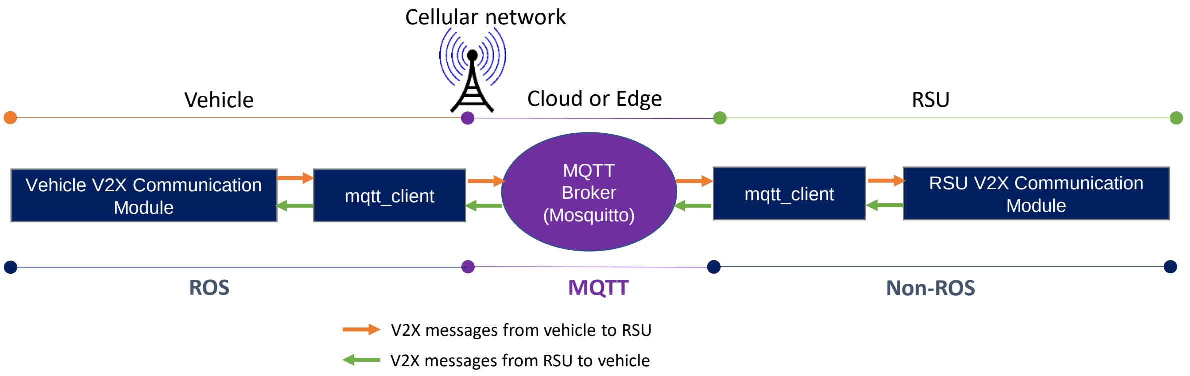


Figure 26: V2X Message exchanges through MQTT

This architecture for V2X messages allows to have ROS nodes on the vehicle side following ROS API defined in the ROADVIEW architecture D2.3 whereas the roadside unit is not running ROS nodes.

Our first experimentation for the bridging between the MQTT topics and ROS agent is done using the mqtt_client ROS package for the vehicle side (https://github.com/ika-rwth-aachen/mqtt_client).

The MQTT broker is implemented using mosquitto open-source (https://github.com/eclipse/mosquitto) that provides a server for several versions of MQTT protocol (MQTT Version 5.0, 2019).

3.5.2 Useful features of MQTT for ROADVIEW use cases

3.5.2.1 Persistent connections

MQTT establishes a persistent connection between the vehicle and the roadside unit. This connection ensures a continuous flow of data, allowing for real-time communication and minimising the latency associated with re-establishing connections. As the vehicle is driving in location where it will not always be connected through cellular or short-range network connectivity this feature is especially interesting for ROADVIEW DEMO 2 (rural roads in the Lapland) and DEMO 4 (highway road in Turkey).

3.5.2.2 One-to-many communications

The publish-subscribe model of MQTT allows for efficient dispatch of communications. A single message published by the vehicle (e.g. RWM) can be simultaneously delivered to multiple subscribers, such as other vehicles, infrastructure or cloud services.

In the context of ROADVIEW, the weather data collected by the vehicles (such as the visibility and slipperiness estimators in Task 5.3) could contribute to weather data collection by the neighbour road side units or to a weather analysis service on the cloud (e.g. Traffic management system). As defined in the D2.4 requirements, the considered relevance area for ROADVIEW use cases is 500 m around the road side unit.

3.5.2.3 Quality of Service levels

MQTT supports three different QoS levels (0, 1 and 2) enabling to choose the appropriate balance between message delivery reliability and network overhead.

3.5.2.3.1 QoS level 0: “at most once” guaranteed delivery of a message

QoS level 0 provides a best-effort delivery mechanism where the sender does not expect an acknowledgement or guarantee of message delivery. The sender does not store or re-transmit the message.

V2X messages, depending on the message type the service may tolerate occasional loss. For example, CPMs or RWMs are intended to be broadcasted to the local area without any prior knowledge that a receiver is present in the area and without acknowledgement that the message is received or not. The RWMs or CPMs are regularly updated with the latest measurement data in a frequency range between 1 Hz and 10 Hz, so some messages might be loss. Only most recent data should be considered by the receiver.

So for regularly broadcasted message such as the CPM, RWM or the vehicle manoeuvre part of MCM it is the preferred mode as a new message will regularly be broadcasted with more up-to-date information

3.5.2.3.2 QoS level 1: “at least once” guaranteed delivery of a message

In this mode, the focus is on ensuring message delivery at least once to the receiver. When a message is published with QoS 1, the sender keeps a copy of the message until it receives an acknowledgement packet from the MQTT broker, confirming the successful receipt. If the sender doesn’t receive the acknowledge packet within a reasonable time frame, it re-transmits the message to ensure its delivery. In this mode, there are some risks of duplicated messages.

For MCM advice part generated by the roadside unit on specific events and not regularly broadcasted, there is an identifier in the message that uniquely identify the advice. So, this QoS level should be suitable.

3.5.2.3.3 QoS level 2: "exactly once" guaranteed delivery of a message

When the QoS 2 flow is complete, both parties are sure that the message is delivered and the sender has confirmation of the delivery. If a packet gets lost along the way, the sender is responsible to retransmit the message within a reasonable amount of time. This is equally true if the sender is an MQTT client or an MQTT broker. The recipient has the responsibility to respond to each command message accordingly.

This mode would require more buffering and have more latency in the message delivery, so it is not planned to use it for ROADVIEW use cases.

3.5.3 MQTT performance test results

In D2.4, the functional requirement for the V2X collaborative perception and weather messaging has defined a latency below 750 ms end-to-end. The latency time should include the sensor data acquisition, the sensor data fusion, the sending and the receiving of the V2X message between the infrastructure system and the vehicle ROS application.

The following topology was used to evaluate the communication layer latency, i.e., latency between message transmission and message reception.

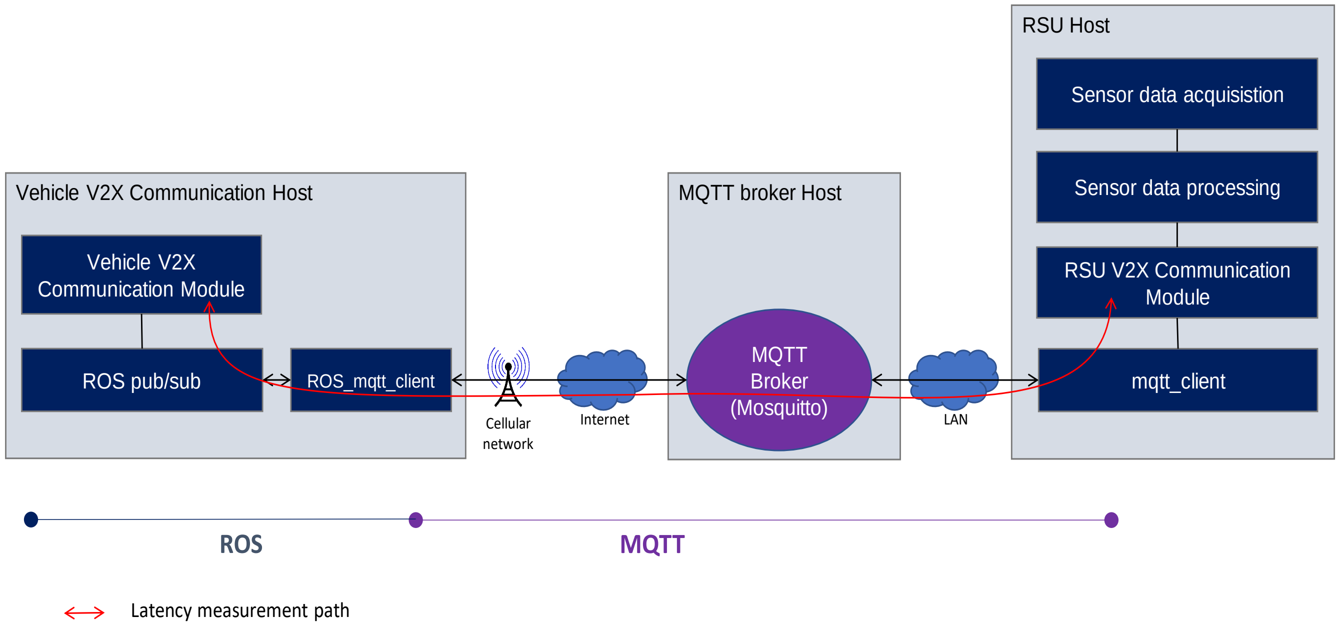


Figure 27: V2X Message latency measurement platform

All hosts involved being time synchronised with NTP protocol, a test message is built on the transmission V2X communication module, including the message build timestamp, and sent to the reception V2X communication module. Upon reception of a test message, reception V2X communication module stores a reception timestamp, extract message build timestamp, and determine the time interval between the two timestamps.

The test is done in both directions simultaneously:

- From vehicle to RSU, also called "up link" in regard to cellular network.
- From RSU to vehicle, also called "down link" in regard to cellular network.

The test has been done outdoor, statically (no movement). The following figure illustrates the obtained results:

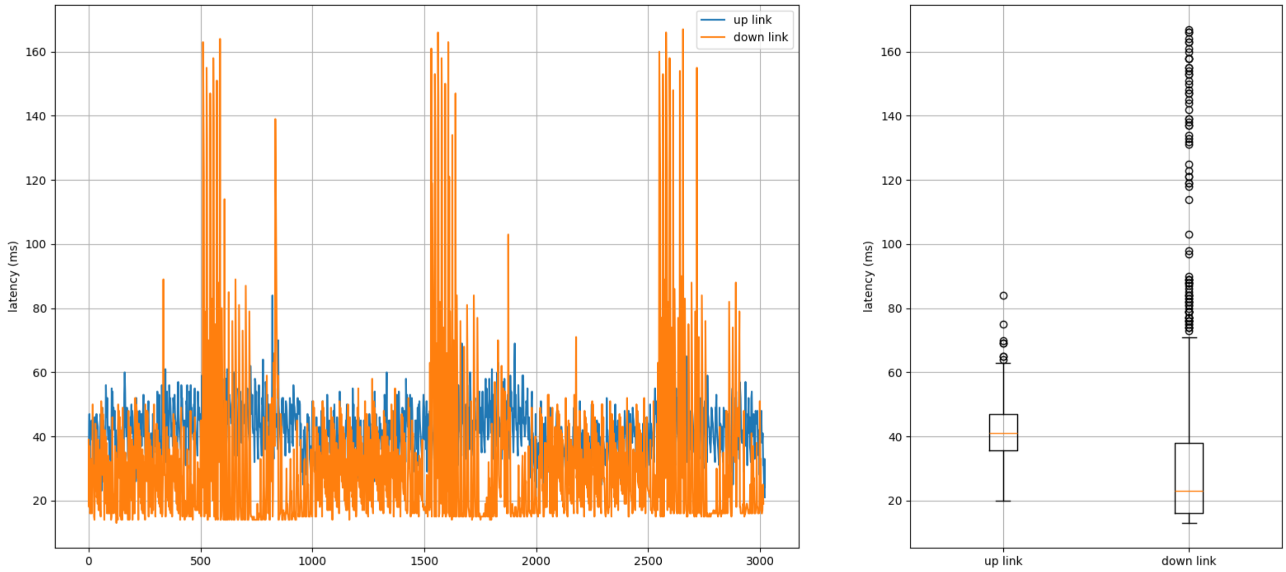


Figure 28: V2X Message latency measurement graph

Latency measurements (in ms)	Down link (RSU -> vehicle)	Up link (vehicle -> RSU)
mean	31.41	41.23
standard deviation	24.63	8.11
minimum	13.00	20.00
maximum	167.00	84.00
25%	16.00	35.00
50%	23.00	41.00
75%	38.00	47.00
median latency	23.00	41.00

Table 18: measurement statistics on v2x communication latency through 4G router

We observe a median latency of 23 ms, with a standard deviation of 24 ms, due to the 4G cellular network characteristics in down link. We observe a median latency of 41 ms, with a standard deviation of 8 ms, due to the 4G cellular network characteristics in uplink. Uplink latency is a bit higher than downlink latency, as this is the expected behaviour using off-the-shelve cellular communications.

In the next steps of task 5.2, further dynamic tests are planned in a moving vehicle, in order to check cellular cell handover impact, but currently, the maximum observed communication latency was about 160ms when there is no loss of cellular network connectivity.

Also from our first measurements, at the road side unit, the video analytics part requires 170 ms for the video frame capture plus 30 ms for the object detection part. In the next steps of the task 5.2, we will collect more data about the additional processing time for the sensor data fusion with the LiDAR or RADAR. But compare to the maximum requirements of 750 ms for the end-to-end latency from the sensor data capture to the reception in the vehicle of the v2x messages there should be enough margin.

4 Conclusions

In the first phase of Task 5.2 we have:

- Reviewed the relevant C-ITS services and selected the one to be implemented and evaluated for ROADVIEW such as Road Weather and Collective Perception services for WP5 and Manoeuvre Coordination service for WP6. An enhancement of the Road Weather Message is proposed.
- Defined the software architecture for the collaborative perception solutions integrating an infrastructure-based perception system comprising:
    - A collaborative road weather service to share the local weather conditions obtained from a weather estimation machine learning module using the same video camera as the one used for the object perception,
    - An infrastructure-based perception system comprising multiple types of sensors, with a sensor data fusion based on the sensor ODD,
    - A collaborative perception solution to share the perceived environment with nearby vehicles,
- Defined the communication architecture for the V2X part using MQTT protocol to support the various demonstration vehicles and the various type of connectivity on each demonstration site. First measurements using MQTT over a cellular 4G router shows a latency of up to 160 milliseconds to the V2X messages transmission between the roadside unit and the vehicle.

Next steps of task 5.2 are to continue the implementation of the various modules, with additional study for the global fusion, and for the congestion-aware collective perception. The software will be then tested on recorded datasets from WP3 and finally the collaborative perception solutions will be evaluated by installing a roadside system to monitor a road intersection in Finland. The evaluation of the solutions will be reported in the next deliverable of task 5.2 scheduled in M36.

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