WEATHERSAFE

SAFETY ENHANCEMENT UNDER ADVERSE WEATHER CONDITIONS THROUGH IMPROVED ADAS/AD ROBUSTNESS

Deliverable 4.1

Benchmark of Existing Infrastructures and Testing Tools for Adverse Weather Conditions

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EXECUTIVE SUMMARY

The development of robust Advanced Driver Assistance Systems (ADAS) and autonomous driving technologies requires comprehensive testing under adverse weather conditions. This report presents a systematic benchmark of existing testing infrastructures and tools capable of reproducing challenging environmental conditions that impact vehicle safety systems. Following the identification of critical weather phenomena (rain, fog, glare) and environmental side effects (low friction surfaces, reflectivity) from previous work packages, this deliverable evaluates major testing facilities across Europe and internationally.

The benchmark analysis encompasses indoor and outdoor testing capabilities, examining their ability to reproduce defined weather phenomena at various intensities and stability levels. A comprehensive evaluation of sensor-specific performance (camera, lidar, radar) under adverse conditions reveals that variability in how testing environments can affect measurement reliability and a definition of permissible characteristics of weather phenomena generated by adverse weather systems is necessary. To this end, an approach to ensure comparable rain and fog systems is being introduced.

A cross-correlation matrix between test requirements and existing capabilities identifies differences in current testing infrastructure for different weather phenomena, which highlights the need for standardization. While critical, but rare, medium and heavy rain events can be reproduced with a high level of realism, test systems are missing for light rain rates. Furthermore, test methods exist at a varying degree of development for the reproducible generation of fog, spray and glare. The report explores complementary testing approaches including simulation, opportunistic weather testing, and specialized low friction tracks. The finding provides essential guidance for selecting appropriate testing environments and methodologies for adverse weather condition testing, supporting the subsequent development of testing means specifications in Task 4.3.

REVISION HISTORY

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V5	13/04/2026	Sent to review	Pending
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V7	16/06/2026	Final reviex before publication	Approved

ABBREVIATIONS

ADAS	Advanced Driver Assistance Systems
AD	Automated Driving
AWC	Adverse Weather Conditions
DSD	Droplet Size Distribution
RCS	Radar Cross Section
PWT	Power Two-Wheeler
MOR	Meteorological Optical Range
ACC	Adaptive Cruise Control
AEB	Automatic Emergency Braking
ESC	Electronic Stability Control
TCS	Traction Control System
VRU	Vulnerable Road User
PTW	Powered Two-Wheeler
WP	Work Package
VUT	Vehicle Under Test
LKAS	Lane Keeping Assistance System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
RADAR	Radio Detection and Ranging
MTF	Modulation Transfer Function
LWC	Liquid Water Content

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1. Introduction

1.1 PROJECT BACKGROUND AND OBJECTIVES

The WEATHERSAFE project (Safety Enhancement Under Adverse Weather Conditions Through Improved ADAS/AD Robustness) represents a focused 36-month initiative designed to address the critical challenges posed by adverse weather conditions on Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) technologies. As these systems become increasingly prevalent in modern vehicles, ensuring their reliable operation across all environmental conditions becomes paramount for road safety.

Weather phenomena such as heavy rain, dense fog, and intense glare can significantly impair both human drivers and sensor-based systems, potentially compromising detection capabilities, decision making, and overall vehicle safety. WEATHERSAFE aims to systematically identify, characterize, and address these challenges through a structured approach to testing and validation, taking into account both sensor performance as well as friction issues.

The project is organized around six core objectives:

- O.1: Manage and coordinate the project to ensure successful preparation, kick-off, progress, closure, and dissemination
- O.2: Compile accident data from Europe to identify the main and more severe weather phenomena and scenarios with their parameters
- O.3: Definition of the meteorological phenomena
- O.4: Study the potential benefits of more robust ADAS systems under such weather conditions
- O.5: Study and specify the testing solutions
- O.6: Define test and assessment guidelines

The previous work packages[1,2] have yielded crucial insights that inform this benchmark study:

- WP1 has identified specific accident scenarios where adverse weather played a significant contributory role, highlighting rain, fog, and glare as particularly impactful conditions for road safety.
- WP2 has characterized these phenomena in detail, establishing key parameters like precipitation intensity ranges, droplet size distribution, visibility thresholds for fog and rain.
- WP3 has quantified the potential safety benefits that could be achieved through improved ADAS performance in these conditions using re-simulation of accidentology scenarios, providing a clear rationale for robust testing methodologies, using re-simulation of accidents.

This deliverable represents a pivotal transition from problem characterization to solution development, providing the technical foundation for subsequent testing protocol development. By comprehensively assessing existing testing capabilities, this report will enable informed decisions about appropriate testing methodologies and identify any gaps that may require novel approaches or facilities to address the specific requirements of adverse weather condition testing.

1.2 SCOPE OF THE DELIVERABLE

1.2.1 PURPOSES AND BOUNDARIES

The deliverable provides a comprehensive assessment of available testing capabilities for evaluating ADAS and AD systems under adverse weather conditions. It also provides a comprehensive synthesis of testing infrastructure capabilities and establishes definitive guidelines for adverse weather condition testing of ADAS and AD systems. The primary focus is to answer two fundamental questions:

- ***How and where can these tests be performed?***
- ***What are the optimal testing approaches for validating system performance under adverse weather conditions?***

The scope encompasses:

- **Testing Infrastructure Assessment**: a systematic evaluation of major testing to determine their capabilities for reproducing the specific weather phenomena and environmental effects identified in Task 4.1.

- **Testing Tools Analysis**: an examination of sensor evaluation equipment, weather generation systems, measurement instruments, and data acquisition tools available across these facilities, with particular attention to their suitability for assessing camera, lidar, and radar performance degradation.

- **Comparative Framework**: development of a structured methodology for comparing different facilities based on their technical capabilities, availability, cost, and other relevant factors to support informed decision-making.

- **Complementary Testing Approaches**: exploration of alternative or supplementary testing methods, including simulation, opportunistic weather testing, and specialized facilities, to address any identified gaps.

- **Testing Means Status Assessment**: a definitive compilation of discussions and results regarding the ability to reproduce adverse weather situations identified in previous work packages within realistic timeframes and resource constraints.

- **Cross-Correlation Matrix Refinement**: complete analysis of testing considerations versus existing facility capabilities, incorporating feedback from benchmark studies and partner testing campaigns to identify definitive capability gaps and coverage areas.

1.2.2 RELATIONSHIP TO OTHER PROJECT ACTIVITIES

This deliverable serves as a critical link between the requirements and the testing means guidelines. It translates the theoretical understanding of adverse weather phenomena and their effects on vehicle systems into practical testing approaches using existing infrastructure and tools.

The findings from this benchmark will directly inform the cross-correlation matrix between test requirements and available capabilities.

1.2.3 EXPECTED OUTCOMES

The primary outcomes of this benchmark study include:

- a comprehensive catalogue of testing facilities and their capabilities relevant to adverse weather testing;
- a structured comparison framework for evaluating testing options;
- the identification of strengths, limitations, and gaps in current testing infrastructures.

These outcomes will provide project stakeholders with the necessary information to make informed decisions about appropriate testing strategies for validating ADAS and AD systems under adverse weather conditions.

1.3 RELATION TO OTHER DELIVERABLES

1.3.1 INPUT RELATIONSHIPS

D4.1 directly incorporates key findings from several preceding deliverables:

- **Deliverable 1.1/1.2 - Assessment of ADAS/AD Performances Under Adverse Weather Conditions**, that provides the fundamental understanding of how current ADAS and AD systems perform when exposed to challenging weather phenomena. This assessment identifies specific performance degradation patterns that must be reproduced in testing environments to effectively evaluate system robustness, as well as accidentology results based on database review.

- **Deliverable 2.1 - Phenomena Characterization**, that offers detailed characterization of critical weather phenomena, including their physical properties, intensity ranges, and temporal characteristics. This information directly informs our benchmarking criteria by establishing the physical parameters that testing facilities must be capable of reproducing.

- **Deliverable 2.2 - Sensors vs Weather**, that analyses how specific weather conditions affect different sensor technologies (camera, lidar, radar). These insights shape our evaluation of testing facilities' capabilities to create appropriate conditions for sensor-specific testing and provide the metrics against which testing tools must measure performance degradation.

- **Deliverable D3.4 - Safety on Wet Roads: Impact of the Friction Estimation**, that explores the relationship between reduced friction conditions and ADAS performance, particularly focusing on how systems estimate available friction. This information directly influences our evaluation of facilities with low friction testing capabilities and specialized measurement equipment.

1.3.2 INFORMATION FLOW INTEGRATION

This deliverable serves as a critical bridge between the theoretical understanding of adverse weather impacts on vehicle systems and the practical implementation of testing protocols. It transforms the "what to test" defined in earlier deliverables into the "how and where to test" needed for subsequent project phases. By providing a systematic assessment of existing capabilities against established requirements, this benchmark enables informed decision-making about testing approaches, highlights areas where additional investment or development may be needed and ensures that subsequent testing guidelines are grounded in practical reality.

1.4 METHODOLOGY USED FOR BENCHMARKING

This benchmark study employed a comprehensive, multi-faceted approach to evaluate existing testing infrastructures and tools for adverse climate conditions. The methodology was designed to gather reliable, comparable information across diverse facilities while identifying both their capabilities and limitations for ADAS/AD testing under challenging weather conditions.

1.4.1 DATA COLLECTION APPROACHES

The benchmarking process incorporated multiple information sources to build a holistic understanding of each facility's capabilities:

1. **Site Visits:** four formal on-site evaluations were conducted to directly observe and assess facility capabilities:
    a. UNIV-EIFFEL (Université Gustave Eiffel) facility evaluation in September 2024;
    b. CARISSMA facility evaluation in March 2025;
    c. Cerema facility evaluation in June 2025;
    d. AstaZero testing evaluation in October 2025.

These visits allowed for first-hand verification of weather generation equipment, testing areas, and measurement systems through standardized observation protocols.
Apart from it, there were other visits on some of the test sites during the project, but no workshop has been held.

2. **Partner-Provided Information**: leveraging the WeatherSafe consortium's expertise, detailed facility information was obtained from project partners with direct knowledge of or operational control over specific testing facilities. This information was collected through structured information requests focused on key performance parameters.

3. **Literature Review**: comprehensive analysis of published materials, including technical papers, facility specifications, and publicly available documentation, supplemented direct observations and partner-provided data.

1.4.2 Evaluation framework

The evaluation employed a systematic framework focused on facilities' capabilities to meet the specific testing requirements:

1. **Facility Classification**: testing facilities were categorized based on
    a. Testing environments
    b. Weather phenomena reproduction capabilities
    c. Maximum testing speeds
    d. Physical dimensions and layout
    e. Specialized capabilities (e.g., low friction surfaces)

2. **Capability Assessment**: each facility was evaluated against its ability to reproduce
    a. Rain at specified intensity levels
    b. Fog at defined visibility ranges
    c. Glare conditions (sunset, daytime reflection)
    d. Surface conditions (wet, reflective)
    e. Repeatable water spray

1.4.3 Cross-Validation Approach

To ensure data reliability and comparability across facilities:

1. **Comparative Testing**: where possible, identical or similar test scenarios were executed across different facilities to directly compare their performance and identify systematic differences in weather reproduction capabilities.

2. **Measurement Standardization**: standard measurement approaches were applied across facilities to ensure comparable data, particularly for key parameters like visibility distance, precipitation rate, and surface friction.

3. **Multi-Source Verification**: information provided by facility operators was cross validated against published specifications, observed capabilities during site visits, and results from previous testing campaigns.

1.4.4 Analysis methodology

The collected data was analysed through a structured process:

1. **Capability Mapping**: documented capabilities were mapped against testing requirements to create a comprehensive cross-correlation matrix.

1. **Gap Identification**: systematic analysis identified areas where testing requirements exceeded available capabilities across all evaluated facilities.

2. **Complementary Approaches Assessment**: where conventional testing approaches showed limitations, alternative or complementary methods (simulation, specialized facilities, etc.) have been evaluated for their potential to address capability gaps.

This methodical approach to benchmarking ensures that the findings provide a reliable foundation for subsequent testing guidelines and recommendations, grounded in verified capabilities rather than theoretical or advertised specifications.

2. Perception oriented testing facilities and tools

This section presents the adverse weather performance facilities where work has been carried out during the various workshops, as well as some of their physical calibration and measurement characteristics that may allow us to achieve a certain degree of comparability and determine the correct reproduction of situations as close to reality as possible.

Each facility assessment encompasses multiple dimensions including physical infrastructure, weather reproduction capabilities, testing speed limitations and sensor evaluation tools. The analysis draws from direct site visits, partner expertise within the consortium, comprehensive literature review, and documented testing campaign results to provide an accurate representation of current testing capabilities.

It is important to mention that, although this project does not specifically address it, there are currently facilities on the market where tests defined as "classic" are conducted, including active safety and durability tests, where brake and dynamics testing is already performed to evaluate vehicle performance under different grip conditions. As will be mentioned in future sections of this document, we propose the possibility of defining various validation criteria involving rain, aligning the surfaces where adverse weather tests are conducted, and establishing a criterion that could take this into account.

2.1 WORKSHOP FACILITIES

Alongside the project WeatherSafe activities, four workshops were held, because of the possibility of reproducing the phenomenon. In this section, all the facilities are described.

2.1.1 SENSE-CITY UNIV-EIFFEL (UNIVERSITÉ GUSTAVE EIFFEL)

A real laboratory for the cities of tomorrow, the Sense-City platform provides both the resources and a rich testing ground to develop and evaluate innovative solutions addressing urban and transportation challenges.

Sense-City [3] consists in two 400 m² experimental areas, known as *Mini-Cities*, in which full-scale (1:1) representative sections of an urban environment have been constructed. These areas include buildings, urban furniture, and roads on which vehicles and pedestrians can circulate. Both Mini-Cities are equipped with a wide range of sensors designed to measure climatic conditions, assess the performance of urban infrastructures and equipment, monitor the behaviour of materials, and track air and water pollution. This fleet of sensors and analysers is connected to a dedicated data acquisition and processing system.

Both areas can be covered by a large volume (3200 m^3) mobile climate chamber. This facility enables the generation of various climatic conditions in a controlled and reproducible manner by adjusting numerous parameters such as air temperature, humidity, solar radiation, rainfall, or air pollution. These programmable climatic parameters can range from standard to extreme conditions, depending on scientific requirements.

Sense-City is also equipped with a rain and fog generation system covering an 11-meter stretch of roadway. Located in Mini-City 1, this test bench can simulate heavy rainfall or fog of varying density. Several dedicated sensors accurately measure the different climatic scenarios generated during these tests.

Combined with the capabilities of the climate chamber, this test bench enables the creation of controlled and reproducible weather conditions to evaluate vehicle perception systems (LiDAR, RADAR, cameras, etc.) under adverse weather conditions. Mini-City 1 allows for both static and low-speed dynamic testing, with adaptable urban furniture.

- **Site Visit**: September 2024
- **Key Capabilities**:
  - 2 areas (Mini-Cities) of 400 m² equipped with real urban equipment (roads, traffic light, road and information signs, different types of buildings)
  - Climatic chamber
    - Air temperature control: from -10°C up to 40°C
    - Air and humidity control: from 25% up to 95%
    - Sun exposure: 30 x 2000W sun-like wavelengths lamps with adjustable intensity
    - Thermo-regulated ceiling: from -10°C up to 40°C
    - Note 1: the climatic chamber maintains air humidity and temperature within +/- 5% accuracy. After a stabilization period, the surface temperature of all equipment in the chamber – including those in contact with the vehicle tires – can be precisely controlled, ranging from -10°C to 40°C (and up to 60°C in sunlit areas).
    - Note 2: the lighting and solar simulation systems can be combined to replicate diverse environmental scenarios, such as glare, low-light conditions or dynamic shadows
    - Note 3: all of the inside climatic simulation in Sense-City capabilities can be performed regardless of the outside meteorological condition and season.
  - Rain & fog generation system
    - 11 x 4 m tunnel
    - Rain: heavy/storm rain intensities
      - 5 mm/h (localized) to 250 mm/h
    - Fog: adjustable visibility (can be reduced to 5 m)
  - 2 small road rings embedded in 20m x 20m platform
  - 2 prototype vehicles that can be equipped with sensor and perception systems (Renault Twizy)
  - targets
    - Metrologic (contrast target, …)
    - Dummies (Pedestrian…)
- **Specialization**:
  - Evaluation of sensors and perception systems under controlled conditions including single climate or combined multifactor and in real urban environments
  - Validation of low-speed vehicle equipped with perception systems/ADAS
  - Real-world urban object detection scenarios in multivariate controlled climatic environments

- **Testing Focus**:

- Rain and fog impact assessment on instrumented vehicles.
- Conducting driving/braking tests on a small ring (within our 20 m × 20 m platforms) with ice, maintaining controlled conditions.
- Performing "sun glare" tests in various configurations using existing lamps with representative solar spectra
- Simulating the presence of snow.
- Simulating air pollution.
- Studying any specific climatic conditions that are not "exceptional" (e.g., cyclones).

A unique feature of the Sense-city platform is the mobility of its climate simulator. This allows us to combine controlled-environment experiments with open-air testing, offering great flexibility in experimental design/evaluation of sensors for example.

The platform's key advantages are:

- **Fully controlled and repeatable** conditions,
- **Metrological reliability** (regular calibrations),
- **Independence from external weather** (thanks to adiabatic walls).



Figure 2-1 Different views of Sense-City. The environment is adapted to urban context testing



(a) (b)

Figure 2-2: Sense-City's Mini-City 1 (a) top bottom view, we see the low speed road ring (b) digital twin integrating the rain and fog bench



(a) (b)

Figure 2-3: Sense-City's weather phenomena, (a) rain, (b) fog



(a) (b)

Figure 2-4: (a)Renault Twizy used for testing purposes, (b) perception sensors (camera, 360° lidar and 4-layer lidar)

Figures 2-5 and 2-6 show the digital twin of the Satory test track developed by UGE. The digital twin is a virtual reproduction of a real object. The figure shows the comparison between the digital twin and a same perspective on the real track. The first line provides virtual renderings, and the second line gives the real pictures from the same point of view.



Figure 2-5: Satory Test track [4]



Figure 2-6: Digital twin of the Satory test track [5]

2.1.2 CARISSMA – ISAFE INSTITUTE INGOLSTADT

As a state-of-the-art laboratory for automated driving and vehicle safety, the indoor test hall at the CARISSMA ISAFE Institute offers a unique research infrastructure for evaluating sensors, driving functions, and safety features. The approximately 100x18-meter hall enables a wide variety of traffic scenarios to be simulated under fully controlled and reproducible laboratory conditions. Thanks to a hybrid design, the also available crash system can be completely dismantled, allowing the hall to be used as a free driving area. Equipped with rain and fog systems, both static and dynamic tests can be conducted under reproducible weather conditions. Additionally, an indoor positioning system is available, enabling high-precision ground-truth data to be obtained during dynamic driving tests with vehicles or robotic platforms. In addition to driving robots and motion platforms, a light simulator is also available to reproduce low sun angles scenarios. Thus, the C-ISAFE indoor hall provides the conditions necessary to systematically investigate the interaction between the vehicle environment, sensor technology, and automated driving functions. The specific subsystems for weather simulation are described in detail in the following sections.

- **Site Visit**: March 2025
- **Key Capabilities**:
  - **Dimensions:** Indoor test facility in a 100 x 18 m hall
  - **Ground truth:** Indoor-Positioning system for static ("mm-accuracy") and dynamic ("cm-accuracy") objects
  - **Speeds:** dynamic driving tests up to 50 kph (in adverse weather ~30 kph) under reproducible conditions

Rain:

- Area: 200 m² (50 m x 4 m)
- Rainfall rates: 18-104 mm/h (continuous spectrum, adjustable in 1 mm/h steps)
- Patented process for generation of a realistic droplet size distribution



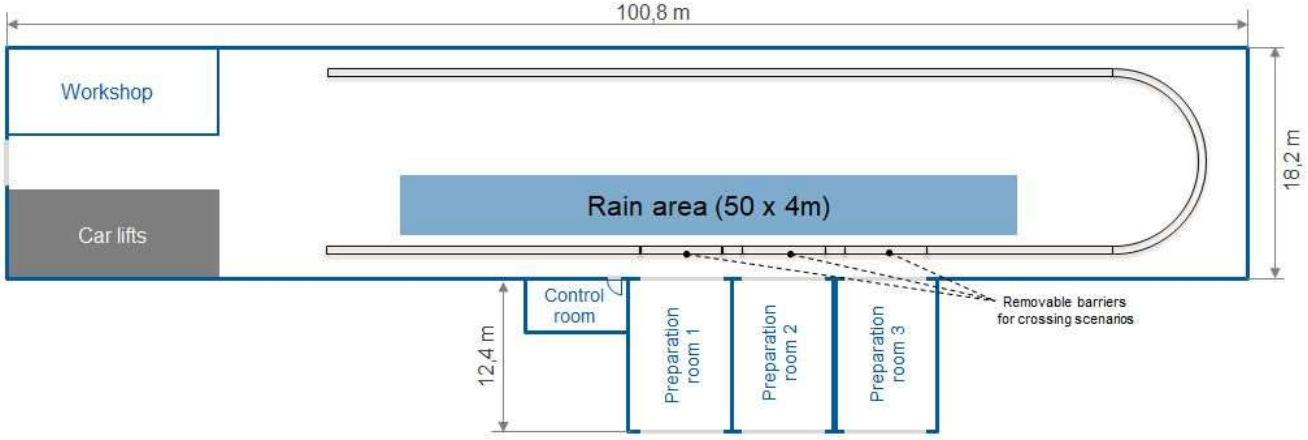


Figure 2-7 Carissma Test Track for Rain area

Fog:

- Area: 65 m x 12 m
- Visibility can be reduced to a minimum of ~10 m
- Operating modes:
  - Ramp mode (10 m to 400 m visibility)
  - Stabilized visibility (between 10 m and 100 m visibility)
- Documentation of actual visibility with visibility meter

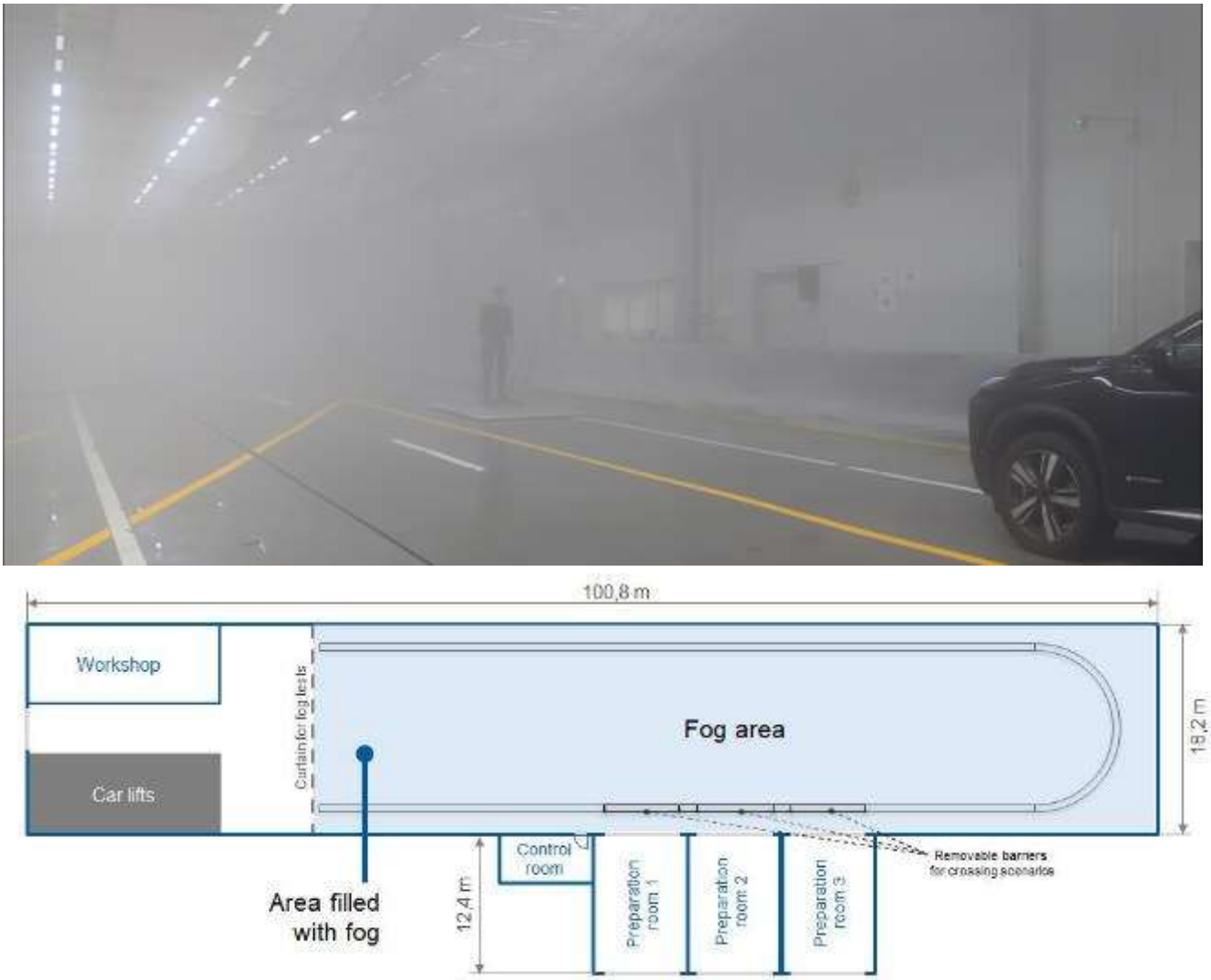


Figure 2-8: Carissma Test Track. Fog

Glare:

- Simulator with sun-like wavelengths (380-1000 nm).
- Freely adjustable Color Temperature from 2700 K to 5600 K.
- Movable glare simulator for static or dynamic tests.



Figure 2-9: Carissma Test Track. Glare

Lightning conditions:

- Controlled lighting from day to full night conditions

Further equipment:

- Driving robot
- Ultra-Flat Overrunable (UFO) Standard Robot Platform
- Selection of standardized vehicle targets
- VRU targets
- Sensor reference/calibration targets

Video impression: https://youtu.be/nbftPhATeeg?si=y6vW8sag0XHgc_Kh

2.1.3 PLATFORM PAVIN AT CEREMA

- **Site Visit**: June 2025
- **Key Capabilities**: PAVIN Extreme Weather Facility



Figure 2-10 PAVIN Extreme Weather Facility. Outside view

  - 50m x 7m indoor testing area (height 5.7m)
  - Static and dynamic tests up to 30 kph

- **Rain area**
  - 50 m x 7m, intensities from 17 mm/h to 300 mm/h (continuous production with parallel recycling)
  - Possibility to generate rain in the entire test room of the platform, thanks to 3 sets of nozzles installed regularly under the roof of the test room.
  - The calibrated rain is generated by injecting water through nozzles with specific dimensions. Depending on the rainfall intensity desired, one or several of the three nozzles set is used.



Figure 2-11: PAVIN Extreme Weather Facility. Inside view

- **Fog area**
  - 50 m x 7m, visibility adjustable up to 10m
  - Visibility can be stabilized around any specific value between 10m and 100m (with about 10% variation).

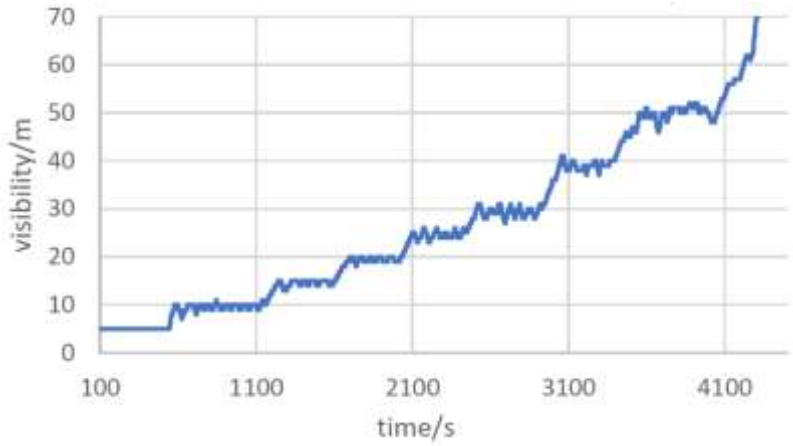


Figure 2-12 Example of stabilized fog steps between 10 m and 50 m of visibility

  - Two droplet size distributions can be generated for similar visibility levels, corresponding to radiative fog (continental fog, peak droplet size around 1 micron) and advective fog (sea fog, peak droplet size around 1 micron and 10 microns)

- **Glare**
  - Simulation with sun-like wavelengths (380-2500 nm) with position adjustable (lateral and vertical) and a power of 15000 lumen.
  - Controlled lighting from clear day to complete night

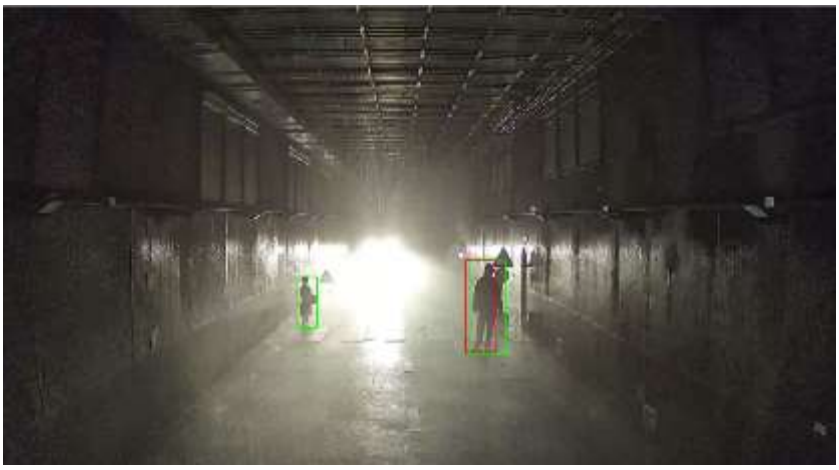


Figure 2-13: Pedestrian detection in PAVIN Test Facility

2.1.4 AstaZero Wet Zone



Figure 2-14 - Top view of the AstaZero Test Site

- **Site Visit**: October 2025
- **Key Capabilities**: AstaZero Spray Rig and WetZone
  - The **AstaZero Spray Rig** is designed to recreate the spray phenomenon created behind a vehicle driving on a wet road surface. More in the chapter 2.4.2.
  - Repeatable and well-documented spray production
  - Mobile design on a trailer
  - Static, Semi-dynamic and Dynamic mode
  - Interchangeable nozzles for droplet sizes between 50 and 400 microns



Figure 2-15 - The AstaZero Spray Rig, running in dynamic mode

- **Wet Zone** is a controlled test environment (10 m x 20 m) designed for stationary spray and glare testing.
    - Built-in spray system
    - Droplet sizes of 50-400 microns (adjustable)
    - Continuous testing with buffer tank
    - Controlled and logged with a dedicated GUI
    - Repeatable and well-documented spray generation



Figure 2-16 - Water spray produced in WetZone at AstaZero

- **Further facilities**
    - **Dry Zone**
        - World's longest indoor test track (700m)
        - Constant light and friction conditions 24h / 7 days
        - Can be used with a dynamic spray rig in speeds > 90 kph
    - **FLX Zone**
        - Flexible urban-traffic environment
        - Closed-environment automation
        - Supports 5G/Wi-Fi/Fast EV charging
    - **High Speed Area**
        - High-speed manoeuvres
        - Advanced measurement tech and connectivity
        - Dynamic performance testing
    - **Multilane Road**
        - Multi-lane scenarios
        - Lane-change and collision tests
        - Flexible traffic configurations
    - **Crossroads**
        - Four-lane straight road with a central intersection
        - Built specifically for crossing-scenario testing
        - Originally designed for Volvo evaluation needs
    - **Generic Site**
        - Gravel-based area for automated construction- and heavy vehicle testing
        - Supports inclines, loading/unloading, and other work-site scenarios
        - Includes infrastructure for charging and autonomous operation
    - **Rural Road**

  - 6.2 km realistic rural loop
  - Human-factors testing
  - Configurable rural scenarios
- **Private, dedicated 5G network**
  - Border roaming
  - Network slicing
  - Load testing

- **Partner Testing Results**: Test results available from Aptiv and AstaZero

2.2 OTHER FACILITIES UNDER THE CONSORTIUM

Inside the consortium there are also facilities on which different types of testing can be held, in this section the capabilities of these are explained, and in the case that no adverse weather conditions can be held, its potential reproducibility.

2.2.1 WEATHER TUNNEL FROM MITSUBISHI HEAVY INDUSTRIES MACHINERY SYSTEMS

- **Key Capabilities**: Weather Simulation Testing Facility in Kobe, Japan
- **Rain Area**
  - Width 7.5 m, height 7 m, length 48 m
  - Rainfall Simulation: Average intensity of 50 mm/h (localized max 350 mm/h)
- **Fog Area**
  - Width 7.5 m, height 7 m, length 35 m
  - Fog Simulation: Visibility ranging from 10 to 200 m. Visibility can be simultaneously measured at 10 different locations within the test area
- **Measurement Equipment**
  - Temperature, humidity, air pressure, illuminance, rainfall intensity, raindrop size distribution, raindrop velocity, fog particle size distribution, and fog visibility
- **Specialization**: Controlled testing of sensor degradation with fully controlled fog visibility, and two different rain droplet size distributions
- **Testing Results**: Comprehensive camera, LiDAR, and radar performance analysis

Overview	Rain	Fog (at 25 m visibility)
		

Figure 2-17 MHI test facility

2.2.2 TEST TRACK IN IDIADA

IDIADA's proving ground is an outdoor test track featuring 15 different circuits, adapted to the needs of different tests for all types of vehicles.
The region's favourable climate allows all-year-round testing. Summer temperatures are ideal for hot climate tests and development programmes are able to continue independently of the weather during the winter months. Even though there is no specific generation of adverse weather conditions at the moment, there are possibilities among some of the proving ground, e.g. the friction.



Figure 2-18: IDIADA's proving ground

Among the different types of testing covered in IDIADA's facilities, special emphasis is put in this document the capabilities for ADAS testing and low friction surfaces.

2.2.2.1 Straight Line Braking Surfaces

IDIADA's Proving Ground facilities include a comprehensive set of tracks specifically designed for wet condition testing, which are essential for braking system evaluation. These tracks feature a flooding irrigation system and a controlled water film system (particularly on the aquaplaning track), allowing for precise simulation of real-world adverse weather scenarios. The facilities offer various surface types with different friction coefficients, including low-friction surfaces such as basalt tiles and epoxy-coated asphalt, as well as standard asphalt surfaces, enabling engineers to assess vehicle and brake performance across a wide range of grip conditions. The aquaplaning track allows testing with controlled water depths to evaluate tire and braking behaviour when hydroplaning occurs. These capabilities are invaluable for studying the effects of reduced friction on accident dynamics under adverse weather conditions, particularly rain, and for developing and validating advanced braking systems such as ABS and other active safety technologies.

In the Table 1, the different surfaces specifications are shown.

Surface	Friction coefficient (μ)	Water depth	Widht	Length	Longitudinal Slope	Transverse Slope	Maximum Axle Weight	Maximum Permitted Speed
Ceramic	0.1	1 mm	7.5 m	250 m	0%	1% double slope	17.5 T	100 km/h
Asphalt	0.8	1mm	5 m	200 m	0%	1%	16 T	-
Basalt	0.3	1 mm	7.5 m	200 m	0%	1% double slope	13 T	120 km/h
Concrete	0.4	1 mm	7 m	200 m	0%	1% double slope	16 T	120 km/h
Aquaplaning	-	6 mm	3.5 m	150 m	0%	0%	16 T	-

Table 1 Surface specification of IDIADA Straight Line Braking Surfaces Test Track



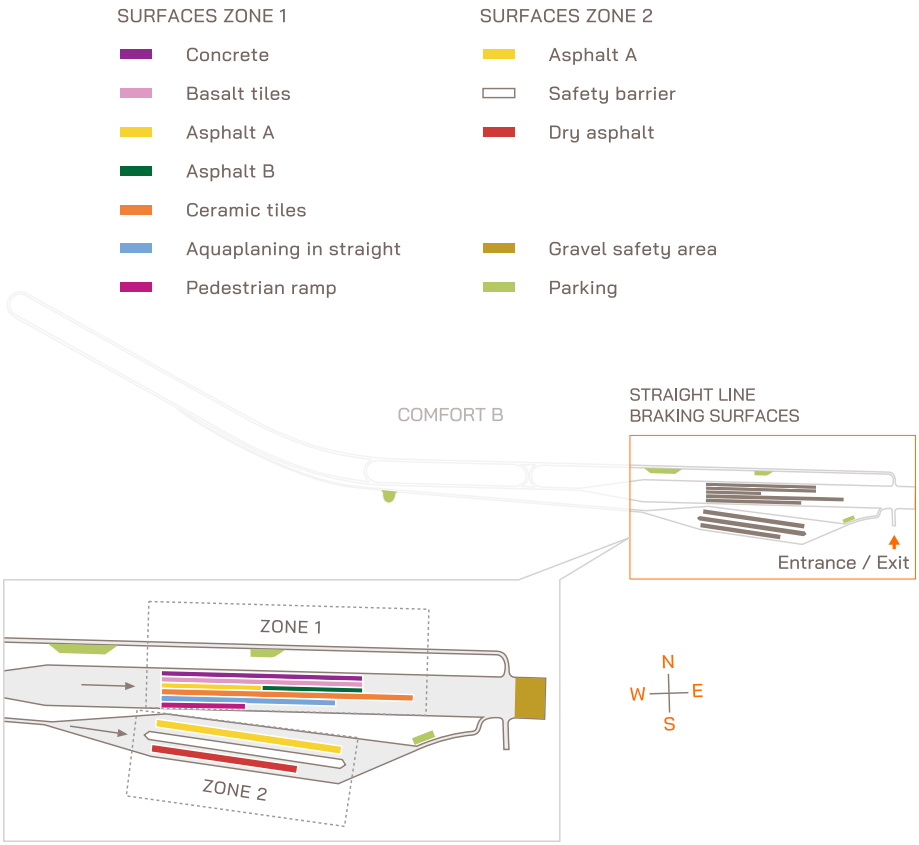


Figure 2-19: Straight Line Braking Surfaces IDIADA Test Track [6]

2.2.2.2 Urban area ADAS & CAV

The Urban Area ADAS & CAV Proving Ground at IDIADA is a comprehensive facility specifically designed for testing Advanced Driver Assistance Systems and Connected & Autonomous Vehicles in realistic urban driving scenarios.

The facility features a main straight of 580 m x 12 m, a circular platform with a 100 m diameter for roundabout testing, intersection configurations at 30° (110 m x 6 m) and 90° (60 m x 12 m), an interurban road section of 540 m x 12 m, a pedestrian sidewalk area (35 m x 28 m), a dedicated VRU (Vulnerable Road User) zone (15 m x 15 m), and an autonomous parking area.

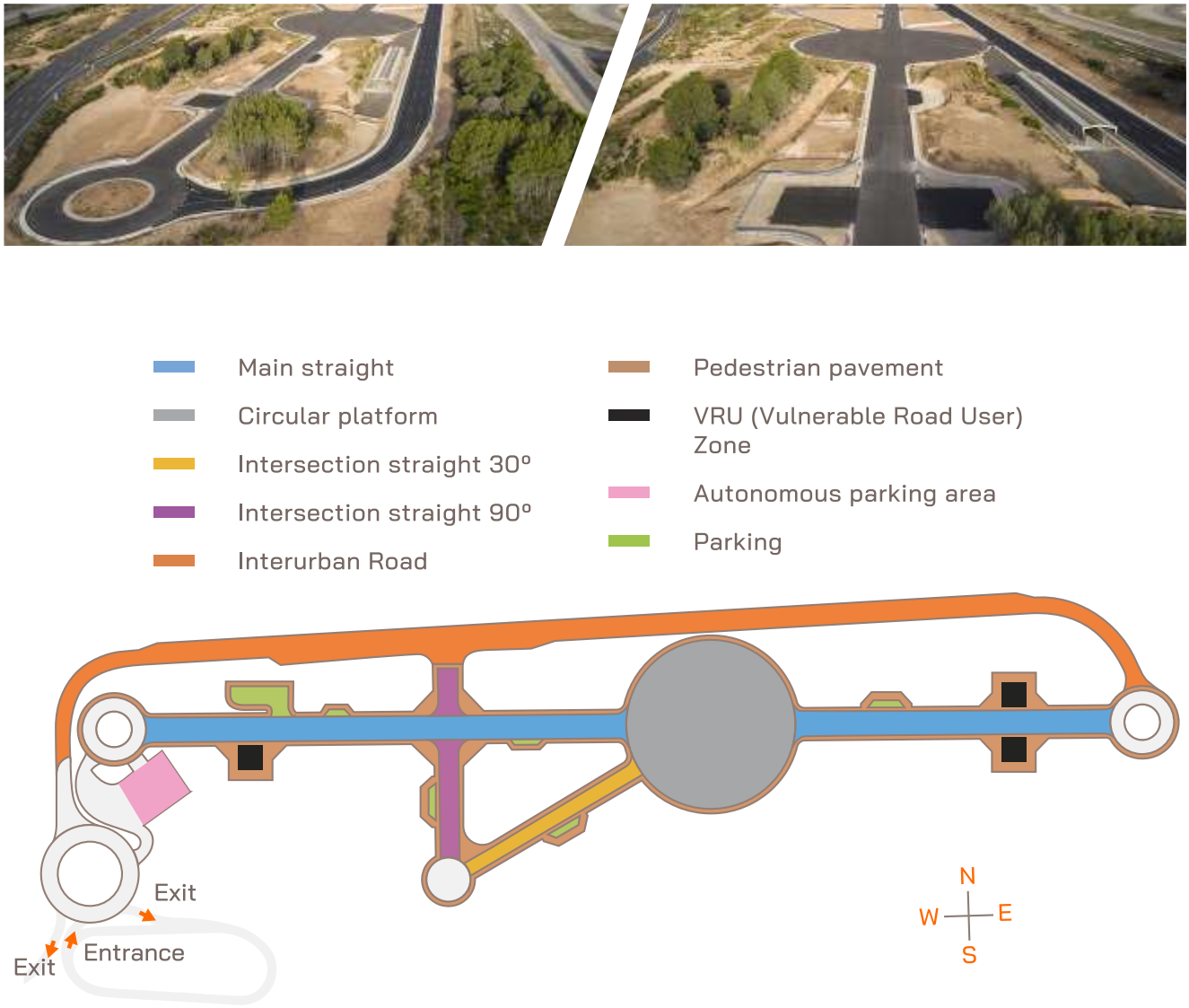


Figure 2-20: ADAS/CAV2 Urban Area IDIADA Test Track [6]

More information about the specific test tracks can be found in the company's website.

2.2.3 TEST TRACK IN UTAC

UTAC operates a global network of proving grounds and laboratories across France, the United Kingdom, Finland, Morocco, and the United States. This footprint is strengthened by service offices in China, Japan, South Korea, Italy, and Romania, enabling us to provide comprehensive testing, development, and certification services for all vehicle types, worldwide and in every environment.
Our proving grounds offer an extensive variety of tracks, including high-speed, road, race, off-road, urban, highway, comfort low-grip, dynamic, and dust circuits. These sites cover a broad range of climates, from the cold conditions of Ivalo to the temperate environments of Millbrook (UK), Linas-Montlhéry and Mortefontaine (France), and the hot climate of Oued Zem (Morocco).

2.2.3.1 Snow, ice, wet and dry testing facility

In Finland, UTAC operates more than 100 km of test tracks across the Mellatracks and Ivalo Airport sites, both fully dedicated to winter testing. These facilities combine a wide range of outdoor circuits with five indoor tracks (snow, ice, wet, and dry), ensuring year-round testing in controlled or natural conditions.

Key capabilities include:

- 100 km of outdoor tracks, including off-road areas suitable for military or off-highway vehicle testing.
- A range of winter surfaces such as slushy snow, soft snow, black ice, icy roads, and slopes at 15%, 20%, and 25%.
- 15 fully equipped workshop-office units supporting test teams on site.

Snow and Ice Platforms

- Snow platforms: Up to 1000 m × 50 m
- Ice platforms: Up to 500 m × 35 m

These large, groomed surfaces allow for objective testing of acceleration, braking, handling, and stability on uniform low-grip conditions.

Snow and Ice Handling Tracks

- Snow handling tracks: Up to 1400 m × 6 m
- Ice handling tracks: Up to 1000 m × 6 m
- Snow hills: Up to 950 m × 6 m

These tracks provide long, narrow routes for evaluating vehicle behaviour, control strategies, and system robustness on varied winter surfaces.

Snow and Ice Circles

- Diameter range**:** 50–200 m

Circular tracks allow controlled testing of lateral dynamics, stability systems, and tire performance in constant-radius manoeuvres.

Vehicle Dynamics Area and Snow Stability Tracks

- Dynamic area: 200 m × 380 m
- Oval track: 3200 m × 10 m
- Stability track: 1830 m × 10 m

Indoor Tracks

- Indoor Tracks 1 and 3 – Snow Surface

- Designed for objective acceleration and braking work, each track features a 205 m × 16 m testing surface, with the possibility to combine them into a 410 m × 16 m configuration.
- Indoor Track 2 – Snow-Holding Surface. A closed-circuit loop designed for snow-maintenance conditions, with a 350 m × 9 m testing surface.
- Indoor Track 4 – Ice Platform. Intended for ice-surface acceleration and braking evaluations, offering a 205 m × 8 m test area.
- Indoor Track 5 – Snow Platform. Designed for spin-traction testing on snow, with a 205 m × 8 m surface.

Environmental Control (All Tracks)
All tracks are fully adjustable, offering:

- Air temperature: −13°C to +15°C (default −8°C during summer)
- Air humidity: 70% to 90% RH
- Track surface temperature: −10°C to +10°C
- Maximum vehicle weight: 3500 kg
- Maximum vehicle height: 2.7 m

Cold Chambers (Rooms 3 & 4)
Two dedicated cold chambers support extreme low-temperature testing with the following specifications:

- Length: 11.7 m
- Width: 2.3 m
- Height: 2.5 m
- Temperature range: down to −40°C



Figure 2-21 UTAC Test track in Ivalo

2.2.3.2 Hot climate, dust

UTAC's new test centre in Oued Zem, Morocco, provides more than 30 km of tracks covering speed, durability, off-road, braking, acoustic testing and more.
Key features include:

- 14 specialised tracks
- A 77,000 m² dynamic testing platform
- Dust track of 300m
- 5 slope's tracks, and 3 have a low adhesion part
- 4 modern workshops
- Ambient temperatures reaching up to 38°C

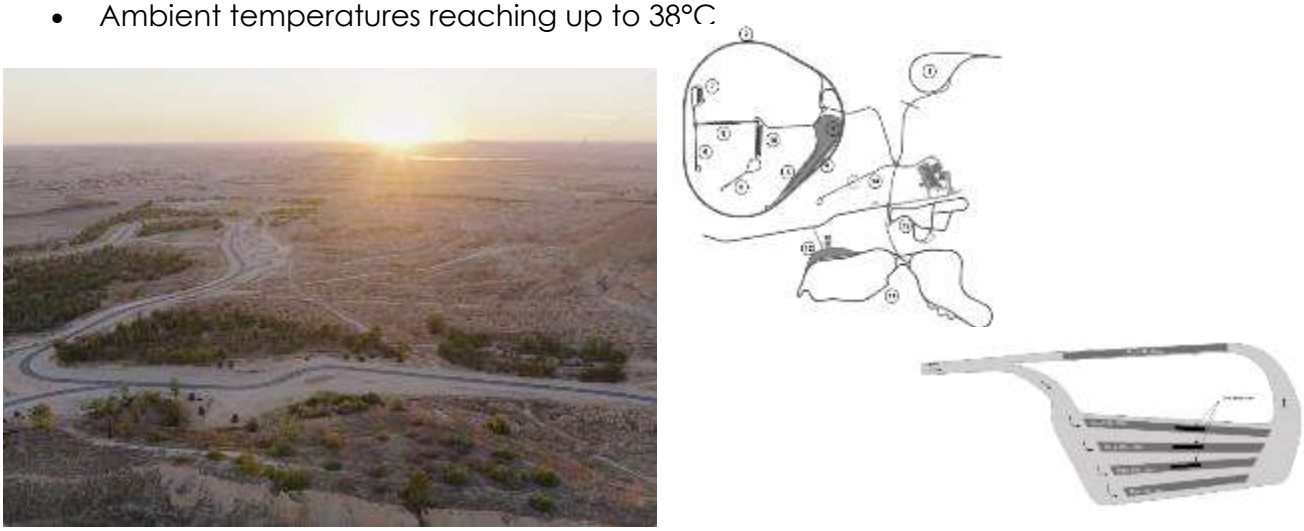


Figure 2-22: UTAC Oued Zem

2.2.3.3 Wet Grip Track

In Montlhéry, France, UTAC operates a 200-meter low-friction Wet Grip track, complemented by a 900-meter launch lane. The adherence coefficients are 0.3 for passenger cars and 0.15 for heavy vehicles. The surface can be uniformly wetted using overhead sprinklers providing a 180° sweep and a 15 m³/h flow rate.
This facility enables detailed evaluation of ABS performance, braking behaviour, and vehicle dynamics in controlled low-grip conditions.



Figure 2-23: UTAC France, wet grip track

2.2.4 FRICTION TRACK FROM MICHELIN

Michelin Technology Centre in Clermont Ferrand present 450-hectare outdoor proving ground comprising 20 test tracks with a total length of approximately 45 km.

High-speed testing

- High-speed track with a total length of 7 800 m and a width between 8 and 11.5 m.
- Banked curves designed for a neutral speed of 100 km/h and a 1 500 m straight section.
- Maximum test speeds up to 250 km/h, subject to conditions.

Dry vehicle dynamics

- Dry handling track, 2 770 m long and 8 m wide, featuring corner radii from 30 m to 240 m.
- Dry dynamic platform measuring 600 m by 25 m, with gradients between 0.5 % and 2 % and maximum speeds up to 200 km/h.

Wet handling and low-friction testing

- Wet handling track of 4 100 m length and 7–9 m width, equipped with an automatic sprinkling system providing a controlled 1 mm water depth.
- Wet dynamic skidpad with a diameter of 120 m, automatic watering, concentric paths up to 50 m radius, and concrete surfaces with varying grip levels.
- Wet handling rings with radii of 36 m, 42 m, 110 m, and 118 m, offering adjustable water depths from 2 mm to 8 mm.
- Multiple surface types including polished concrete, paving stones, and asphalt concrete, plus a curved pool for lateral hydroplaning tests at 8 mm water depth.

Noise, comfort, and NVH evaluation

- Noise and comfort track 600 m long (2 200 m including the acceleration lane) and 18 m wide.
- Incorporates simulated European road obstacles for realistic comfort and acoustic assessments

Electric vehicle infrastructure and support facilities

- Modular high-power EV charging systems up to 175 kW, located close to workshops and handling tracks.
- Dedicated EV recharge bays, vehicle wash station, unloading ramp, and secure technical buildings.
- Infrastructure designed with provisions for future expansion and evolving test requirements.

2.3 OTHER FACILITIES OUT OF THE CONSORTIUM

Based on public information available, there have been detected other facilities outside the consortium that are interesting to reproduce this weather phenomenon, which are mentioned in this section.

2.3.1 AVL INDOOR LABORATORY

The indoor laboratory at the AVL Mobility and Sensor Test Center in Roding is a state-of-the-art environment for reproducible adverse weather and lighting testing of automotive sensors and advanced driver assistance systems (ADAS/AD).
Covering 1600 m² — including 1000 m² dedicated to rain and fog facilities — the test hall enables **controlled generation of precipitation** with intensities **ranging from 15 mm/h up to 120 mm/h**, featuring realistic droplet size distribution and terminal falling velocities that closely mimic real-world rain characteristics.
A sophisticated **fog generation system** creates dense visibility conditions, supporting comprehensive evaluation of perception performance under low-visibility scenarios.
The integrated **high-fidelity lighting infrastructure** reproduces critical luminance conditions "From Dusk till Dawn," with a maximum illuminance of 2000 lux defined 10 cm above the asphalt surface in accordance with NCAP criteria, and adjustable color temperature and light intensity to replicate diffuse and indirect daylight effects without introducing unrealistic reflections on wet pavement surfaces.
Together, these capabilities support repeatable, traceable, and documented testing across a wide spectrum of environmental conditions for robust validation of sensor function and performance.

2.3.2 JARI (JAPAN AUTOMOBILE RESEARCH INSTITUTE)

The source of this information is the public organization's website[8].

- **Dimensions:** Indoor test facility, 200 m length × 3 lanes (3.5 m each = 10.5 m width)
- **Ground truth:** Not specified in document
- **Speeds:** Not specified in document
- **Rain**
  - Area: 200 m total (configurable in two 100 m sections)
  - Rainfall rates: 30/50/80 mm/h (three stages: heavy, very heavy, extremely heavy rain)
  - Particle size: Equivalent to large raindrops
  - Continuous rainfall time: 30 minutes (at 50 mm/h over entire 200 m)
  - Water replenishment time: ~120 minutes

- **Fog**
  - Area: 200 m length
  - Visibility: Adjustable from 15 m to 80 m
  - Particle size: 7.5 µm (ultra-fine mist)
  - Spray flow rate: 2.4-9.6 l/hr per unit
  - Continuous production time: 60 minutes
  - Visibility setting time: ~30-60 minutes

- **Glare**

  - Maximum luminous intensity: 350 million candelas
  - Maximum irradiation distance: 6 km / 10 Lx
  - Illuminance: 20,000-35,000 lux (simulates sunlight at 15:00-17:00 on a clear day)
  - Color temperature: 6000K (daylight white), 2200K (amber white)
  - Position: Variable in vertical, horizontal, yaw, and pitch directions
  - Lighting placement distance: ~70 m from measurement point

- **Lighting conditions**
  - Horizontal illuminance: 200-1,600 lx (dimmable in 4 divisions every 50 m)
  - Color temperature: 5,000K (daylight white)
  - Waterproof specification

- **Traffic Light System:**
  - 3 installation positions (adjustable left-right; one adjustable up-down)
  - Types: 3 light / 3 light + arrow
  - Technology: LED type / Bulb type
- **Further equipment:**
  - Waiting room (test chamber)
  - 2 vehicle preparation buildings
  - 2 garages

2.3.3 DIGITRANS

The source of this information is the public company's website[7].

- **Dimensions:** Outdoor test facility with 80 m length × 6 m width × 10 m height steel structure
- **Ground truth:** Road Weather Information System (RWIS) providing real-time measurements of air temperature, air pressure, humidity, road temperature, water film thickness, road condition, wind speed/direction, and precipitation intensity/type
- **Rain:**
  - Area: 80 m × 6 m
  - Light rain: 20-30 mm/h (variable) across 2 lanes
  - Heavy rain: 100 mm/h across 4 lanes
  - Patented system with natural droplet size distribution
- **Lighting conditions:**
  - 11 dimmable LED street lights
  - Maximum luminous flux: 15,597 lm
  - Supports lighting classes M1-M6
  - Day to full night testing capability
  - EURO NCAP compliant
- **Video System:**
  - 7 color cameras along the steel structure
  - 4 rotatable cameras with programmable motion control
  - 1920×1080 HD resolution
- **Further equipment:**
  - T-intersection with pedestrian crossing
  - Controllable traffic light system with flexible phase control
  - C-ITS interface for vehicle communication
  - Various road markings (structural, surface, crosswalks, edge markings, center lines, direction arrows)

2.3.4 HORIBA RAINFALL SIMULATION SYSTEM

The **HORIBA Real Environment Rainfall Simulation System** delivers an advanced outdoor rainfall and fog test capability designed for connected and autonomous vehicle (CAV) and ADAS sensor evaluation.
The system can reproduce naturalistic precipitation with intensities in the range of **20 – 100 mm/h**, enabling controlled simulation from moderate rain to heavy downpour conditions while maintaining realistic droplet characteristics rather than simple spray patterns. This ensures that environmental recognition sensors on vehicles experience rainfall signatures that closely approximate real-world environmental effects on perception performance.
The setup includes a **static test bench** capable of accommodating vehicle test articles at speeds **up to 130 km/h**, allowing both stationary sensor evaluation and dynamic testing scenarios under controlled rainfall conditions. By integrating high-intensity rainfall simulation with high-velocity bench operation, this system facilitates quantitative assessment of sensor degradation and overall system behaviour in challenging wet weather environments, supporting robust validation of ADAS and autonomous driving functions.

2.3.5 CHINA AUTOMOTIVE ENGINEERING RESEARCH INSTITUTE (CAERI) WIND TUNNEL

CAERI is a long-established national automotive research institute and testing organization in China. It operates under Chinese regulatory supervision and serves as a core technical service provider for vehicle evaluation, safety testing, and certification.

Key capabilities

- National-level automotive testing, evaluation, and certification, including safety, emissions, and mechanical performance.
- Official involvement in Euro NCAP testing — With the CATARC and the SMVIC, CAERI overseas non-European facility recognized for performing Euro NCAP tests (collision and safety assessments).
- **Large environmental and wind tunnel laboratories** (e.g., climatic and aeroacoustics wind tunnels) capable of simulation of rain, temperature, wind, and more, enhancing environmental robustness evaluation of vehicles and components.
- **Technical data**
  - Max. speed: 200 km/h
  - Nozzle diameter: adjustable, 6/8/12 mm
  - Fan capacity: 935 kW
  - Fan diameter: 4,5 m
- **Innovations and special features**
  - Adjustable nozzle sizes
  - Adjustable collector for cars, SUV's and busses
  - Snow-, rain- and sunlight simulation
  - First competitive wind tunnel center in Southwest China

- Support for comprehensive evaluation protocols, including high and low temperature tests and dynamic performance under simulated weather.

Category	Feature	Specifications / Details
Dimensions	Total length	300 meters (continuous test section)
	Lane width	Multi-lane configuration (highway type)
Rain Simulation	Intensity	From 1 mm/h (light rain) to >100 mm/h (storm)
	Drop size	Controlled spectrum from 0.5 mm to 5 mm
	Rain type	Uniform, localized, or spray simulation
Fog Simulation	Visibility (V)	Adjustable from < 5 m to > 1000 m
	Particle size	Micro-droplets from 1 μm to 10 μm
	Technology	High-pressure nozzles with stable laminar flow
Lighting Environment	Lighting	Day/night simulation and glare (headlights/sun)

Table 2 Technical characteristic of the rain and fog tunnel in CAERI

CAERI is deeply involved in safety/regulatory testing with a proprietary protocol (C-IASI) and provides facilities that can support research into adverse environmental conditions affecting vehicle systems, including environmental wind/water simulation.

2.3.6 China Automotive Technology & Research Center (CATARC) tunnel

CATARC is a major national technical research center focused on automotive industry standards, testing, policy support, and certification. Administered by China's State-owned Assets Supervision and Administration Commission (SASAC), it also plays a lead role in C-NCAP development and governance in China.

Key capabilities

- Comprehensive automotive proving grounds, including expansive outdoor test tracks and specialized facilities in Yancheng, available since March 2025/
- Scale: 300 m in length, 4 lanes in width.
- Control system: centralized control + mobile control + zonal control.
- Predefined test scenarios with one-click activation.
- Rainfall: 5 – 120 mm/h.

- Fog: visibility 15 – 500 m.
- Lighting: illumination 5 – 3000 lux with tunable color temperature.
- Lighting simulation.
- Traffic signals.

2.3.7 China Merchants Testing Vehicle Technology Research Institute (CMVR) weather tunnel

Often referred to in sources as CMVR (China Merchants Testing Vehicle Technology Research Institute), this institute is part of the China Merchants Group's automotive testing and innovation ecosystem.

Key capabilities

- Operates a **large extreme weather and traffic environment test la**b in Chongqing (~5,000 m²) designed to simulate dense fog, heavy rain, and complex dynamic scenarios for ADAS and autonomous systems.
- Ability to **test vehicles at up to ~130 km/h** under **challenging simulated weather and light conditions** (dawn/dusk/overcast) — exceeding many industry benchmarks.
- **Integrates whole-vehicle dynamics**, traffic participant behavior, and climate simulation to evaluate perception and safety system performance.
- Acts as both a testing authority and research hub for ADAS/ICV validation, collaborating with government regulators, OEMs, and standards groups.

While CMVR is not the primary NCAP laboratory itself, it significantly extends China's capacity for evaluating ADAS and autonomous vehicle behavior in adverse weather conditions (AWC). Its facilities support research that complements regulatory validation and informs system robustness expectations in NCAP-like frameworks.

2.3.8 GEELY Automotive

Geely operates one of the largest automotive environmental wind tunnel facilities in the world, located at its Safety Centre in Ningbo (China). The Geely climatic wind tunnel is specifically designed to reproduce severe and reproducible environmental conditions, essential for ADAS/ADS validation:

- rain, snow, and solar radiation can be simulated in controlled conditions.
- The facility can combine weather effects with aerodynamic flow.
- It reproduces "nearly all natural environments" through hundreds of scenarios.

Key capabilities

- Scale: 300 m in length, 2 lanes in width.
- Control system: centralized control + mobile control.
- Predefined test scenarios with one-click activation.
- Rainfall: 5 – 100 mm/h.
- Fog: visibility 15 – 500 m.
- Snow simulation.
- Lighting: illumination 5 – 3000 lux.
- Sun glare (backlighting): max 200,000 lux.
- Lighting simulation.
- Oncoming vehicle headlights.

- Traffic signals and signal lights.

2.4 ADDITIONAL TOOLS TO EVALUATE WEATHER PHENOMENA

2.4.1 MESSRING SPRAY TOOL



Figure 2-24 MESSRING SprayMaker mounted on car

The MESSRING Spray Maker is easy and fast to mount on almost any vehicle with a belt. The water nozzles thus attached to the rear and side of the car are connected to two 100l water tanks strapped to the seats of the car via a hose and pump system. The Spray Maker is switched on and off with the supplied remote control. Different water nozzle kits are available, which allow different flow rates. With a total of twelve nozzles, a continuous spray of up to 16 minutes can be generated. Depending on the choice of nozzle, the carrier vehicle equipped with the Spray Maker sprays either a fine spray mist or a stronger spray cloud.

The system consists of the following main **parts**:

- Spray Maker Box **Power Supply** Module
- SprayMaker Box **Pump Module**
- Water **tank**
- Water **pipes**
- Window **adapters**
- Spray Maker **modules** to apply to vehicle outside.

Depending on mounting position and angle on the spray vehicle and choice of nozzles for the spray modules different types of scenarios are feasible. Ranging from small mist to heavy rain application.

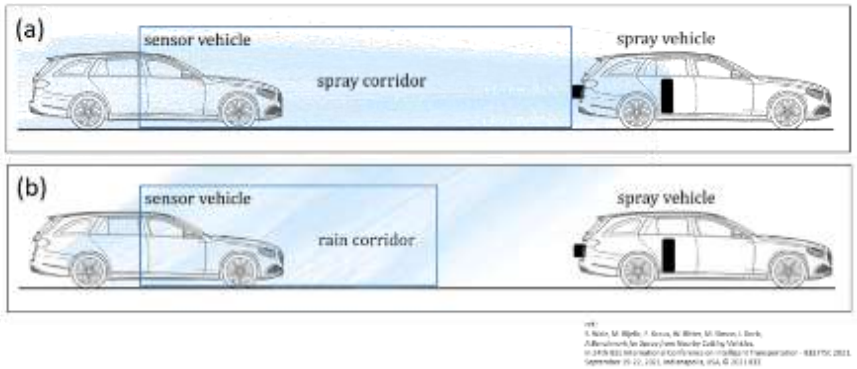


Figure 2-25: Schematic spray and rain Application

The generated spray or rain can be used in static and dynamic test setups.

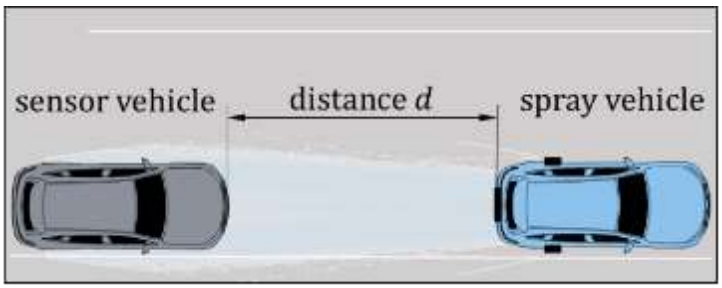


Figure 2-26: Example for static or follow testing

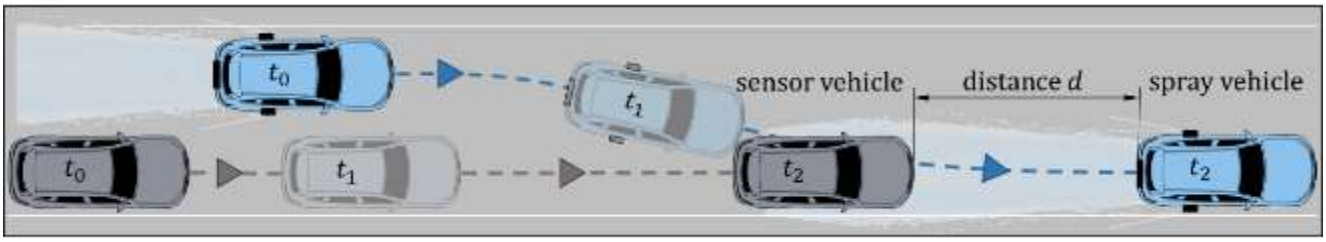


Figure 2-27:Example for reeving manoeuvre spray testing

2.4.2 AstaZero Spray Rig



Figure 2-28 The Asta Zero Spray Rig

The AstaZero Spray Rig is mounted on a standard trailer with a steel frame covered with a thick tarpaulin. Building on a trailer significantly increases the equipment's mobility and enables dynamic testing by towing the trailer behind a car in front of the test object. A petrol generator is mounted in the trailer to supply power to the system during dynamic spray testing.

It uses a centrifugal pump with a 230 l/min and 10 bar capacity connected to a 250-litre tank with 40 mm piping to facilitate high flow rates.

The complete system comprises multiple ball valves, manometers, and adjustment nobs. In principle, it has four "output channels", a main dump valve, one external refill connection, and three adjustment valves with manometers for pressure readings.

In standby state, the water is circulated from the tank through the main dump valve and back into the tank via the return pipe.

In refill state, the pump will suck water from the external refill pipe via the main dump valve and into the onboard tank.

By opening any number of the four output channels and closing the main dump valve, different amounts of spray can be produced with attached nozzles (currently producing droplets of 50-400µm diameter).

In the current setup, with all nozzles open full throttle, the rig will consume upwards of 100 litres per minute, meaning just over 2 minutes of constant spray. However, the tank can be refilled through the onboard pump at a rate of over 200 litres per minute by connecting to an external buffer tank. The rig can then be refilled in just a couple of minutes.

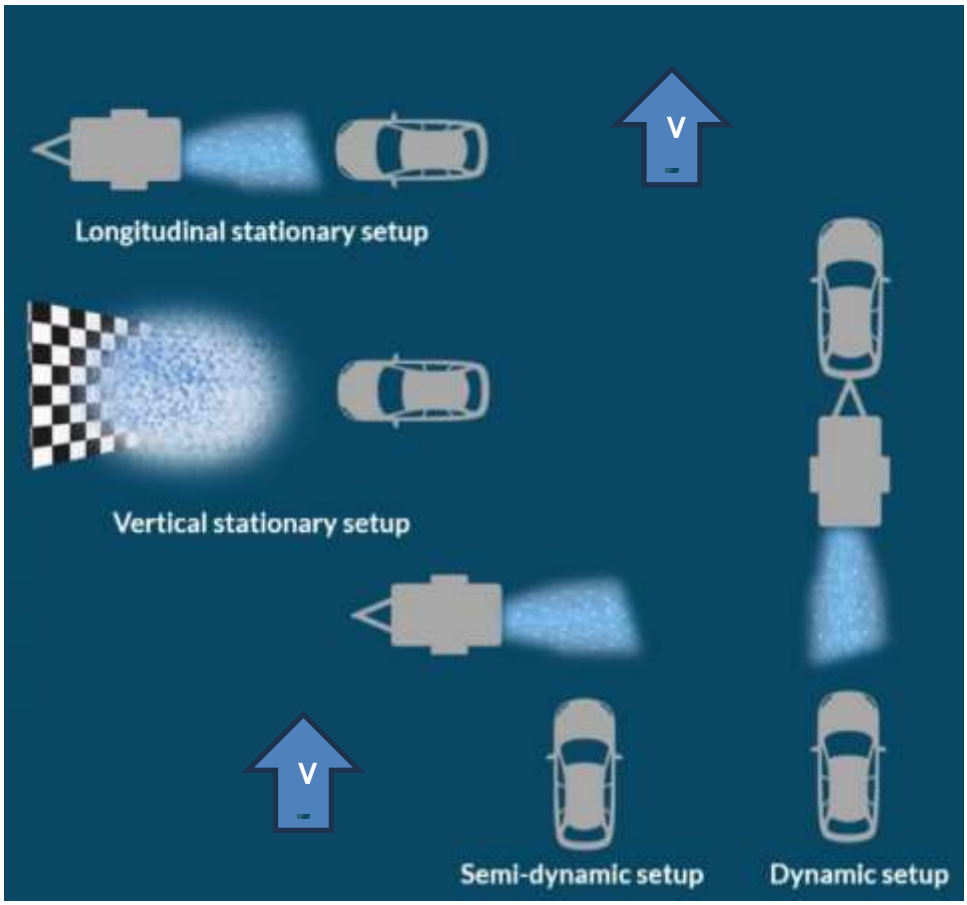


Figure 2-29 The 3 different setups of the spray rig

2.5 COMPARATIVE ANALYSIS AND CLUSTERISATION

2.5.1 EVALUATION CRITERIA

In this section, the different criteria for evaluating the facilities and its further analysis will be held. This evaluation will be done via a cross-sectional analysis of the results of testing held in the different testing facilities workshops during the project.

The decision to include these criteria is based on the results of accidental analysis and phenomena characterisation in the work package 2, as well as the analysis of the workshop's facilities and also the different encounters we had during the testing campaigns.

2.5.1.1 Physical Dimensions

Facilities are evaluated based on their physical dimensions to determine suitability for ADAS adverse weather testing scenarios.

This includes:

- **Total facility dimensions**: Length × width × height measurements of the complete testing infrastructure.
- **Usable testing space for ADAS adverse weather testing**: The specific area within the facility can effectively reproduce adverse weather conditions with adequate sensor coverage.
- **General usable testing area**: Total available space for any testing activities, providing context for facility versatility.
- **Minimum dimension requirements**: Critical spatial parameters necessary to conduct meaningful ADAS adverse weather testing scenarios.

The distinction between general testing area and adverse weather testing area is necessary as weather reproduction systems require specific spatial configurations and may not utilize the entire facility footprint effectively.

2.5.1.2 Available weather phenomena reproduction

Facilities are evaluated on their technical capacity to reproduce specific weather phenomena.

2.5.1.3 Testing speed capabilities

- **Static Testing Capabilities**: the highest vehicle speed achievable while maintaining controlled weather conditions for stationary target scenarios. Analysis of test plans indicates:
  - **CARISSMA**: up to 50 km/h under controlled indoor conditions;
  - **CEREMA**: up to 30 km/h for static and dynamic tests in controlled environment;
  - **UNIV-EIFFEL**: up to 20 km/h for static and dynamic evaluations on a small road ring, with adjustable air /surface temperatures and multifactor climatic conditions (e.g., humidity, lighting).

- **Dynamic Testing Capability**: whether the facility can accommodate moving vehicle-to-vehicle interactions under adverse weather conditions.

- **Dynamic Testing Maximum Speed**: When dynamic testing is feasible, the maximum achievable speed for multi-vehicle scenarios while maintaining weather condition control and safety parameters.

2.5.1.4 Rain Reproduction capabilities

- **Rain Intensity Range Specification**: critical analysis of partner testing results reveals the complexity of rain effects on sensor performance.
    - Current facilities capabilities span from **17 mm/h to 300 mm/h** based on the consortium's state of the art facility analysis.

- **Droplet size distribution**
    - The accurate measurement of rainfall droplet size distribution (DSD) is fundamental for reproducing weather conditions that genuinely replicate real outdoor environments. The study from PAVIN Extreme Weather Facility [9] states that DSD represents one of the most critical parameters for characterizing rain events, as it directly influences LiDAR sensor performance in ways that rainfall intensity alone cannot predict. Without proper DSD calibration, there is significant risk of skewing test outcomes, potentially making moderate rainfall appear more disruptive than heavy rain. The study conclusively establishes that validating agricultural robotic sensors requires not only matching macroscopic parameters like rainfall rate, but also ensuring microscopic DSD accuracy to reflect real-world meteorological conditions and guarantee reliable safety certification results. In conclusion, the control of DSD has a big impact on the reproducibility of natural rian characteristics.

2.5.1.5 Fog Reproduction Features

- **Fog Density Control**: facilities must demonstrate capability to produce controlled fog conditions with measurable Meteorological Optical Range (MOR). Based on World Meteorological Organization, [10] the testing requirements include:
    - Very dense fog: less than 30m visibility
    - Dense fog: 30-60m visibility
    - Medium fog: 60-90m visibility
- **Progressive fog capability**: ability to create graduated fog density changes. Two approaches are possibles:
        - **Ramp-wise fog**, like in CARISSMA
        - **Step-wise stabilized fog**, like it in CEREMA

2.5.1.6 Maximum allowed speeds

Facilities are classified into three speed categories based on their maximum capabilities.

- **Low-Speed Facilities (<30 km/h)**:
    - Primarily used for controlled indoor testing where weather phenomena reproduction requires lower speeds
    - Ideal for static perception testing and detailed sensor performance analysis
    - Allows precise control of vehicle motion and sensor sampling rates
- **Medium-Speed Facilities (30-70 km/h)**
    - Capable of simulating realistic urban and highway driving conditions
    - Suitable for active safety tests and dynamic driving scenarios

- Provides balance between speed and environmental control capabilities

- **High-Speed Facilities (>70 km/h)**
  - Designed for high-speed highway testing and advanced autonomous driving validation
  - Limited to outdoor facilities due to safety and control requirements, with the exception of AstaZero's DryZone proving ground, because of large dimensions it can be up to 90 kph.
  - Critical for evaluating system performance under demanding conditions

2.5.1.7 Speed Limitations vs. Weather Phenomena Reproduction

- **Rain Testing**: As established in the testing workshops, on which rain testing was planned to be conducted under 10 kph as primary speed configuration, and 20 kph after, the idea is to check that lower speeds (10-30 km/h) provide better sensor sampling and weather condition stability, particularly for camera systems where motion blur affects performance analysis.

- **Fog Testing**: When testing in CEREMA's PAVIN facility, the methodology consists of testing with the static ego vehicle evaluates sensor performance, and perform visibility transitions, in lower speeds (10-20 km/h) to allow better sensor integration and more reliable perception metrics, especially with these fog ramp testing scenarios.

- **Glare Testing**: Glare testing demonstrates speed independence; however, 10-30 km/h range provides optimal conditions for evaluating camera exposure adaptation, allowing sufficient time for the camera exposure to respond to glare conditions and measure detection failure rates.

2.5.1.8 Indoor vs. Outdoor Facility Speed Capabilities

- **Indoor Facilities**
  - **Max speeds**: 10-50 km/h, with the exception of DryZone (but not prepared to controlled weather phenomenon, only spray tests)

  - **Speed limitations**: Primarily due to facility dimensions, safety constraints, and weather generation system stability

  - **Weather phenomena limitations**: Optimal for rain and fog. Glare is also possible and feasible.

- **Outdoor Facilities**
  - **Max speeds**: 80+ km/h (weather-independent)

  - **Weather phenomena limitations**: Natural weather only; no controlled reproduction of specific weather intensities

  - **Primary use**: Spray testing, high-speed scenarios, and real-world validation

A synthetic overview of all the capabilities is provided in Tables 2 and 3.

FACILITY	INDOOR / OUTDOOR	SPEED CATEGORY	RAIN	FOG	GLARE	SPRAY TESTS	GROUND TRUTH POSITIONNING SYSTEM
CARISSMA	Both	Medium	✓	✓	✓	Limited	✓
CEREMA	Both	Medium	✓	✓	✓	Limited	✗
UNIV-EIFFEL	Indoor	Low	✓	✓	✓	Limited	✗
MHI-MS	Indoor	Static	✓	✓	✓	✗	✗
ASTAZERO	Both	High	✗	✗	✓	✓	✗
IDIADA	Outdoor	High	✗	✗	✗	✓	✗
UTAC	Outdoor	High	✗	✗	✗	✓	✗

Table 3 Capabilities of the facilities under the consortium

FACILITY	INDOOR / OUTDOOR	SPEED CATEGORY	RAIN	FOG	GLARE	SPRAY TESTS	GROUND TRUTH POSITIONNING SYSTEM
AVL	Both	Medium	✓	✓	✓	✗	✓
DIGITRANS	Outdoor	High	✓	✗	✗	✗	✗
JARI	Both	Medium	✓	✓	✓	✗	✗
HORIBA	Outdoor	High	✗	✗	✗	✗	✗
CAERI	Both	Static	✓	✓	✓	✗	✓
CATARC	Both	High	✓	✓	✓	✗	✓
CMVR	Both	High	✓	✓	✓	✗	✓

Table 4 Capabilities of the facilities out of the consortium

2.6 MAIN OUTCOMES FROM WORKSHOPS IN PERCEPTION-ORIENTED VALIDATION FACILITIES

The results presented herein are based on extensive workshop sessions carried out during testing campaigns conducted at multiple facilities. These workshops served as a platform for systematic evaluation and cross-functional analysis, yielding the findings detailed below.

2.6.1 WORKSHOP AT SENSE-CITY UNIV-EIFFEL

Inside the Sense-City platform, we tested two lidars and one camera. We put a target at some distance from the sensor. For the target used, a same wood cube structure was used.



Figure 2-30 Wood structure used as target

We also integrated the weather phenomena that Sense-City could produce: rain and fog. The targets were also tested at several distances as shown in the figure below. Only one distance at a time was tested.



Figure 2-31: Tested distances

The fogs generated during the tests were light fog. Below, we described the processing that we applied to the data to get usable results from it.
We did the tests described above and we calculated several metrics from the dataset collected:

- number of points on the target;
- number of points between the sensor and the target;
- spatial distribution of points between the target and the lidar.

The metrics were calculated exclusively from a 360° Ouster lidar. For calculating the spatial distribution of lidar points our method consisted of dividing the area between the lidar and the target in 8 sub-areas and counting the number of points in each area. The figure below shows the division of the area between the target and the sensor.

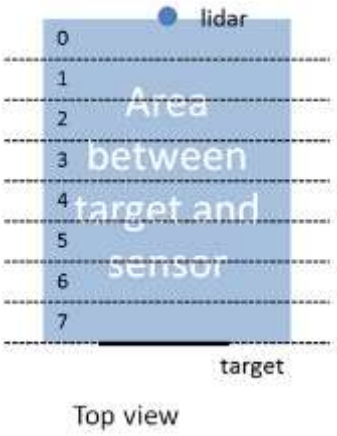
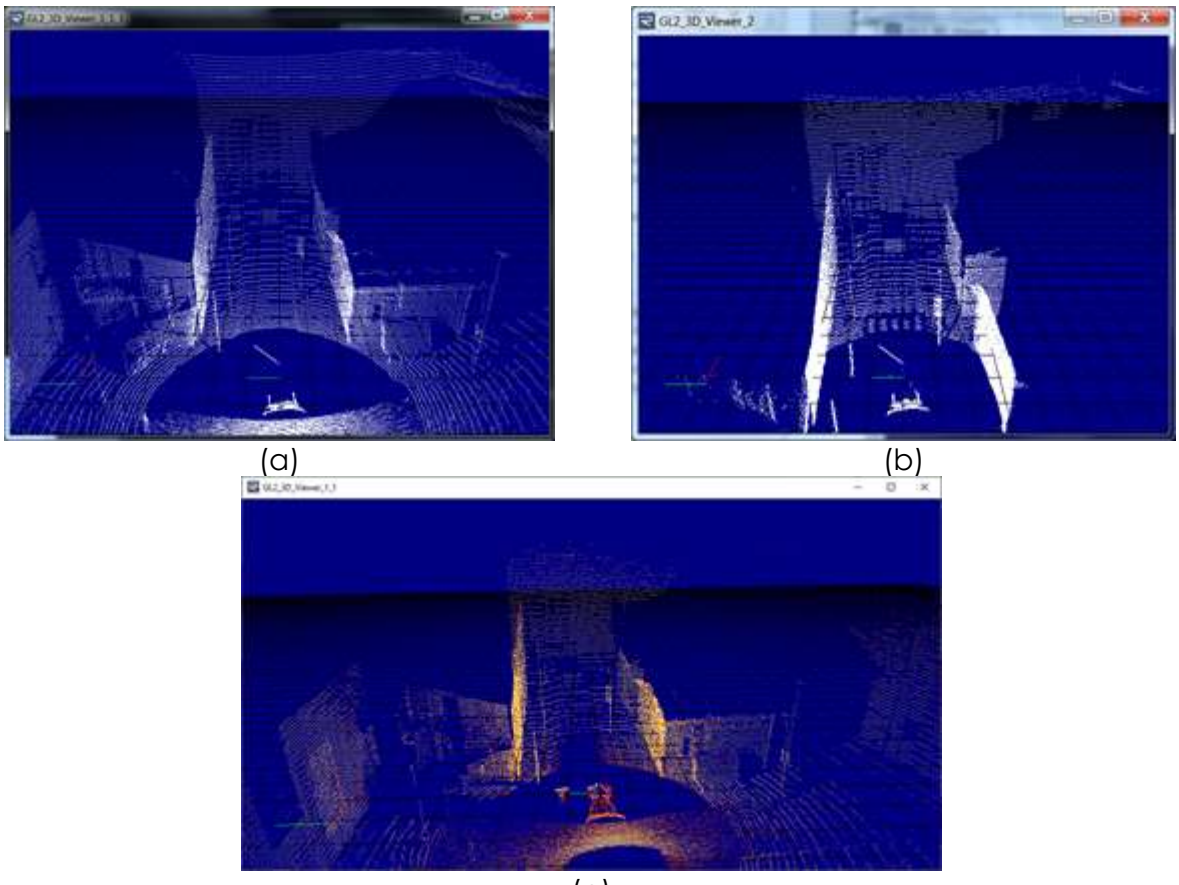


Figure 2-32: Sub-areas 0 to 7

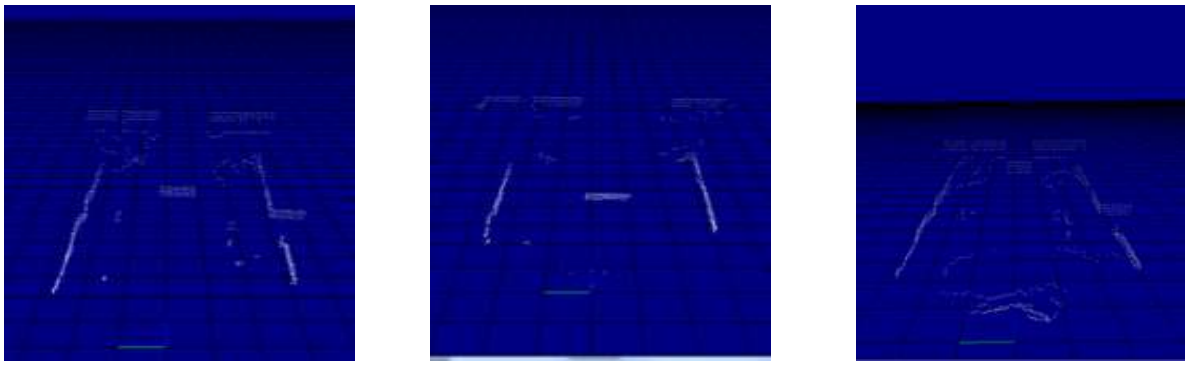
We provided photos below to show the outputs of the tested sensors: lidar and camera.



(a) (b)

(c)

Figure 2-33: 360° Ouster lidar outputs. (a) undisturbed conditions, (b) rain, (c) fog. In fog we see the "reflection ring" around the lidar



(a) (b) (c)

Figure 2-34: 4-layer Sick lidar outputs. (a) undisturbed conditions, (b) rain, (c) fog



(a) (b)



(c)

Figure 2-35: Camera test images. (a) undisturbed conditions, (b) fog, (c) rain

Images captured in fog appeared blurrier than those taken in clear conditions. Rain did not noticeably affect photo clarity, but water on the windshield caused distortion and blurring of the view behind it.

For the lidars, observations indicated that lidar echo points were detected in front of the device under rainy conditions. This phenomenon was not observed during undisturbed conditions. The presence of falling raindrops in front of the lidar appeared to be a contributing factor. In foggy environments, a ring surrounding the lidar was observed (see Figure 5-5), which was absent in undisturbed scenarios. It is presumed that this effect results from nearby fog particles reflecting the lidar's emissions.

When the target was positioned 6 meters from the sensor, the number of points detected on the target remained consistent. However, fog and rain conditions resulted in a reduction in the number of points between the sensor and the target compared to undisturbed conditions. Under foggy conditions, fewer points were observed in the last sub-areas relative to undisturbed scenarios. This phenomenon can be attributed to the absorption and diffusion of laser wavelengths by fog particles, which reflect laser beams before they reach distant surfaces (refer to the "reflection ring" in Figure 5-4). In contrast, the spatial distribution of lidar points in rain was similar to that in undisturbed conditions, except for a decrease in point count within the first sub-area.
Normally, it is anticipated that only a few points would be present directly in front of the lidar under undisturbed conditions. However, the point count was comparable across all weather conditions, likely due to the presence of an individual in the study area (adjacent to the lidar, in sub-area 1) during the collection of undisturbed data.

Weather	A: Nb of points on target – distance 6 m	B: Nb of points between target and sensor	Total (A+B)	Ratio (%)
Undisturbed	237	983	1220	80,574
Fog	224	635	859	73,923
Rain	236	536	772	69,43

Sub-area Index with target at 6 m	Weather		
	Undisturbed	**Fog**	**Rain**
0	444	437	167
1	142	194	72
2	0	0	0
3	0	0	0
4	0	0	0
5	168	0	116
6	128	0	71
7	101	4	110
Tot. Number of points between the sensor and the target	**983**	**635**	**536**

The algorithm was unable to differentiate the target when it was positioned 10 meters away from the sensor. Consequently, we analysed how many points lay between the sensor and a selected position situated close in front of the target.

Sub-area Index with target at 10 m	Weather		
	Undisturbed	Fog	Rain
0	434	1898	423
1	0	0	0
2	0	0	0
3	293	92	173
4	448	80	204
5	246	52	211
6	164	99	132
7	104	62	82
Tot. Number of points between the sensor and the target	**1689**	**2283**	**1225**

Sub-area 0's red value in fog is due to the open car door being within the laser range and a "reflection ring" from fog particles around the lidar. Without disturbance, the lidar showed no reflection ring and detected more data points per sub-area. Other distributions were largely consistent.

2.6.2 WORKSHOP AT CARISSMA ISAFE INSTITUTE

2.6.2.1 Test plan

In the CARISSMA Workshop there were planned over 85 detailed test scenarios designed to evaluate vehicle safety systems under various environmental conditions. The tests are organized into five main categories:

- Dry conditions (with/without glare): evaluating vehicle response on dry roads with different lighting and glare situations.
- Rain and/or Glare with wet ground: testing performance under rain intensities of 20, 60, and 100 mm/h combined with wet surfaces.
- Dry, Glare, Rain combinations: additional scenarios focusing on predecessor targets with mixed weather conditions.
- Fog scenarios: assessing visibility and detection capabilities at fog densities ranging from 10 to 400 meters visibility.
- Outdoor Spray tests: follow scenarios simulating spray from other vehicles under moderate to heavy rain.

Each test is defined by specific parameters including:

- Vehicle speed and type of vehicle (APTIV, Denso, Nissan, CARISSMA);
- Target type (pedestrians, cyclists, children, adults);
- Environmental conditions (day/night/dawn, rain intensity, fog presence);
- Location (indoor/outdoor) and priority level;
- Timing and measurement references.

The **conceptual structure and planning criteria** for the different types of safety tests to be conducted. It categorizes scenarios by the type of interaction being evaluated:

- **Car-to-Bicycle**: tests involving vehicle detection and response to cyclists;
- **Car-to-Pedestrian**: scenarios with targets positioned longitudinally (0°) or crossing perpendicularly;
- **Car-to-Car**: vehicle-to-vehicle interactions following ENCAP offset protocols.

Key planning considerations include:

- Compliance with **ENCAP 26 Robustness crash avoidance** [11] standards
- Target orientation variations (250-290°)
- Changing target appearances (reflective vs. dark clothing)
- Space requirements for vehicles, targets, and facility layout

2.6.2.2 Analysis from UNIV-EIFFEL

A camera has been used to log some of workshop's test plan scenarios.



Figure 2-36: An image of the camera test logs

Data were collected under three weather conditions: glare, fog, and rain. The videos analysed were from Carissma Test Plan scenarios 79, 81, 83, and 88; relevant test photos are provided in the qualitative results below.

For camera protection, its position was adjusted during fog tests. The following figure illustrates camera placement for each weather condition.

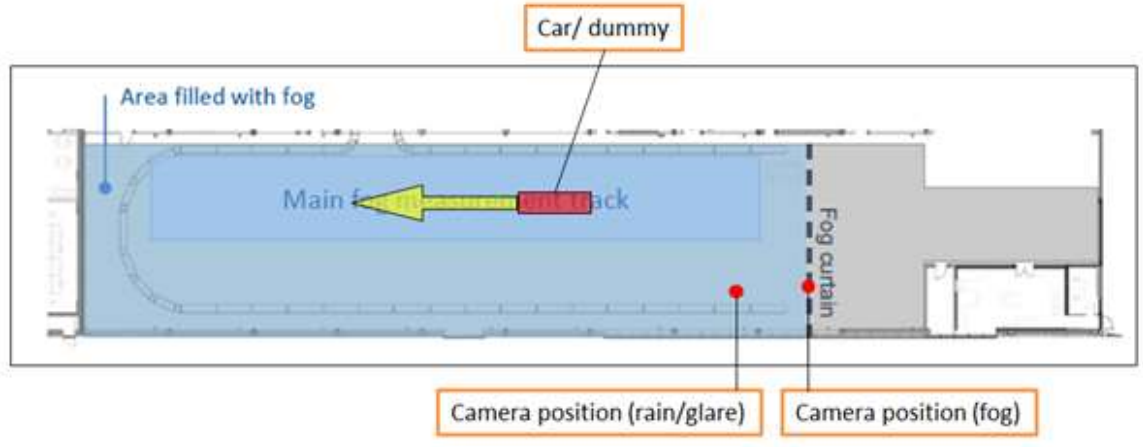


Figure 2-37: Approximative positions of the camera in the test room depending on the climatic condition tested

We reviewed videos by evaluating the detections made by two object detection models: YOLO V8 and RT-DETR [12]. Using Python's Ultralytics library [13], we loaded coco [14] pre-trained models.
In the next section, we start with a qualitative assessment of the predictions from both detection models. We also provide statistics on detections under various weather conditions and compare their outcomes. During our quantitative analysis, we discuss issues related to the road mirroring effect.

2.6.2.2.1 Qualitative analysis

Several logs were unusable due to visibility issues, such as those from scenarios with night or fog. In the images below, class IDs match the COCO format: 0 is person, 1 is bicycle, and 2 is car.

- **Rain at 20 mm/h**

The detections were fairly accurate while the ego vehicle was driving forward. However, as the vehicle reached the target and switched on its reversing lights, the detected class for the ego vehicle became incorrect until it got close enough. This error occurred because the reversing lights reflected off the ground, disrupting the system's perception and causing the algorithm to detect both the vehicle and the reflections as a single object.



(a) (b)

Figure 2-38: Detections during a 20mm/h rain. (a) Correct detections, (b) the reflects of the reversing lights of the vehicle on the ground disturbed the perception of the vehicle

- **Rain at 100 mm/h**

The target vehicle was not detected.

- **Fog**

Initially, the dense fog prevented any detection of the pedestrian. As the fog cleared, the pedestrian was detected only at close range.



Figure 2-39: Pedestrian detection in fog detenuation

- **Glare**

For this scenario, data were recorded after completion of the test. The ego vehicle was reversing. The results were comparable to those obtained under rainy conditions. The target vehicle was detected; however, the corresponding bounding box also encompassed its ground reflection. The ego vehicle was either not detected or incorrectly detected, primarily due to reflections caused by the reversing lights.



Figure 2-40: Detection of target but not ego vehicle

2.6.2.2.2 Quantitative analysis

This section presents quantitative results for both detection **models YOLO and RT-DETR** under different weather conditions, focusing only on videos with detections. Tables and graphs display detection data and timing. The "frames with detection" metric in tables refers to the proportion of video frames containing at least one detection.

- **YOLO Detection for Fog (test 88)**

Metric	Class	Value
Frames with detection		0,796%
Class detection ratio	person	100,000%

Figure 2-41: Detection frames under YOLO algorithm. Fog. UNIV-EIFFEL.

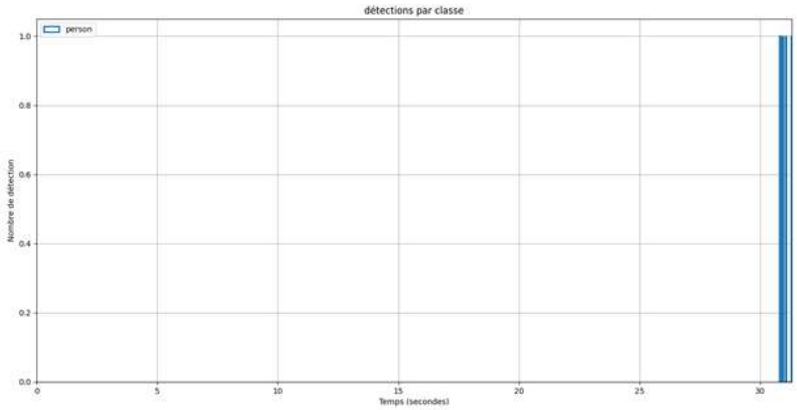


Figure 2-42: Detections (n) YOLO algorithm. Fog. UNIV-EIFFEL

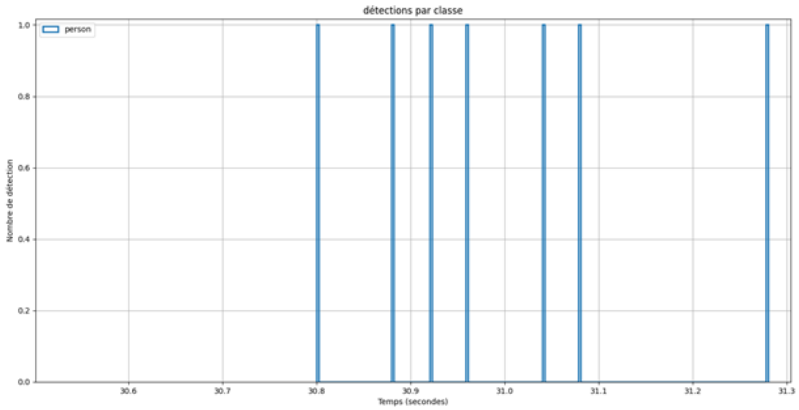


Figure 2-43: Zoom of detection, last period. YOLO algorithm. Fog. UNIV-EIFFEL

A single pedestrian was identified, which aligns with the objects observed within the video. Due to the high density of the fog, the dummy remained undetected until the conclusion of the recording, when visibility improved as the fog dissipated.

- **YOLO Detection for Glare (test 83)**

Metric	Class	Value
Frames with detection		100,000%
Class detection ratio	car	100,000%

Figure 2-44: Detection frames under YOLO algorithm. Glare. UNIV-EIFFEL.

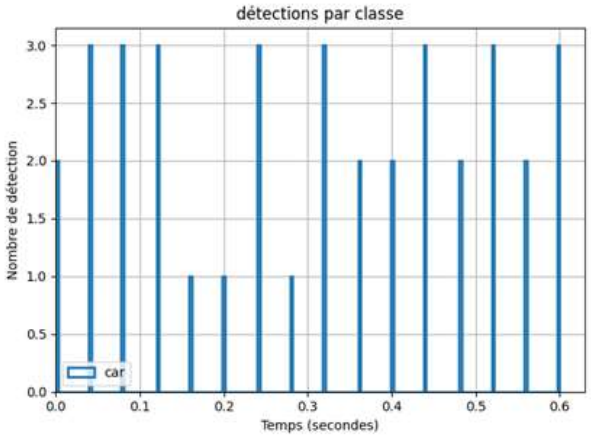


Figure 2-45: Detections (n) YOLO algorithm. Glare. UNIV-EIFFEL

All detections identified vehicles as cars; however, the number of cars occasionally deviated from expectations.

- **YOLO Detection for Rain (test 79)**

Metric	Class	Value
Frames with detection		61,538%
Class detection ratio	Car	79,012%
	Person	20,988%

Figure 2-46: Detection frames under YOLO algorithm. Rain. UNIV-EIFFEL.

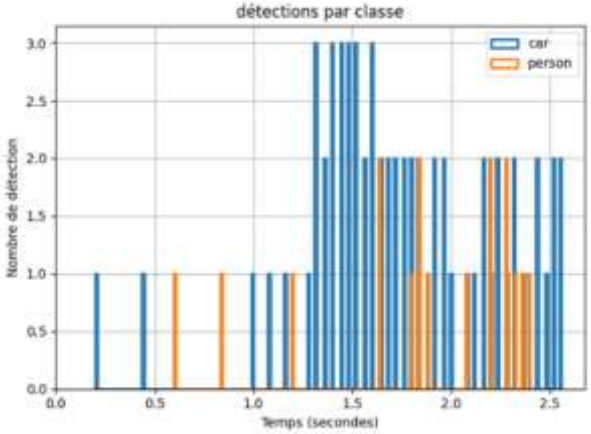


Figure 2-47:Detections (n) YOLO algorithm. Rain. UNIV-EIFFEL

Over 20% of detections falsely identified people, despite none appearing in the video. The model was confused by wet ground reflections from vehicles - a road mirroring effect discussed later in the document.

- **RT-DETR Detection for Fog**

We were unable to run predictions with this detection model during foggy conditions because of issues with the video.

- **RT-DETR Detection for Glare (test 83)**

Metric	Class	Value
Frames with detection		100%
Class detection ratio	car	70,13%
	truck	29,87%

Figure 2-48: Detection frames under RT-DETR algorithm. Glare. UNIV-EIFFEL

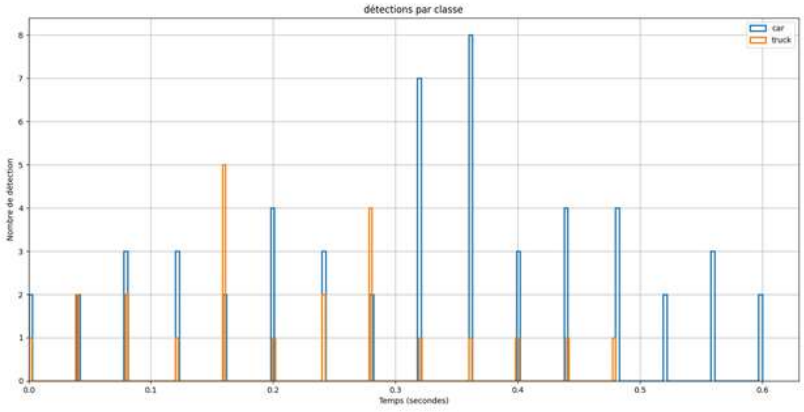


Figure 2-49: Detections (n) RT-DETR algorithm. Glare. UNIV-EIFFEL

During daytime glare scenario, more than 29% of detections were trucks even though there were none in the video.

- **RT-DETR Detection for Rain (test 79)**

Metric	Class	Value
Frames with detection		100%
Class detection ratio	car	72,483%
	truck	25,503%
	traffic light	1,342%
	person	0,671%

Figure 2-50: Detection frames under RT-DETR algorithm. Rain. UNIV-EIFFEL



Figure 2-51: Detections (n) RT-DETR algorithm. Rain. UNIV-EIFFEL

Overall, the camera-based perception performance was significantly affected by adverse weather and lighting conditions. Both YOLO v8 and RT-DETR demonstrated sensitivity to environmental artifacts, particularly ground reflections caused by rain, glare, and vehicle lighting. Wet road surfaces and extended light reflections frequently led to misclassifications, such as false pedestrian detections or incorrect object classes, and in some cases prevented reliable detection of the ego vehicle itself. Fog primarily impacted detection range, with objects only identified once visibility improved. While detections were generally consistent when visibility was adequate, these results highlight the limitations of current vision-based object detection models in handling reflection-induced road mirroring effects. This underlines the need for improved robustness, additional filtering strategies, or sensor fusion approaches to mitigate false detections under challenging weather and illumination conditions.

2.6.2.3 Results from Aptiv

The CARISSMA workshop results provide a detailed comparative assessment of radar and vision sensor performance under controlled and outdoor adverse weather conditions, highlighting sensor-specific sensitivities and methodological limitations:

2.6.2.3.1 Radar sensing performance and robustness

Radar exhibited a high level of robustness to environmental disturbances, with no measurable degradation in detection accuracy or tracking stability under diverse lighting conditions (low light, daytime glare, sunset glare, and night-time headlight glare) and in fog scenarios.
Under precipitation, radar performance remained largely stable, although heavy rain (≈20 mm/h) induced specific phenomena:

- A decrease in mean Radar Cross Section (RCS) was observed with increasing rain density, indicating attenuation effects and modified scattering behaviour.
- Ghost detections appeared under high rain intensity, particularly in dynamic outdoor configurations using artificial water projection.
- Despite RCS reduction, target tracking remained reliable at short range, suggesting limited operational impact for typical ADAS scenarios at close distances.

A key limitation identified is the absence of quantitative assessment of angular discrimination under rain, which remains an open point for future dynamic testing with crossing targets.

2.6.2.3.2 Vision (camera) system performance

Vision-based perception demonstrated globally stable performance in nominal and moderate weather conditions (dry, rain, fog), but showed critical sensitivity to glare conditions, which constitutes the main operational limitation:

- In indoor dry conditions, complete failure to detect pedestrians under all glare configurations was observed, alongside degraded vehicle detection performance.
- In indoor wet conditions, detection capability persisted but with reduced quality and confidence, although pedestrian targets were sometimes more visible than vehicles.
- In outdoor scenarios, camera systems maintained overall detection functionality under low and moderate rain but exhibited classification instability and flickering effects under heavy rain, particularly for stationary pedestrians.

These results confirm that illumination artefacts (glare) have a more critical impact than meteorological attenuation for vision sensors, unlike radar.

2.6.2.3.3 Test methodology and infrastructure limitations

The experiments highlighted significant constraints affecting reproducibility and regulatory applicability:

- Spray-based systems were identified as a promising alternative, especially for ACC-relevant scenarios, enabling better control of water projection effects at test speeds where natural spray phenomena are otherwise difficult to reproduce.

Overall, the results confirm a clear complementarity between radar and vision sensors, with radar providing stable detection under adverse weather and lighting conditions, while vision systems remain more vulnerable to optical disturbances, particularly glare. At the same time, the study emphasizes the need for improved, repeatable and standardised environmental simulation methods to support robust ADAS validation and future homologation frameworks.

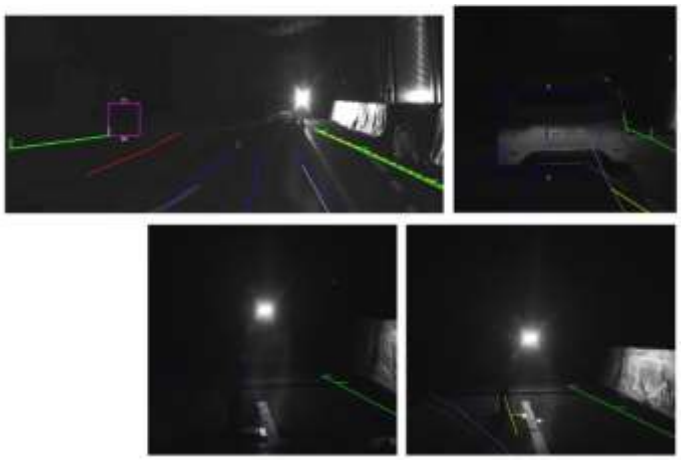


Figure 2-52 Frames from APTIV camera during the workshop in CARISSMA

2.6.2.4 Analysis from AstaZero

To perform the analysis of the results of camera performance under indoor rain and fog, the Michaelson Contrast [15] attenuation through seconds was analysed as can be seen in the following figures.

- **Rain**



Figure 2-53: Positioning of the vehicle and vision of contrast target for rain performance. AstaZero

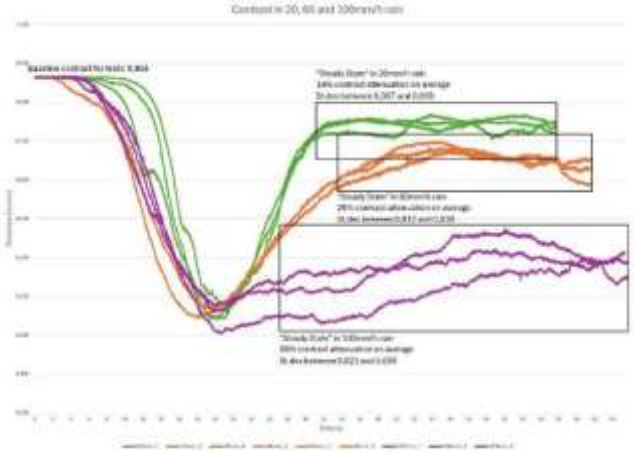


Figure 2-54: Michelson Contrast attenuation under different rain intensities. AstaZero

This figure shows the results of the different perception attenuation in the different rainfalls is a contrast of 14%, 25% and 58% for 20, 60 and 100 mm/h respectively.
This demonstrates that the attenuation is non-linear, having an increase of 33% between the medium and high intensity rain in comparison to light and medium, which is and 11%. **Water film formation** on the lens is likely the dominant factor rather than just rain in the air.

- **Fog**

For fog measurements, the position of the target, contrast target, camera and VUT are the same as the rain.



Figure 2-55: Positioning of the vehicle and vision of contrast target for fog performance. AstaZero

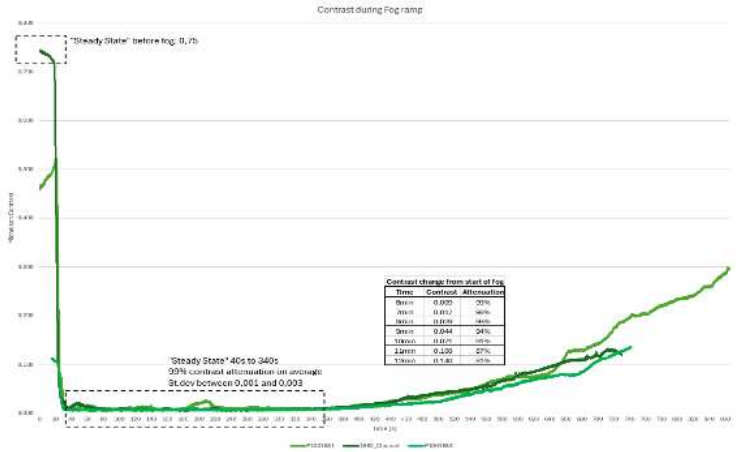


Figure 2-56: Michaelson Contrast attenuation under fog. AstaZero

As seen in the figure above, the contrast attenuation is about the 99% in the first 5 minutes of fog ramp, and still at 81% after 12 minutes. This initial fog onset represents the 25-30 seconds approximately of transition from vision to blindness, and then, a long period of non-vision, and we come to the affirmation that fog blinds the camera system and, if the fog down phase is not done, the vision remains the same.

But during the testing, there was a falling of the dummy, and the contrast increased when falling. This can indicate the camera's sensitivity to foreground occlusions, because of the contrast spike during the interference.

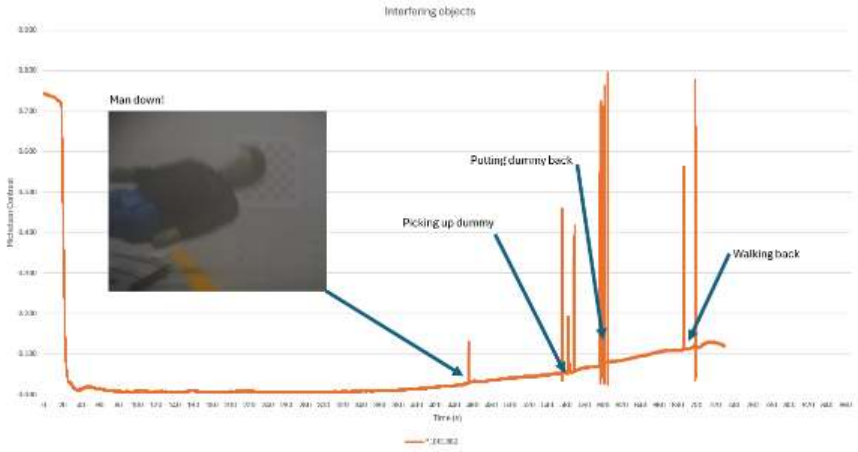


Figure 2-57: Michaelson contrast attenuation under fog with interfering object (target). AstaZerp

Logs couldn't be analysed in poor lighting because of bad exposure settings. AstaZero is working to improve the software for these conditions.

Data collected from outdoor tests proved difficult to analyse due to insufficient contrast attenuation duration. The brief, transient nature of outdoor weather conditions prevented establishment of steady-state measurements comparable to controlled testing.



Figure 2-58: Positioning in outdoor testing in Carissma Workshop. AstaZero

2.6.2.5 Results from Nissan

2.6.2.5.1 Radar Performance

Radar performance testing revealed significant vulnerabilities under rain and fog conditions. Environmental signal noise severely degraded radar accuracy.

All test scenarios exhibited ghost object generation, escalating from minimal levels under dry conditions to operationally unacceptable clutter fields during moderate rainfall, where hundreds of false detections obscured legitimate target tracking.

Lateral object detection proved consistently unreliable in rain conditions likely due to multipath signal reflections from wet surfaces and precipitation, being insufficient accuracy to determine whether objects are within the vehicle's path.

This baseline test demonstrates good radar performance under ideal conditions. Longitudinal tracking shows excellent convergence between radar detections and GPS ground truth.

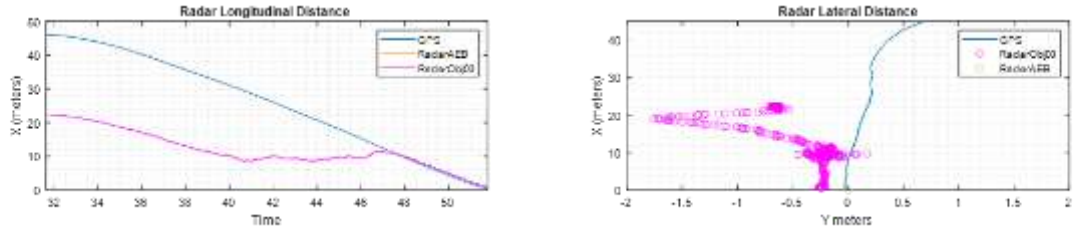


Figure 2-59: Test #6 Day, No rain, GVT, 10km/h. Nissan

The presence of notable scatter in this optimized environment suggests real-world performance will be considerably worse. This highlights CCR-based testing limitations in predicting operational performance with realistic targets under adverse conditions.

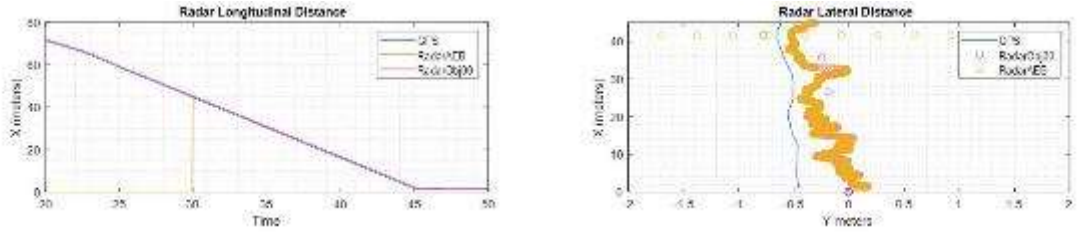


Figure 2-60: Example NCAP Lab Test, CCRs, 10km/h, 25%. Nissan

This test exposes a critical false positive: the glare simulator was erroneously classified as an AEB target. This demonstrates radar vulnerability to metallic infrastructure and reflective objects, particularly problematic in rain where multipath reflections amplify interference effects.

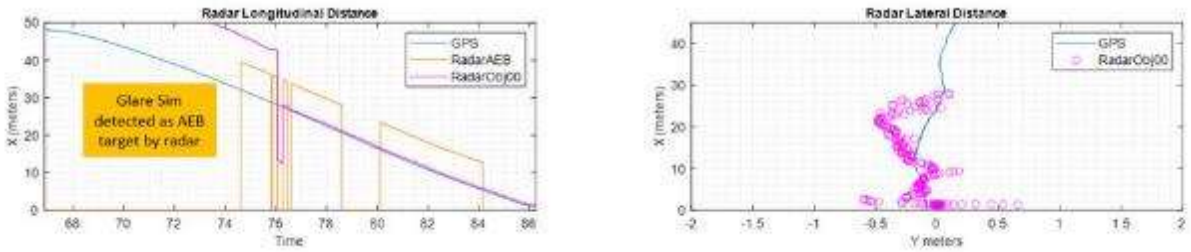


Figure 2-61: Test #46 Day, 20mm/h Rain, Adult Target, with Glare sim. Nissan

Removing the glare simulator improved detection range by 10 meters but revealed lateral positioning failure. The lateral plot shows detections scattered across 6 meters, representing hundreds of ghost objects from rain-induced multipath and droplet backscatter. Moderate rainfall (20mm/h) causes near-complete failure of lateral positioning for small targets like pedestrians.

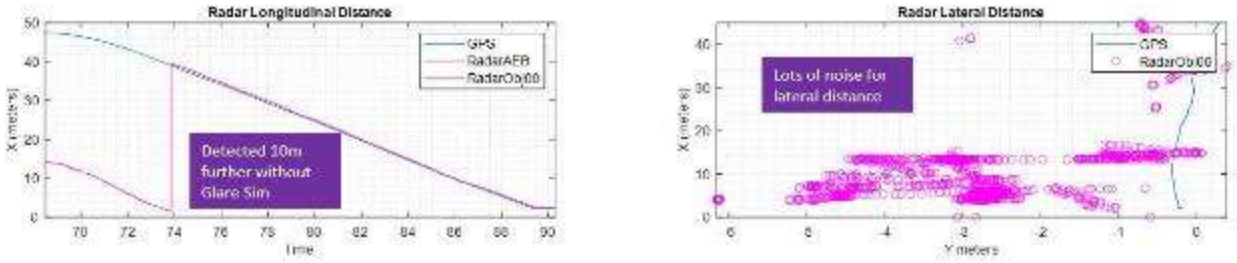


Figure 2-62: Test #73 Day, 20mm/h Rain, Adult Target, Glare sim removed. Nissan

2.6.2.5.2 Camera Performance

Camera-based longitudinal distance detection demonstrated progressive degradation under increasing rainfall conditions.
At 20mm/h rainfall, the camera maintained reliable target tracking with no measurable impact on detection performance.
However, at 60mm/h, a systematic offset of approximately 3 meters emerged in distance measurements until targets reached 20 meters range, indicating initial degradation of optical clarity.
Under rainfall conditions of 100mm/h, camera performance deteriorated critically, with no target detection occurring beyond 30 meters. Detection capability dropped completely due to rain accumulation on the windscreen, creating an optical barrier that fundamentally compromised the camera's ability to perceive the environment. This non-linear degradation pattern reveals that moderate rainfall causes manageable offsets, while heavy rainfall produces detection failure, which is a critical limitation for camera-dependent ADAS functions.

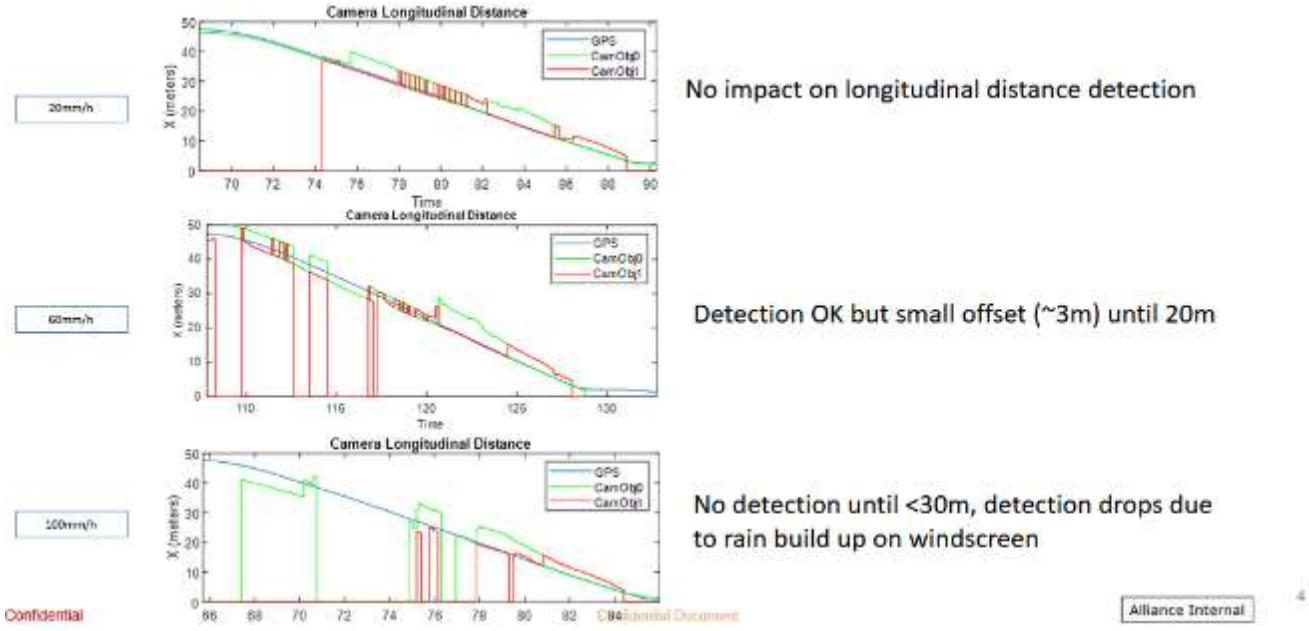


Figure 2-63: Camera performance under rainfall of 20, 60 and 100 mm/h. Nissan

2.6.2.5.3 Glare testing

The positioning and brightness of the glare simulator resulted in complete camera sensor saturation across all test cases, preventing meaningful data collection and analysis.
Due to this fundamental limitation, no figures or quantitative camera performance metrics are available for glare test scenarios.
One recommendation from Nissan's side is that future test protocols should incorporate revised glare simulator positioning that maintains representative glare exposure for driver visibility assessment while enabling camera sensor evaluation.

2.6.2.6 Conclusions

From Aptiv's perspective, the test campaign highlighted several sensor-specific sensitivities and environmental dependencies. In particular, radar performance was influenced by vehicle-induced noise at higher speeds, with roof pipe noise becoming a noticeable factor above approximately 40 km/h. This acoustic and structural interference was observed to affect radar signal quality and stability, potentially introducing noise into the detection and tracking outputs. As a mitigation strategy, Aptiv proposed the integration of radar-absorbent foam insulation on roof-mounted structures and metallic fixtures. Such measures could reduce parasitic reflections and mechanical vibrations, thereby improving radar signal integrity under dynamic driving conditions.
Regarding vision-based systems, Aptiv reported that rain and fog had a comparatively limited impact on overall detection performance. While some degradation in detection range and confidence was noted under reduced visibility, these effects did not fundamentally compromise object detection or tracking continuity. In contrast, glare conditions—particularly those involving strong light sources, reflections, or direct illumination—were identified as the most critical challenge for camera-based perception. Glare-induced artifacts significantly affected image quality and frequently led to misdetections, incorrect object classification, or unstable bounding boxes, underscoring glare as a primary limitation for vision systems in adverse environmental conditions.
In contrast, radar sensors demonstrated strong robustness to variations in illumination and fog density. Changes in ambient lighting conditions, including low-light, glare, and headlight illumination, had minimal impact on radar detection performance. Similarly, fog conditions did not result in measurable degradation of radar tracking capability. Under heavy rain conditions, however, a reduction in Radar Cross Section (RCS) values was observed. This reduction is consistent with signal attenuation and scattering effects caused by precipitation. Nevertheless, the observed RCS decrease was relatively minor and did not reach a threshold that would compromise ADAS–level tracking performance. Targets remained consistently detectable and trackable, indicating that radar systems retained operational reliability even under intense rainfall.
From Nissan's point of view, the outcomes of the test campaign were more constrained by environmental and methodological limitations. While the impact of rain on front camera detection performance could be partially assessed, the results for the front radar were significantly affected by environmental disturbances. These disturbances introduced substantial variability and noise into the radar data, making it difficult to isolate the effects of adverse weather conditions from other confounding factors. As a result, Nissan concluded that the available radar data did not allow for reliable conclusions to be drawn regarding sensor performance under adverse weather scenarios.
Furthermore, Nissan identified shortcomings in the glare test configuration. The glare setup was deemed insufficiently representative of real-world driving conditions, resulting in data that lacked practical relevance. Consequently, the glare test results were considered unsuitable for detailed analysis, and a redesign of the test configuration was recommended to better

reflect realistic illumination geometries and intensities encountered in operational environments.
Fog testing also presented significant challenges. Nissan reported that a detailed performance assessment was not feasible due to the absence of reliable ground truth data for the adult pedestrian target. In addition, the instability of fog density and visibility during the tests introduced inconsistencies that further limited the interpretability of the results. These factors collectively prevented a robust evaluation of sensor behavior in foggy conditions.
Similarly, the Spraymaker testing did not allow for in-depth analysis. The lack of precise ground truth measurements regarding spray characteristics and environmental conditions limited the ability to correlate sensor performance with controlled inputs. Without accurate reference data, it was not possible to quantify detection degradation or validate sensor responses under spray-induced visibility reduction.

Beyond partner-specific observations, complementary research conducted by project partners revealed counterintuitive radar performance characteristics in rain. In particular, radar systems were found to exhibit improved detection performance under heavy rain compared to medium rain conditions. This phenomenon suggests that sensor degradation is not solely dependent on rain intensity expressed in millimeters per hour, but is also strongly influenced by raindrop size distribution (DSD). Experimental evidence indicated that identical rain intensities with different particle size distributions can lead to significantly different levels of sensor degradation, affecting attenuation, clutter, and target scattering behavior in distinct ways.
These findings highlight the necessity of redefining rain characterization for sensor testing. Rather than relying on a single continuous rain intensity metric, it is recommended to define at least three distinct rain intensity ranges, each associated with specific raindrop size distributions. Such an approach would enable more comprehensive sensor performance evaluation and improve the representativeness of proving ground validation activities.
As a basis for defining raindrop size distribution parameters, recommendations could include, as referenced in [16], the specification of scenarios with a maximum concentration of small droplets, as well as conditions characterized by the presence of larger droplets. Incorporating these parameters into test definitions would allow for a more nuanced and physically meaningful assessment of sensor robustness under adverse weather conditions.

2.6.3 WORKSHOP AT CEREMA

2.6.3.1 Test plan

The CEREMA Test Plan was initially conceived based on the principle of achieving comparable results with the CARISSMA testing campaign. Given that both facilities operate in enclosed environments with similar dimensional characteristics, the objective was to reproduce as closely as possible the test scenarios executed at CARISSMA.
This approach would enable comparability of results across facilities when identical tests were repeated, while also allowing systematic analysis of differences arising from variations in rain intensity reproduction and location-specific factors affecting sensor performance. The dual-facility testing strategy provides valuable insights into both facility capability consistency and sensor performance sensitivity to environmental reproduction methods.

Building upon the same baseline test structure as CARISSMA, the CEREMA Workshop incorporates facility-specific enhancements that leverage CEREMA's unique capabilities:

- **Extended Rain Intensity Range**: CEREMA's rain generation system supports more rain intensity.

- **Different way to emulate fog visibility**: CEREMA supports **stabilized fog from 10-80m visibility** for controlled testing, plus **non-stabilized fog up to 1000m visibility** for extended-range sensor evaluation, providing broader fog density coverage.

2.6.3.2 Results from Aptiv

Radar performance in the PAVIN tunnel was influenced by significant environmental noise, primarily caused by signal reflections from a large metal door located at the far end of the tunnel. Despite these local disturbances, radar behaviour remained stable and largely insensitive to lighting variations, consistent with observations made during the CARISSMA tests. Analysis of the Radar Cross Section (RCS) showed a decrease in mean RCS values as rain density increased, confirming trends previously identified at CARISSMA. Owing to the short test distances, this attenuation did not hinder target tracking. However, strong multipath reflections from the garage door introduced localized artifacts, resulting in false detections, frequently observed at approximately twice the actual target distance.

In contrast, the **vision system** demonstrated robust performance under indoor dry and wet conditions, with glare remaining the only significant limiting factor. During outdoor tests involving sunlight and a water-spraying target vehicle, the camera system exhibited stable tracking without confidence flicker.
Compared to CARISSMA, the reduced spray rate and the absence of artificial rainfall likely contributed to the improved robustness of the vision system under these conditions.

2.6.3.3 Results from Denso

2.6.3.3.1 Radar performance

Effect from rain was observed and showed that it can decrease the detection distance. From the radar point of view, the surrounding structures inside the facility (walls, lights, ceiling) create disturbance with the target signals. It is not representative of the real-world, therefore some improvements such as installing radio-wave absorbers would be necessary to correctly evaluate application functions such as AEB.

2.6.3.3.2 Camera performance

The effects of rain and fog were observed to reduce object detection distance. From a camera system perspective, certain test scenarios did not fully reflect real-world operating environments. To ensure reproducible and comparable evaluations, it is therefore essential to tightly control operational parameters and to define acceptable tolerances when assessing camera performance.
Illumination conditions must be both realistic and controlled, for example by specifying daytime lighting with a defined lux range. During spray tests, the quantity and distribution of water splash should be regulated to ensure consistency across runs. More generally, test conditions must be carefully managed to avoid cross-contamination between environmental effects; for instance, rain tests should be conducted in a manner that prevents unintended fog formation. This is particularly important given that fog-like effects can occur at specific rain intensities due to droplet size distributions, as described by CEREMA.
For fog testing, visibility levels must be explicitly controlled and maintained in accordance with the defined test condition to ensure valid and repeatable performance assessments.

2.7 WORKSHOP IN ASTAZERO

The AstaZero workshop aimed to achieve more precise spray testing results. Earlier tests at Carissma and Cerema faced issues with wind on open tracks, which caused water spray to miss sensors and produced unreliable data.
By using AstaZero's Dryzone proving ground—an enclosed indoor facility—wind interference is eliminated. This allows for controlled, high-speed tests that mirror highway conditions and enables daytime testing in artificially dark environments, ensuring repeatable and accurate sensor degradation assessment.

2.7.1 RESULTS FROM APTIV ANALYSIS

Indoor testing was carried out in the AstaZero DryZone with the specific objective of isolating and evaluating the effects of artificial spray generated by two distinct systems: a vehicle-mounted spray rig supplied by MESSRING and a trailer-mounted spray system operated by AstaZero. This controlled setup enabled a focused assessment of spray-induced disturbances without the confounding influence of natural rain or fog.
Across both configurations, radar and vision sensors demonstrated a high level of robustness to spray, maintaining stable detection and tracking of the target vehicle under moderate and sustained spray conditions. This indicates that, in general, artificial spray alone does not significantly degrade sensor perception performance. However, under extremely dense spray conditions, limitations were observed in distance estimation accuracy, particularly for the target vehicle. The high concentration of water droplets increased signal scattering and visual occlusion, leading to unstable range measurements even though object detection itself was often preserved.
In addition, ADAS systems did not classify the artificial spray as rain or fog, highlighting a limitation in current weather classification algorithms when exposed to synthetic or non-natural precipitation patterns. While this behaviour avoids false weather state detection, it also suggests that artificial spray does not fully replicate the physical and optical characteristics of real adverse weather. Consequently, while indoor spray testing is valuable for stressing sensor robustness and isolating specific failure modes, it should be complemented by natural or physically representative weather conditions to fully assess perception and weather classification performance.

2.8 CONCLUSIONS ON PERCEPTION ORIENTED WORKSHOPS

In conclusion, the CEREMA Test Plan effectively fulfilled its original objective of enabling meaningful comparability with the CARISSMA testing campaign while simultaneously extending the scope of adverse weather evaluation through facility-specific enhancements. By reproducing equivalent scenarios in enclosed environments with similar geometrical characteristics, the dual-facility approach provided a robust framework for assessing both sensor performance and the influence of environmental reproduction methods. The extended rain intensity range and the broader fog visibility control available at CEREMA significantly increased the representativeness of the test matrix and enabled more granular analysis of sensor behaviour under adverse conditions.

Across partner analyses, radar systems generally demonstrated strong resilience to changes in illumination and moderate precipitation; however, their performance was shown to be highly sensitive to the test environment itself. Structural elements within the facilities, such as

walls, ceilings, lighting fixtures, and large metallic surfaces, introduced multipath reflections and electromagnetic disturbances that generated false detections or affected signal stability. While short test distances limited the operational impact on target tracking, these artifacts reduce the representativeness of the results for real-world applications such as Automatic Emergency Braking (AEB). Consequently, improvements to the test infrastructure, including the integration of radio-frequency absorbing materials, are necessary to better isolate sensor behaviour from facility-induced effects.

Vision-based systems exhibited complementary strengths and limitations. Under controlled dry and wet conditions, camera performance was generally stable, particularly when spray intensity and environmental parameters were well regulated. However, glare remained a dominant challenge, and both rain and fog consistently reduced detection range. The analyses highlighted that insufficient control of illumination, spray distribution, and visibility leads to variability that limits result reproducibility and cross-test comparability. Moreover, unintended interactions between environmental effects—such as fog-like phenomena arising from specific rain droplet size distributions—further complicate interpretation when test conditions are not strictly separated and stabilized.

Overall, the findings demonstrate that the validity of enclosed-facility testing for ADAS sensor evaluation is strongly dependent on the precision with which environmental conditions are generated, controlled, and monitored. While CEREMA and CARISSMA provide complementary and largely consistent platforms, achieving reliable cross-facility comparisons requires tighter definition of test parameters, acceptable tolerances, and ground truth references. Implementing these improvements will be essential to ensure that adverse weather testing yields robust, repeatable, and operationally relevant conclusions for both radar and vision-based perception systems.

2.9 ADDITIONAL IMPACTS OF ADVERSE WEATHER ON SENSOR PERFORMANCE

This section summarizes key testing features for adverse weather conditions by taking into account the experiences of the four workshops, each conducting tests based on partner capabilities. The outlined features are recommended for reproducing tests in such conditions.

2.9.1 INTRAVEHICULAR WEATHER IMPACT

According to the analysis from Deliverable 2.2 "Sensors vs Weather," various weather conditions have been found to affect the performance of radar, lidar, and cameras to different degrees.
The workshop findings highlight how adverse weather conditions impact vehicle sensors by causing light scattering, sensor surface contamination, and reflections, among other effects. These impacts are unique to each type of sensor and are non-linear, varying with factors such as rain intensity, droplet size distribution, fog density, glare, and spray.
However, it is important to note that, according to the benchmarking of testing facilities by different partners, limitations in methodology, measurements, and time meant not all aspects discussed here were addressed during the workshops.

2.9.1.1 Rain

The testing campaigns were defined since the perception systems have different degradation performance depending on the weather condition that is exposed to.

- **Camera systems:** experimental evidence shows that camera degradation under rain is strongly dependent on rainfall intensity and water accumulation on the lens or windshield. Nissan testing at Carissma demonstrates a non-linear target detection degradation, and a collapse in high intensities.
  UNIV-EIFFEL at Carissma have seen wet ground reflections (false detections) during this type of scenarios.

- **Radar systems:** although radar is traditionally described as the most rain-resilient sensor, workshop evidence contradicts this under certain conditions: Aptiv observed ghost detections at only 20 mm/h in outdoor testing, while Nissan recorded false detections due to multipath reflections from wet surfaces.

- **LiDAR systems:** at UNIV-EIFFEL, rain produced echo points directly in front of the LiDAR, not present in dry conditions, due to falling droplets intersecting the laser beam path.

2.9.1.2 Fog

Fog caused significant performance issues, particularly affecting camera and LiDAR systems.

- **Camera systems:** AstaZero results showed 99% contrast loss within 5 minutes after fog onset, with visibility remaining extremely low for extended durations. YOLO detection rates dropped to 0.796% of frames, indicating almost total failure under dense fog, during the workshop in CARISSMA.

- **Radar systems:** Denso in CEREMA workshop reported reduced radar detection distance under fog, contrary to the assumption that fog is transparent at radar wavelengths.

- **LiDAR systems:** at UNIV-EIFFEL, even light fog created a reflection ring around the sensor, reducing available points at longer ranges and distorting spatial distributions.

2.9.1.3 Glare

- **Camera systems:** Nissan's tests at CARISSMA showed that the camera was completely saturated by glare, producing no usable data in any scenario. YOLO/RT-DETR misinterpreted glare-induced reflections as parts of objects, frequently generating oversized bounding boxes extending onto reflective ground patches.

- **Radar systems:** Nissan found that the glare simulator was falsely detected as an AEB target, due to reflections on metallic infrastructure.

- **LiDAR systems:** LiDAR was moderately affected by receiving parasitic noise points at glare angles.

2.9.1.4 Spray and Splash Effects

Spray is different from rainfall, and studies show that droplet size, direction, and speed play crucial roles. Heavy spray made it difficult for radar and vision systems to estimate distances accurately. ADAS systems did not identify spray as either rain or fog, highlighting weaknesses in current weather classification algorithms.

When examining spray effects using the Messring and AstaZero spray generators:

- Messring: produces larger droplets, which are more effective at high speeds.
- AstaZero: generates smaller droplets, reducing sensor performance at lower speeds.

These findings also underscore the importance of standardizing DSD for consistent results.

2.9.1.5 Critical Testing Requirements Derived from Findings

Ddata on performance degradation define clear requirements for testing facilities:

- **Rain Testing**: facilities shall recreate both intensity ranges and realistic particle sizes and velocities, as sensor responses vary with these factors.
- **Fog Testing**: facilities shall generate controlled visibility conditions.
- **Combined Phenomena Testing**: facilities shall simulate rain with spray, fog with changing light, and variations in surface friction at once.
- **Measurement Standardization**: use quantitative tools to ensure consistent results across facilities.

These requirements address sensor-specific vulnerabilities and complex weather effects, ensuring controlled, reproducible conditions and precise measurements.

2.9.2 EXTRAVEHICULAR WEATHER IMPACT

Weather phenomena not only directly affect sensor performance but also create significant environmental side effects that further impact ADAS system operation. These environmental changes alter the physical testing context and create additional challenges that must be reproduced in testing facilities.

2.9.2.1 Environmental Testing Challenges

Workshop results reveal that while radar are generally more resilient than cameras, they still experience environmental interference including:

- signal reflections causing unreliable lateral object detection;
- noise effects;
- disturbance in the target signal.

These side effect like are partially linked to the closed environment and metallic beams or tunnels, that may contain. Installation of radio-wave absorbers could be necessary to limit this kind of phenomena.

2.9.2.2 Reproducibility and repeatability challenges

Testing under adverse weather conditions shall consider distinct aspects of measurement quality: repeatability and reproducibility representations of the phenomenon.

- **Reproducibility** concerns the ability to obtain comparable results across different testing environments. The workshop concluded that reproducibility can be ensured by:
  - rain systems maintaining consistent drop size distributions (DSD),
  - spray rigs producing uniform droplet dynamics,
  - and facility structural homogeneity to safeguard radar functionality against erroneous detections.

- **Repeatability** refers to achieving consistent results when all testing parameters are comparable.
  - Across the workshops, repeatability was generally good for rain and fog generation within a single facility, particularly at CARISSMA and CEREMA, where controlled indoor equipment ensured stable rain rates and fog visibility values during static and low-speed tests.
  - However, repeatability became more challenging when weather phenomena were highly sensitive to facility airflow or space constraints, particularly for spray tests. At AstaZero and in outdoor sessions, even small changes in vehicle speed or droplet trajectories produced observable variability in sensor degradation.

2.9.2.3 Space Limitations

Another topic to mention is the limitations of space in adverse weather conditions, due to the dimensions of the facilities are reduced to make dynamic tests, only possible at low city speeds.

The workshops highlighted that physical space constraints in adverse weather testing facilities influence not only the dynamic range of possible tests. Across workshop's facilities dynamic tests, there were frequently restricted to low-speed operation, most of them below 30 km/h (UNIV-EIFFEL, CARISSMA and CEREMA), due to the limited length or layout of indoor rain and fog facilities benches and safety margins required for stopping distances. This has direct consequences on the testing activities, because many real-world adverse weather scenarios (e.g., highway rain spray, glare-induced misperception at speed, radar multipath under wet pavement conditions) occur at significantly higher speeds than those achievable indoors.

Space constraints also influenced spray representativeness. Outdoor spray tests at CEREMA demonstrated that wind exposure caused spray plumes to drift outside the intended sensor field, making them unrepresentative of real-vehicle spray dynamics. By contrast, AstaZero's Dry Zone, with its fully enclosed layout and high-speed capability, provided a more representative environment for realistic spray formation and sensor degradation, but with no other than spray effect.

In summary, space limitations reduce the representativeness of adverse-weather testing, particularly for high-speed or large-scale phenomena such as spray aerodynamics and fog dispersion, but they remain essential for repeatable and reproducible testing.

3. Friction oriented testing facilities

The use of dedicated low-friction, wet grip, and ice/snow test tracks provides a structured and complementary basis for reproducing adverse traction conditions in a controlled and repeatable manner. While dedicated low-friction, wet grip, and ice/snow tracks provide essential infrastructures to reproduce degraded adhesion conditions, each of these facilities exhibits intrinsic limitations that constrain their applicability for comprehensive ADAS/AD testing under adverse weather conditions.

3.1 LOW-FRICTION TRACKS

Low-friction tracks typically used for braking and vehicle dynamics assessments (e.g., ABS or ESC validation), enable reproducible and well-controlled degradation of tyre–road adhesion. However, their limited surface dimensions restrict the execution of complex or multi-phase scenarios (e.g., long approach phases, interaction with multiple targets, or combined longitudinal and lateral manoeuvres). In addition, such tracks generally rely on uniform artificial surfaces (resin, basalt, polished concrete), which do not fully capture the variability of real-world wet road conditions, such as heterogeneous friction patches, water accumulation zones, or surface ageing effects. As a result, they are well-suited for system characterization but less relevant for full-system validation in realistic environments.



Figure 3-1 Exemple of low-friction tracks from TOYOTA

3.2 WET GRIP TRACKS

Wet grip tracks, widely used for tyre labelling and regulatory assessments, provide a controlled and repeatable environment through the application of a constant and homogeneous water film. This ensures high reproducibility and comparability across test campaigns, which is essential for certification purposes. However, this controlled water distribution does not reflect real-world rainfall conditions, where water depth can vary spatially and temporally (e.g., puddles, spray, drainage effects). Furthermore, like low-friction tracks, geometric constraints (length, width) may limit the deployment of advanced ADAS scenarios involving higher speeds, longer trajectories, or interactions with moving targets such as dummies on propulsion platforms. As example, we have 200 m of length for 6 m width for the UTAC wet grip. The absence of dynamic water disturbances (e.g., spray generated by other vehicles) also reduces the representativeness for perception system testing.



Figure 3-2 Example of UTAC wet grip track

3.3 ICE AND SNOW TRACKS

Ice and snow tracks, used for tyre certification and winter performance evaluation, allow the reproduction of extreme low-friction conditions and can be operated in both indoor (controlled) and outdoor (natural) environments. Despite their high relevance for winter scenarios, they present significant accessibility and scalability limitations, as such facilities are predominantly located in Northern regions. This introduces logistical constraints for testing campaigns (transport, scheduling, weather dependency for outdoor tracks). Additionally, natural snow and ice conditions may exhibit significant variability (temperature gradients, compaction, surface roughness), impacting repeatability unless indoor facilities are used. Finally, these tracks are primarily designed for vehicle–road interaction studies and may not be fully adapted to the integration of complex ADAS test setups (e.g., moving targets, sensor validation instrumentation).



Figure 3-3 UTAC ice/snow track in Finland

3.4 CONCLUSIONS

Overall, the combination of these infrastructures provides a strong basis for friction-related testing but reveals a common limitation: a trade-off between controllability, representativeness, and scalability. This highlights the need for complementary approaches

(e.g., hybrid proving grounds, controlled adverse weather installations, or virtual simulation) to achieve comprehensive and realistic validation of ADAS/ADS performance under adverse conditions.

4. Target degradation under adverse weather conditions

The consortium consolidated open technical questions regarding:

- the stability of dummy radar reflectivity when targets are wet
- and (ii) the ability of propulsion platforms to remain operational on wet or flooded surfaces.

The underlying need is to ensure that adverse-weather testing remains both *representative* (i.e., capturing genuine perception degradations) and *repeatable* (i.e., not dominated by artefacts from the test equipment itself)

- **Radar signature: what is known (and what is not)**

Available measurements collected by AbDynamics were performed in dry conditions, consistent with Euro NCAP practices, using a motorized rig integrating a radar sensor and GPS navigation to map radar reflectivity. These plots indicate that the dominant reflection originates from the dummy, while the platform beneath has a *very small* impact on the overall radar signature. For wet conditions, no dedicated scientific study was identified in the notes; instead, the current evidence base is mainly customer feedback reporting that dummy reflectivity can change when wet and that surface water droplets may affect radar-based detection performance. This gap justifies treating wet-reflectivity as a *known risk* requiring targeted characterization rather than an already-quantified effect.

- **Dummy construction and cover behavior in rain**

The dummies are described as being built according to established ISO-derived specifications, originally developed in previous SER-related activities, covering parameters such as weight, water resistance, strength and wear resistance. Importantly, the notes highlight that radar reflectivity is more influenced by internal materials than by the fabric cover, although the cover is not fully impervious and droplets on the surface may still perturb radar performance. As an illustration of robustness targets, the consolidated notes capture cover requirements including area weight < 300 g/m², water resistance > 600 mm, strength > 350 lbs, light fastness > 6000 h, and wear resistance > 500 cycles.

- **Platform operability: primary limitation in wet testing.**

The main concern in rainy conditions is the platform (launchpad) rather than the dummy, as dummy materials are described as relatively water resistant. Low-profile platforms running on rubber tyres without tread may aquaplane when standing water is present, especially given limited ground clearance. This is critical because current Euro NCAP scenarios require dummies/platforms to achieve 2.5 m/s² acceleration, which may become challenging if the surface is fully covered with water deeper than the ground clearance, creating a hydroplaning risk. In contrast 4A platforms are IP65 certified and have shown reliable operation in heavy rain and standing water, whereas non-IP65 competitor systems experienced water infiltration issues in tests at CARISSMA Technical Center. The same notes indicate a representative mass level of ~120 kg for these fully waterproof platforms, mitigating buoyancy/damage concerns in flooded conditions

- **Implications for WP-level guidance (quantified checkpoints)**

Based on these elements, adverse-weather test protocols should explicitly separate (a) *perception effects* (e.g., droplet-induced changes in radar scattering) from (b) *test-tool operability effects* (e.g., aquaplaning preventing the 2.5 m/s² dynamic requirement). As a minimum, the equipment specification baseline can include: IP rating targets (e.g., IP65 for platforms), dynamic performance retention against the 2.5 m/s² requirement on wet surfaces, and textile durability thresholds (e.g., <300 g/m², >600 mm, >350 lbs, >6000 h, >500 cycles) to support repeatability over repeated wet exposures.

As a conclusion, the overall material robustness of the dummies can be considered sufficient for operation under rainy conditions, as their design—based on ISO-derived specifications—ensures adequate resistance to water exposure. However, the primary limitation identified lies in the traction and operability of the propulsion platforms, particularly in the presence of standing water where low-clearance systems are prone to aquaplaning and reduced dynamic performance.
In this context, residual validation activities remain necessary to confirm the reliable use of both targets and propulsion systems under adverse weather conditions, ensuring that test results are not biased by equipment limitations. The key technical challenges to be addressed therefore include the characterization of radar reflectivity variations of test dummies in wet conditions, the impact of standing water on the ability of platforms to meet required acceleration levels, and the assessment of waterproof performance and long-term durability of testing platforms.

5. Testing Requirements Implications

The identified environmental side effects establish requirements for testing facilities:

1. **Friction Testing Capability**: facilities should incorporate low-friction surface testing with quantifiable friction coefficient measurement across various surface conditions and water film thicknesses.
2. **Environmental Reproducibility**: testing protocols shall address the challenge of creating consistent, repeatable environmental conditions while maintaining realistic physical phenomena.
3. **Multi-Sensor Validation**: testing under adverse weather conditions affects each sensor type (camera, radar, LiDAR) differently. Therefore, testing facilities shall be able to evaluate all sensors at the same time under the same controlled weather conditions to capture these differences accurately, to ensure that the environment is suitable for all of them.

These environmental side effects demonstrate that comprehensive ADAS testing requires facilities capable of reproducing not only direct weather phenomena but also their complex interactions with road infrastructure and vehicle systems.

5.1 RECOMMENDED TEST TYPES FOR EACH PHENOMENA

Based on the comprehensive analysis from project deliverables and the detailed test plans from CEREMA and CARISSMA facilities, specific test methodologies have been proposed for each weather phenomenon. These test types are designed to systematically evaluate ADAS sensor performance under controlled adverse weather conditions.
These test have been done in the workshops

- **Rain Testing Recommendations**
  - **Static Perception Tests**
    - **Configuration**: Static targets with moving ego vehicle at controlled speeds (10-30 km/h) as specified in both CEREMA and CARISSMA test plans.
    - **Rain Intensity Levels**: Testing should cover graduated intensities.
    - **Test Objectives**: Measurement of detection range degradation, classification accuracy, and sensor signal attenuation across camera, LiDAR, and radar systems.
  - **Active Safety Tests**
    - **Configuration**: Vehicle approach scenarios with static and dynamic targets, evaluating system intervention timing and effectiveness.
    - **Speed Ranges**: Testing at 10 km/h, 30 km/h, and 50 km/h with various lighting conditions (daylight, dawn, complete night)
  - **Dynamic Driving Tests**
    - **Configuration**: Vehicle following scenarios with Adaptive Cruise Control (ACC) active, maintaining approximately 2-second time gaps at speeds of 10, 30, and 50 km/h in heavy rain conditions (>65 mm/h)

- **Fog Testing Recommendations**
  - **Static Perception Tests**
    - **Configuration**: Stationary vehicle with active sensors evaluating detection capabilities at graduated fog densities
    - **Visibility Levels**: Testing should cover very dense fog (15m visibility), dense fog (30m visibility), and medium fog (60m visibility).
  - **Dynamic Fog Tests**
    - **Configuration**: Progressive fog ramp testing using UFO (mobile target) system with visibility ranging from 10m to 400m over 30-minute test periods.
    - **Test Conditions**: Both day and night conditions with low beam headlights, measuring distance detection correlation with visibility degradation.

- **Glare Testing Recommendations**
  - **Static Perception Tests**
    - **Configuration**: Static targets with controlled glare sources positioned at various angles to simulate real-world sun positions (CEREMA).
    - **Glare Types**: Three standardized glare conditions - sunset glare (red), daytime glare (white), and high-power mode for extreme conditions (CARISSMA).
    - **Combined Testing**: Glare effects tested in combination with fog and rain conditions to evaluate compound environmental impacts. (Aptiv results?).
  - **Active Safety Tests**

- **Configuration**: Vehicle movement at 10 km/h toward targets with various glare intensities and positions, measuring detection failure rates and intervention capability.

5.2 CROSS-CORRELATION MATRIX

Based on the existing capabilities section, a cross-correlation matrix has been developed to have a vision on the ability to reproduce weather phenomena in the different facilities of the consortium (which information has been given in detail) and conclude with how the facilities can help us reproduce these adverse weather events.
The assessment has been done based on a Likert scale structure with a colour guide, employing each facility capability of reproducing phenomena in the colour-scale, where **greener** colours are more adapted to reproduce **realistic weather phenomena** than the ones that are more red.



Ad hoc reproduction (uncontrolled)
Basic simulation (some control, limited reproducibility)
Defined testing (standard protocols, consistent results)
Quantified testing (measured, controlled parameters)
Optimized testing (continuous improvement, multiple phenomena)

This approach is consistent with established practices in capability assessment.
The patterns and categories chosen for performance topics are:

- **Rain testing capability**, being the topics related to raining performance reproduction in a facility (spray not contemplated) which are:
  - Bench area for rain
  - Rain intensity
  - Droplet size distribution (DSD) reproducibility
- **Fog testing capability**
  - Bench area for fog
  - Fog visibility minimum
  - Fog droplet size
  - Fog stability
- **Glare conditions**
  - Glare types supported
  - Glare simulation specifications
- **Operational characteristics**
  - Spray capability
  - Low friction surface (and measurable) availability

On other hand, the raw data matrix contains heterogeneous information because of the nature of the facilities (which are not homogeneous in terms of design and definition), so the scale definitions are evaluated per topic.

Evaluation criteria	Measured parameter	Scoring rationale
Bench Area for Rain and Fog Testing	Physical testing space available for controlled rain simulation	▪ Larger testing areas enable longer exposure times, higher test velocities, and more realistic scenario reproduction. ▪ Fog dissipation characteristics require adequate spatial volume for stable, uniform conditions. Larger areas reduce edge effects and enable more realistic sensor exposure scenarios.
Rain Intensity Range	Range and precision of controllable rainfall intensity	▪ Extreme precipitation events are critical for validating sensor performance under challenging conditions. ▪ High precision control enables systematic sensitivity analysis and is weighted equally to extreme intensity capability.
Fog Visibility and Stability	Minimum achievable visibility distance (lower values indicate denser fog and superior capability), combined with the ability to maintain this condition stable.	▪ Dense fog represents critical test conditions where camera and LiDAR performance degrades substantially. This capability is essential for validating sensor robustness under adverse conditions as specified in automotive safety standards. A good maintenance of this fog density is key to gather good quality data.
Glare Types Supported	Variety and controllability of lighting/glare conditions within the facility	▪ Camera-based ADAS systems are particularly vulnerable to direct and reflected glare. ▪ Facilities offering multiple, controllable glare scenarios enable comprehensive validation across diverse environmental conditions.
Glare Simulation Technical Capability	Technical sophistication and reproducibility of glare simulation infrastructure	▪ Spectral control is critical for evaluating camera sensor performance across different lighting conditions, as spectral response varies significantly by sensor technology.
Reproducible Rain Droplet Size	Control precision over rain droplet size distribution (DSD)	▪ Droplet size distribution significantly affects sensor performance, particularly for LiDAR (backscatter characteristics) and cameras (light diffusion). ▪ Customizable DSD enables investigation of sensor-specific vulnerabilities and supports development of rain-intensity-independent detection algorithms.
Fog Droplet Size	Control precision over fog droplet size characteristics	▪ Fog droplet size affects light scattering properties and thus sensor visibility. ▪ Advective fog (mechanically generated) and radiative fog (naturally formed) exhibit different droplet size distributions; facilities capable of reproducing both types enable more comprehensive sensor validation.
Spray Capability	Ability to generate realistic water spray from vehicle wheels or dedicated spray systems	▪ This criterion was scored as binary based on available data. Spray significantly degrades camera and LiDAR performance through dynamic occlusion and light scattering. ▪ Future refinement could differentiate between natural spray (from vehicle motion) and controlled spray systems with reproducible characteristics.
Low Friction Surface	Low-friction surfaces enable evaluation of safety systems under challenging vehicle dynamics conditions (ESC, ABS, traction control) concurrent with adverse weather sensor testing.	▪ Future scoring refinement could incorporate friction coefficient measurement capability and variable friction control

Based on this rationale, a general overview of the facilities that precisely characterize and measure their performance in rain, fog, glare, the capability to use spray tools and test under low friction surfaces is shown on the table 5.

Facility	Rain	Fog	Glare	Spray	Friction
CARISSMA					
CEREMA					
AstaZero Wet Zone					
AstaZero Dry Zone					
MHI					
Université Gustav Eiff					
IDIADA / UTAC					

Table 5 Cross-correlated overview of facilities versus adverse weather, spray usage and friction testing.

The cross-correlation matrix methodology provides valuable insights into the current landscape of facility capabilities for adverse weather ADAS testing, while highlighting key opportunities for further alignment and enhancement across the consortium.

From a reproducibility perspective, the analysis shows that facilities benefit from diverse and complementary infrastructures, each offering unique strengths. Although this diversity currently limits fully standardized cross-validation of test results, it also reflects a rich foundation of expertise. The presence of shared parameters across facilities represents a strong starting point for future harmonization and convergence toward best-in-class specifications.

In terms of measurement accuracy, several core environmental parameters—such as bench area, rain intensity ranges, and fog visibility thresholds—already demonstrate solid performance levels. At the same time, emerging capabilities, particularly friction coefficient characterization in indoor environments, offer clear potential for development. Strengthening these areas will further support advanced vehicle dynamics validation and enhance overall testing robustness.

The observed heterogeneity between facilities, while currently limiting direct comparability, can be seen as an opportunity to define common benchmarking frameworks and establish equivalency criteria. This evolution would significantly reinforce the consortium's ability to objectively assess and compare capabilities across sites.

Importantly, the framework itself demonstrates strong strategic value through its structured and systematic approach. It effectively identifies priority areas for improvement—such as spray characterization, friction measurement, and spectral control—while providing a clear roadmap for capability enhancement. As the framework evolves, the progressive integration of detailed measurement protocols, uncertainty quantification, and formal validation procedures will enable alignment with regulatory expectations and future ADAS certification requirements.

In summary, the methodology already serves as a robust coordination and capability mapping tool for the consortium. With targeted developments in standardization, measurement precision, and validation processes, it is well positioned to achieve the levels of reproducibility and accuracy required for advanced benchmarking and future certification frameworks.

5.3 COMPLEMENTARY TESTING MEANS

5.3.1 OPPORTUNISTIC TEST

Opportunistic use of existing test tracks under natural adverse weather conditions represents a highly valuable and complementary approach for capturing critical and safety-relevant driving situations in real-world environments. By leveraging naturally occurring adverse weather conditions (AWC) during testing campaigns, and combining these with dedicated weather stations—either static or embedded systems—this methodology enables the acquisition of reliable ground truth data for perception systems. It allows for the observation of authentic environmental phenomena, including rain, fog, and low visibility, and their direct, often nonlinear impact on sensor behaviour (camera, lidar, radar), which remains difficult to fully replicate in controlled facilities.

One of the key strengths of this approach lies in its ability to expose ADAS and ADS functions to genuine, unaltered weather dynamics, thereby providing highly realistic sensor responses and system-level interactions. Furthermore, the availability of large and flexible test areas—significantly greater than those typically offered by indoor facilities such as climatic tunnels—enables the execution of complex scenarios, including high-speed manoeuvres, long-distance perception tasks, and multi-actor interactions. This is particularly relevant for the evaluation of rare or critical scenarios, such as sudden loss of grip, visibility drops, or mixed weather conditions, which are essential for safety validation but difficult to artificially reproduce.

In addition, the integration of ground truth measurement systems and synchronized data acquisition frameworks enhances the overall quality and usability of the collected data, supporting advanced analysis, model validation, and AI training processes. This makes opportunistic testing a powerful tool not only for validation but also for enriching datasets used in perception and decision-making algorithms.

However, despite these advantages, this approach also presents inherent limitations that must be carefully managed. The unpredictability of weather conditions introduces significant uncertainty in test planning and execution, often leading to extended test durations and reduced efficiency. Moreover, the lack of repeatability remains a major challenge, as identical environmental conditions cannot be reliably reproduced, limiting the ability to perform controlled comparative assessments or regression testing. Finally, the difficulty in isolating and controlling specific parameters—such as precise rainfall intensity, droplet size distribution, or road surface friction—restricts the level of experimental control required for rigorous system validation and benchmarking.

Overall, while opportunistic test track usage under natural adverse weather conditions provides unmatched realism and access to critical scenarios, it should be considered as a complementary approach within a broader testing strategy. Its full value is realized when combined with controlled and reproducible testing environments, enabling a balanced trade-off between realism, repeatability, and parameter control in ADAS and ADS validation frameworks.

5.3.2 EXAMPLE OF WEATHER STATION FROM PERSIVAL

Consortium partner Persival has developed a specialized testing infrastructure that implements localized meteorological measurement stations integrated with vehicle-mounted sensor systems to enable real-time correlation of environmental parameters with ADAS sensor outputs. This approach includes synchronized data acquisition through integrated

timestamping, mobile testing capability for deployment across various geographic locations, and systematic documentation of naturally occurring weather phenomena characteristics.
This opportunistic testing approach provides critical validation data that complements controlled facility testing, tot test that ADAS systems have robust performance not only under reproducible facility conditions but also under the full spectrum of naturally occurring adverse weather scenarios encountered in real-world operation.
The measurement setup consists of a stationary unit and two protected target housings positioned at defined distances on a roof in Darmstadt, Germany. The station includes a waterproof enclosure for the power supply and the measurement PC, as well as modularly mounted perception sensors and reference weather sensors. The targets are placed at 21.5 m and 78.5 m from the station inside weather-protected housings. The front housing contains four 0.5 × 0.5 m diffuse reflecting targets with reflectance levels of 5%, 50%, 80%, and 95%, while the rear housing holds a single 1 × 1 m target with 10% reflectance.
Measurements are triggered automatically when defined thresholds of weather parameters are reached, as reported by the reference sensors. These parameters include precipitation rate, ambient temperature, relative humidity, air pressure, wind velocity and direction, brightness, and SYNOP present weather codes, as well as fog-related quantities such as meteorological optical range and extinction coefficient. This automated approach ensures that data is collected under representative environmental conditions without manual intervention.



Figure 5-1: Persival Weather Test Bench setup on a roof top

5.3.2.1 Sensors

The measurement station consists of a waterproof housing that contains the power supply and an OnLogic Karbon 800 industrial PC running Ubuntu and ROS 2 for data acquisition and synchronization. The perception sensors under test are positioned at the front of the station at a height of 0.4–0.6 m above ground level, and their exact mounting positions are recorded in the /tf_static topic within the measurement data for precise spatial referencing.



Figure 5-2: Weather station with lidars and a camera in the front and weather reference sensors on top

To capture the present weather conditions, the station is equipped with multiple reference sensors. The general weather sensor (Thies Clima 4.9200.00.000) operates at a measurement interval of 0.5 s and provides:

- precipitation rate (mm/h)
- ambient temperature (°C)
- relative humidity (%)
- air pressure (hPa)
- wind velocity and direction (m/s)
- brightness (lx) with light source direction
- SYNOP present weather code for classification

A disdrometer (Thies Laser Precipitation Monitor) with a 60 s interval measures the number of drops per drop size and velocity bin. Additionally, a fog sensor (Biral SWS-050) with a 10 s interval provides meteorological optical range (m) and extinction coefficient (1/m).

5.3.2.2 Targets

The measurement setup in winter season 2025/2026 included two target housings that protected the targets from environmental influences. One housing was positioned at a distance of 78.5 m from the station and contains a single target with dimensions of 1 × 1 m:

- Sphere Optics Zenith Lite Diffuse Reflecting Target, 10% reflectance (PTFE foil) mounted on a honeycomb structure board

The second housing was located at 21.5 m and contained four targets provided by the customer, each measuring 0.5 × 0.5 m, with different reflectance levels:

- Target 2: Sphere Optics Zenith Lite Diffuse Reflecting Target, 95%
- Target 3: Sphere Optics Zenith Lite Diffuse Reflecting Target, 5%
- Target 4: Sphere Optics Zenith Lite Diffuse Reflecting Target, 50%
- Target 5: Sphere Optics Zenith Lite Diffuse Reflecting Target, 80%



Figure 5-3: Target housing with 4 different Lambertian targets

These targets provided controlled and reproducible reflection characteristics for evaluating the perception sensor performance under varying environmental conditions.

5.3.2.3 Measure automation

The station records data of the reference sensors as well as the perception sensors listed below in ROS2 MCAP files. Recordings are started automatically depending on the following thresholds of the different weather sensors. The thresholds are derived from commonly used classifications of weather conditions.

- Meteorological Optical Range in m: 2000, 1000, 500, 220

- Precipitation intensity in mm/h: 1.9, 8.1, 34, 50
- SYNOP: 65, 69, 70, 71, 72, 73, 74, 87, 88, 89, 90

Recordings are stopped after a duration of 2 min.

Additionally, daily verification measurements are taken automatically at 04:00 and 13:00. These measurements are only taken in clear conditions.

5.3.2.4 Data structure

The measurement data of all perception sensors and the weather reference sensors is captured in ROS2 MCAP files. On the first hierarchy level, the data is sorted into folders according to the weather category: fog, hail, rain, and snow. The daily measurements are in a separate folder. Each measurement of the respective category has its own folder with the date and time of the start of the measurement. Within that folder, there is the MCAP file with the corresponding metadata.yaml.
Additionally, each measurement has a JSON file with the same file name as the measurement. This JSON file contains information about the weather condition in the measurement, such as minimum, mean and maximum values for meteorological optical range, brightness, precipitation intensity, etc. The folder also contains pre-processed lidar data in a Python Pickle file for each sensor. These Pickle files contain evaluations of the number of detections, intensity, reflectivity and distance on the 5 targets and in the atmosphere for each timestep in the measurement. For each lidar timestep, the matching weather sensor data is also contained.

5.3.2.5 Evaluation procedure for Cameras

In the first step, all measurements are classified into four categories: fog, rain, snow, and hail. Rain, snow and hail are distinguished by their respective SYNOP codes, while fog is identified by low visibility combined with a non-precipitation SYNOP code. Brightness is considered as another category. The daily reference measurements are taken for this evaluation.
For each category, environmental parameters (e.g., precipitation rate in mm/h, extinction coefficient in 1/meters or brightness in lux) are paired with perception sensor KPIs across all measurements within that category. Filter regions in the images are defined, to evaluate a square part of the image on each of the 5 targets. The following KPIs are all calculated per target area by always considering 3 consecutive images.

- Mean intensity
- Variance of intensity
- Signal to noise ratio (mean / variance)

Additionally, the contrast between pairs of target regions is calculated as the difference of the means divided by the sum of the means.
The following image shows the 5 target regions in the image.



Figure 5-4: Different target regions in the camera image

5.3.2.6 Evaluation procedure for Lidars

In the first step, all measurements are classified into four categories: fog, rain, snow, and hail. Rain, snow and hail are distinguished by their respective SYNOP codes, while fog is identified by low visibility (high extinction coefficient) combined with a non-precipitation SYNOP code. Brightness is considered as another category. The daily reference measurements are taken for this evaluation.

For each category, environmental parameters (precipitation rate in mm/h, extinction coefficient in 1/meters or brightness in lux) are paired with sensor detection data across all measurements within that category. The analysis focuses on the (relative) number of detections and the detection intensities to quantify environmental impact.
Two kinds of regions of interest are defined for filtering sensor detections:

- Atmospheric Region: This region covers azimuth angles from 0° to 10° and a maximum distance of 20 m from the station. Under clear conditions, no detections are expected in this region; detections originate only from precipitation or fog. The filter excludes ground reflections by applying only positive elevation angles.
- Target Regions: A Cartesian filter is applied to isolate detections corresponding to individual targets.

The primary metric to determine the influence of a weather condition on the perception sensor in the atmosphere is the relative number of detections, defined as the ratio of detection count within the filter region to the total number of beams entering that region. This yields a detection probability per beam under given environmental conditions. On the targets, the absolute numbers of detections are considered.
As a second metric, the intensities of the individual detection points are evaluated. They are affected by the attenuation due to environmental influences.

For each evaluation, not only measurements from the respective weather categories are considered, but also the daily reference measurements. This way, a solid baseline for 0 mm/h precipitation intensity and 0 1/m extinction coefficient is established and present in all plots.

5.4 OPEN ROAD TESTING

For non-critical situations, real-world validation relies on the exploitation of naturally occurring weather events on test tracks. This approach is supported by the deployment of embedded weather stations, enabling the acquisition of reliable ground truth data for perception systems through continuous in situ monitoring of environmental conditions. It provides clear advantages, including exposure to authentic weather conditions and corresponding sensor responses, ensuring a high level of realism in system behavior assessment. It also enables the execution of high-speed and fully representative driving scenarios, which are difficult to reproduce in controlled environments. The use of natural weather phenomena strengthens the representativeness of collected data, while the virtually unlimited outdoor testing space allows for a wide diversity of use cases and configurations. In addition, this approach supports long-duration testing campaigns, offering the ability to assess system performance under evolving and heterogeneous weather conditions over time.

However, these benefits are balanced by several inherent limitations. Weather conditions remain inherently unpredictable, making test planning and scheduling challenging and limiting operational efficiency. The approach is primarily suited to non-critical situations, as the lack of control over environmental variables restricts its applicability for safety-critical validation. Furthermore, repeatability is limited, as identical environmental conditions cannot be reliably reproduced, which constrains comparative testing and regression analysis. The difficulty in controlling specific parameters—such as rainfall intensity, droplet characteristics, or surface conditions—reduces the level of experimental control. Finally, ground truth acquisition can be complex, particularly for parameters such as road friction, and ensuring accurate data synchronization between environmental measurements and vehicle sensor data remains a technical challenge.

Importantly, this field-testing approach also aligns with the ongoing "soft transition" in Euro NCAP robustness expectations, where robustness demonstrations increasingly consider degraded perception conditions such as adverse weather and illumination effects (including glare/nighttime) and require evidence that perception is not significantly degraded, typically supported by real-world driving logs. In that context, the robustness intent requested from OEMs already points toward documenting the road scene and verifying the capability of the vehicle sensors to detect key objects (lane boundary, car, PTW, pedestrian, bicycle) in adverse weather and glare; yet, a current limitation is the lack of defined quantitative indicators specifying "how much" rain or fog qualifies as adverse conditions.

Building on the project workshop outcomes, a pragmatic pathway is therefore to conduct controlled studies across multiple rainfall/fog intensities to identify sensor-specific degradation onset and then use those values as operational thresholds for fieldwork. Doing so requires accurate measurement of rain/fog intensity and, ideally, droplet size distribution (DSD) during open-road testing—hence the proposal to integrate a weather station directly into the vehicle to capture these parameters at the time of the test, enabling subsequent comparison and an initial, data-driven classification of precipitation levels even before exact regulatory thresholds are formally defined.

6. Conclusions and next steps

This deliverable provides a comprehensive benchmark of testing facilities and methodologies for evaluating ADAS/AD systems under adverse weather conditions, addressing a key gap in current validation practices. The results highlight the strong sensitivity of perception systems to environmental conditions: camera performance degrades significantly under rain, fog, and glare, radar systems show relative robustness but remain affected by false detections and infrastructure artefacts, while LiDAR performance is highly dependent on particle interactions (rain, fog). Spray effects also emerge as a critical and still insufficiently characterised factor, particularly impacting distance perception at low speeds.

The benchmark confirms that no single facility can cover the full range of required test conditions. Indoor infrastructures ensure high repeatability and precise environmental control but are limited in dynamics and spatial representativeness, whereas outdoor facilities enable realistic, high-speed scenarios but lack reproducibility. This complementarity supports the need for a coordinated multi-facility testing strategy.

Based on these findings, key priorities for standardisation include the definition of quantitative weather parameters (rain intensity, droplet size distribution, fog visibility), the development of dedicated glare methodologies, the harmonisation of measurement variables (environment, sensors, vehicle response), and improved infrastructure design to reduce test artefacts. Additional focus is required on friction characterisation and the integration of opportunistic real-world testing supported by embedded weather measurement systems.

Looking forward, the evolution of Euro NCAP 2026 robustness requirements—introducing performance assessment under degraded environmental conditions—reinforces the urgency of defining measurable thresholds and validation criteria. In this context, integrating weather instrumentation directly into test vehicles represents a promising approach to bridge controlled testing and real-world validation.

Overall, while current facilities provide a solid basis for adverse weather testing, achieving reproducible, comparable, and certification-ready methodologies will require significant progress in standardisation, measurement accuracy, and protocol harmonisation. The WEATHERSAFE consortium is well positioned to drive this transition and contribute to the safe deployment of automated driving systems under all weather conditions.

7. Annexes

7.1.1 CAMERA SYSTEMS SPECIFICATIONS IN ADVERSE WEATHER

Concerning the contrast and sharpness metrics, we find it relevant to talk about the concept of MTF (modulation transfer function). The latter incorporates resolution and contrast into a single specification [18].

- Resolution is an imaging system's ability to distinguish object detail. It is often expressed in terms of line-pairs per millimetre (where a line-pair is a sequence of one black line and one white line).
- Contrast or modulation can then be defined as how faithfully the minimum and maximum intensity values are transferred from object plane to image plane.

There are several ways to calculate the contrast in an image. One way is, for example, to use Michelson's contrast, whose formula is given below.

$$contrast = [(Imax - Imin)/(Imax + Imin)]$$

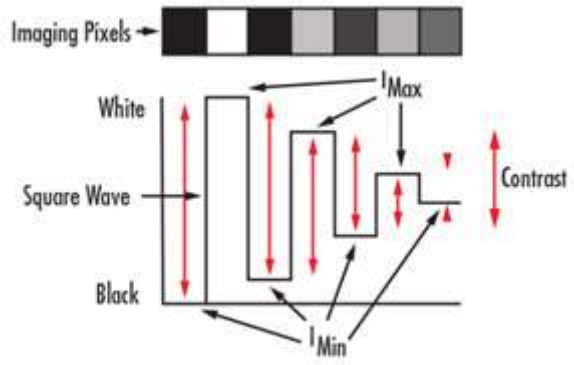


Figure 3: *Contrast Expressed as a Square Wave*

Figure 7-1: Contrast expressed as a square wave [18]

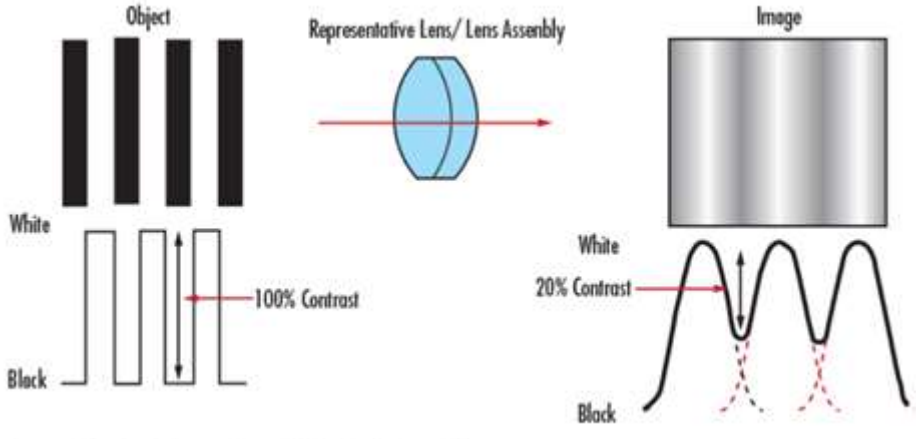


Figure 5: *Contrast Comparison at Object and Image Planes*

Figure 7-2: Contrast comparison at object and image plane [18]

Other calculation methods exist and can be easily found on the web.

Thus, the MTF of a lens, as the name implies, is a measurement of its ability to transfer contrast at a particular resolution from the object to the image. As the line spacing decreases (or the spatial frequency increases), it is more difficult for the lens to transfer this decrease in contrast. The Figure 7-3 below represents the MTF for an aberration-free lens with a rectangular aperture. We can see that, as we said previously, the contrast decreases with the spatial frequency.

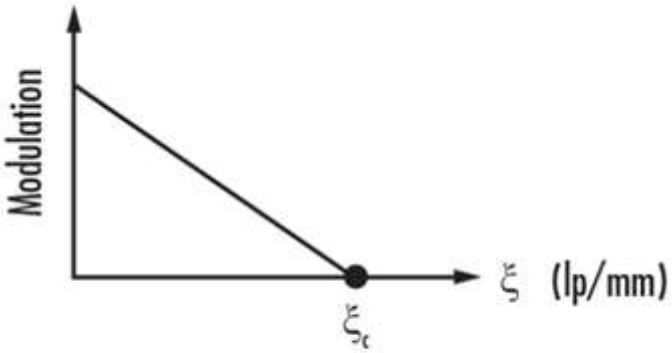


Figure 6: *MTF for an Aberration-Free Lens with a Rectangular Aperture*

Figure 7-3: MTF for an aberration-free lens wtih a rectangual aperture [18]

To measure the MTF of a camera, we can use the targets usually used for camera sharpness measurements. Among them, we can cite:

- Slanted edge
- Siemens star
- Log-F contrast
- Dead leaves

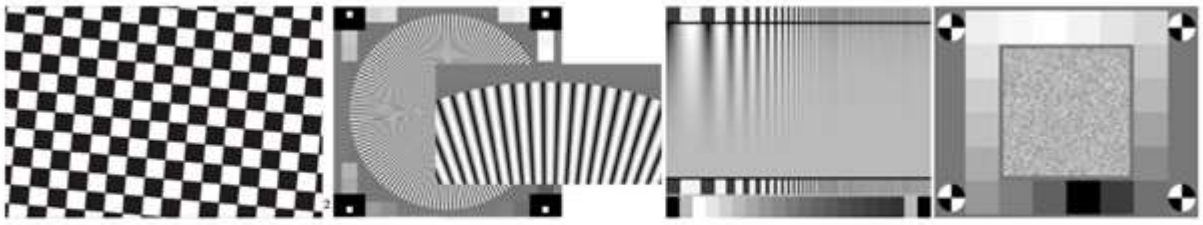


Fig. 4. Different targets for sharpness measurements. Their properties are summarized in the following table. None of them are satisfying for texture quality measurement.

Figure 7-4: targets for sharpness measurement. From left to right: slanted edge, Siemens star, Log-F contrast, Dead leaves [19]

Each chart has its advantages and disadvantages. To know more about these charts, we refer the reader to [20].

Several industrials, such as DxO or Imatest, specialized in camera calibration, have expertise in MTF calculation. An open-source software able to calculate the MTF from a slanted edge chart picture is available on the web[21].

To know more about the MTF method and the processing's associated the reader should read [22].

8. Acknowledgements

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9. References

[1] Cerema, CARISSMA, Université Gustave Eiffel . (2024). Sensors limits under Adverse Weather Conditions. WeatherSafe Project.

[2] VUFO. (2024). Assessment of ADAS/AD performances under adverse weather conditions. WeatherSafe Project.

[3] Sense-City. (n.d.). Sense-City: Climate chamber for sustainable city research. Retrieved 2026, from https://sense-city.ifsttar.fr/

[4] Blosseville, Jean-Marc & Ehrlich, Jacques & Glaser, S. & Hautière, Nicolas & Peyret, François. Vers une sécurité routière accrue par la coopération véhicule-infrastructure : contributions du LCPC au projet SAFESPOT.

[5] D. Gruyer, S. Pechberti and S. Glaser, "Development of Full Speed Range ACC with SiVIC, a virtual platform for ADAS Prototyping, test and evaluation," 2013 IEEE Intelligent Vehicles Symposium (IV), Gold Coast, QLD, Australia, 2013, pp. 100-105, doi: 10.1109/IVS.2013.6629454

[6] Applus+ IDIADA. (n.d.). Test tracks. Retrieved 2026, from https://www.applusidiada.com/global/en/what-we-do/service-sheet/test-tracks

[7] digitrans. (n.d.). Outdoor rain plant. Retrieved 2026, from https://www.digitrans.expert/en/outdoor-rain-plant/

[8] Japan Automobile Research Institute. (n.d.). Jtown. Retrieved 2026, from https://www.jari.or.jp/en/test-courses/jtown/46111/

[9] Duthon, P., Liandrat, S., Ben-Daoued, A., Bicard, J.-L., Ferreira-Fernandes, M., Bicard, D., & Bernardin, F. (2025). PAVIN Extreme Weather Facility: A Cutting-Edge Testing Environment for Agricultural Robotics. 8th AGRITECH DAY by Axema, Edition 2025, 1-9.

[10] World Meteorological Organization. (2019). Manual on codes – International codes, Volume I.1: Annex II to the WMO technical regulations: Part A – alphanumeric codes (WMO-No. 306). https://library.wmo.int/index.php?lvl=notice_display&id=10684

[11] Euro NCAP. (n.d.). Euro NCAP supporting protocol: Safe driving – crash avoidance virtual testing (Version 1.0). Retrieved 2026, from https://www.euroncap.com/media/85832/euro-ncap-supporting-protocol-safe-driving-crash-avoidance-virtual-testing-v10.pdf

[12] Lv, W., Xu, S., Zhao, Y., Wang, G., Wei, J., Cui, C., Du, Y., Dang, Q., & Liu, Y. (n.d.). RT-DETR: DETRs beat YOLOs on real-time object detection.

[13] Ultralytics. (n.d.). Ultralytics documentation. Retrieved 2026, from https://docs.ultralytics.com

[14] Ultralytics. (n.d.). COCO detection dataset documentation. Retrieved 2026, from https://docs.ultralytics.com/datasets/detect/coco/

[15] Michelson, A. A. (1927). Studies in optics. University of Chicago Press.

[16] Marshall, J. S., & Palmer, W. M. K. (1948). The distribution of raindrops with size. Journal of Meteorology, 5, 165–166.

[17] National Academies of Sciences, Engineering, and Medicine. (2009). Guide for Pavement Friction. Washington, DC: The National Academies Press. https://doi.org/10.17226/23038

[18] Edmund Optics. (n.d.). Introduction to Modulation Transfer Function. https://www.edmundoptics.com/knowledge-center/application-notes/optics/introduction-to-modulation-transfer-function/

[19] F. Cao, F. Guichard, Hervé Hornung, "Measuring texture sharpness of a digital camera," Proc. SPIE 7250, Digital Photography V, 72500H (19 January 2009); https://doi.org/10.1117/12.805853

[20] Imatest. (n.d.). Sharpness. Imatest. “MTF Measurement Matrix” section. https://www.imatest.com/imaging/sharpness/

[21] MTF Mapper. (n.d.). MTF Mapper. SourceForge. https://sourceforge.net/projects/mtfmapper/

[22] Strolls With My Dog. (n.d.). MTF [Blog category]. https://www.strollswithmydog.com/category/mtf/

[23] Euro NCAP Testing protocols (2025). CA-003 Field Data Template v1.0. European New Car Assessment Programme. Available at: https://www.euroncap.com/media/91715/ca-003-field-data-template-v10.pdf

[24] ISO 11270:2014 Intelligent transport systems — Lane keeping assistance systems (LKAS) — Performance requirements and test procedures

[25] Likert, R. (1932). "A Technique for the Measurement of Attitudes." Archives of Psychology, 140, 1-55.

[26] ISO/IEC 15288:2015. "Systems and Software Engineering – System and Software Engineering – Life Cycle Processes."