WEATHERSAFE

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

Deliverable D5.1

Test and assessment guidelines

Project Name	WeatherSafe	
Dissemination level	Consortium	
Written by	Valentina CIARLA	UTAC
Issue date	04/07/2025	
Reviewer	Aurelien GARCIA Damien DUESO	
Keywords	ADAS, automated driving, adverse weather conditions (AWC), test and assessment guidelines, Euro NCAP, accidentology, scenario-based testing, perception sensors, sensor fusion, camera, radar, LiDAR, fog, rain, spray, sun glare, visibility threshold, tire–road friction, friction estimation, wet/icy roads, simulation validation, reproducibility, operational design domain (ODD), V2X	
Version	2.0	

EXECUTIVE SUMMARY

This deliverable of the WeatherSafe project provides test and assessment guidelines to evaluate the robustness of Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) functions under adverse weather conditions (AWC).
Building on accidentology analyses, sensor performance characterization, friction studies, re-simulation results, simulation validation work, and a reproducibility benchmark of test facilities, the report identifies the most safety-relevant weather-driven scenarios (notably rain/wet roads, reduced visibility, and sun glare) and explains why current assessment schemes—especially those based on nominal conditions—leave a critical gap in real-world safety coverage.
The document proposes a structured approach to close this gap by (i) defining measurable and reproducible AWC classes and parameters, (ii) prioritizing scenario families grounded in real crash data, and (iii) validating system performance across three complementary dimensions: perception robustness, friction awareness/estimation, and their coupled impact on closed-loop decision making.
Finally, it outlines supportive methodologies—such as a WeatherSafe ranking method, a minimum visibility threshold concept, and dossier-based guidance for degraded-friction testing—aimed at enabling harmonized, repeatable, and Euro NCAP / regulation-ready evaluation procedures that improve safety in AWC without compromising performance or user acceptance in nominal driving.

REVISION HISTORY

Revision	Date	Description, updates and changes	Status
1.0	28/04/2026	First draft version, open for discussion	Draft
2.0	22/06/2026	Update with VUFO feedback	Draft
			Approved

ABBREVIATIONS

Abbreviation	Definition
ABS	Anti-lock Braking System
ACC	Adaptive Cruise Control
AD	Automated Driving
ADAS	Advanced Driver Assistance Systems
ADS	Automated Driving System
AEB	Autonomous Emergency Braking
ASAM OpenX	Association for Standardization of Automation and Measuring Systems – OpenX standards family
AWC	Adverse Weather Conditions
CEPRA	Cause-Effect-Pathway Risk Assessment
DSD	Droplet Size Distribution
DVM	Double Validation Metric
ESC	Electronic Stability Control
Euro NCAP	European New Car Assessment Programme
FMCW	Frequency-Modulated Continuous-Wave
GIDAS	German In-Depth Accident Study
GNSS	Global Navigation Satellite System
HMI	Human–Machine Interface
IGLAD	Initiative for the Global Harmonization of Accident Data
IMU	Inertial Measurement Unit
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Lane Change Assist
LKA	Lane Keeping Assist
MOR	Meteorological Optical Range
MTF	Modulation Transfer Function
MVT	Minimum Visibility Threshold
ODD	Operational Design Domain
SOTIF	Safety Of The Intended Functionality (ISO 21448)
SRTT	Standard Reference Test Tire
TCS	Traction Control System
TTC	Time To Collision
V&V	Verification and Validation
V2V	Vehicle-to-Vehicle communication
V2X	Vehicle-to-Everything communication
VV&UQ	Verification, Validation, and Uncertainty Quantification

1. TABLE OF CONTENT

EXECUTIVE SUMMARY 2
REVISION HISTORY 3
ABBREVIATIONS 4
INTRODUCTION 7
2. MAIN CONCLUSIONS FROM PREVIOUS ANALYSIS 8
2.1 ACCIDENTOLOGY ANALYSIS 8
2.1.1 Impact of the AWC on the accidentology 8
2.2 SENSOR PERFORMANCE IN AWC 10
2.2.1 Phenomena Characterization 10
2.2.2 Key Environmental Phenomena and Characterization Parameters 11
2.2.3 Impact of Adverse Weather on Perception Sensors 11
2.3 SAFETY ON WET ROADS: IMPACT OF FRICTION ESTIMATION 14
2.3.1 Role of Friction in Road Safety 14
2.3.2 Accidentology and Friction Thresholds 14
2.3.3 Physical Mechanisms of Tire–Road Friction 14
2.3.4 Longitudinal and Lateral Forces and Friction Sharing 15
2.3.5 Factors Affecting Available Friction 15
2.3.6 Impact of Friction Estimation on Vehicle Control Systems 15
2.3.7 Conclusion 15
2.4 KEY INSIGHTS FROM RE-SIMULATIONS 16
2.4.1 Selected Scenarios for resimulation 16
2.4.2 Relevant AWC impacting the accidentology 19
2.4.3 Sensor Perception Degradation because of AWC 20
2.4.4 Reduced Road Surface Friction 20
2.4.5 Combination of sensor perception degradation and reduced friction 21
2.4.6 Contribution of the V2X 21
2.5 SIMULATION OF ADVERSE WEATHER EFFECTS ON PERCEPTION SENSORS 22
2.5.1 State of the Art, Measurement Evidence and Validation Guidelines 22
2.5.2 State of the Art and Identified Gaps 22
2.5.3 Measurement-Based Performance Characterization 23
2.5.4 Validation Methodology and Guidelines 23
2.5.5 Consolidated Conclusions and Outlook 24
2.6 REPRODUCIBILITY STUDY 25
2.6.1 Objectives and Context 25
2.6.2 Scope and Methodology 25
2.6.3 Benchmark of Testing Facilities and Tools 25
2.6.4 Sensor Performance Findings under Adverse Weather 26
2.6.5 Reproducibility, Repeatability, and Key Limitations 26
2.6.6 Environmental Side Effects and the Role of Friction 27
2.6.7 Complementary Testing: Opportunistic Weather Measurements 27
2.6.8 Key Recommendations 27
2.6.9 Overall Conclusion and Path Forward 28
3. DEFINE TEST PROTOCOL GUIDELINES 28

3.1 ADDRESSING THE AWC GAP IN EURO NCAP SAFETY TESTING 28
3.2 RECOMMENDATION AND STRATEGIC ALIGNMENT 29
3.3 SUPPORTIVE METHODOLOGIES FROM WEATHERSAFE 31
3.3.1 WeatherSafe Ranking Method 32
3.3.2 WeatherSafe Minimum Visibility Threshold 34
3.3.3 Guideline to assess vehicle in degraded friction conditions 35
3.3.4 Overall methodology for ADAS / AD assessment 38
CONCLUSIONS 43
4. ACKNOWLEDGEMENTS 45
5. TABLE OF ILLUSTRATIONS 46

Introduction

The progressive deployment of Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) functions is changing how road safety is achieved and assessed. While current consumer and regulatory procedures provide a structured basis for evaluating system performance, most established protocols are still executed under nominal environmental conditions (e.g., dry road surface, good visibility, stable illumination). Accident data and prior WeatherSafe analyses show that this assumption leaves a critical gap: adverse weather conditions (AWC)—such as rain and spray, wet or icy road surfaces, fog and reduced visibility, and sun glare—are disproportionately associated with severe crashes and simultaneously degrade both perception and vehicle controllability.

Deliverable D5.1 addresses this gap by proposing test and assessment guidelines to evaluate ADAS/AD robustness under AWC in a way that is safety-relevant, measurable, and reproducible. The deliverable aims to support the evolution of assessment schemes (including Euro NCAP-oriented perspectives) by translating WeatherSafe research outcomes into practical guidance for: (i) selecting AWC that matter most for safety; (ii) defining AWC classes using physical parameters that can be measured on proving grounds, in test facilities, and in simulation; and (iii) assessing system performance and failure modes when weather affects perception, friction, or both.

The guidelines build on the project results consolidated in previous work packages, including accidentology analyses (e.g., GIDAS and IGLAD), characterization of weather phenomena and their parameters, evidence on perception sensor degradation, studies on tire–road friction and friction estimation, scenario re-simulations quantifying safety benefits of perception and friction awareness, simulation validation methodologies for weather-affected sensor models, and a benchmark of test facilities and reproducibility constraints. D5.1 therefore functions as a synthesis deliverable: it connects evidence to testable requirements and provides a structured path from real-world risk drivers to assessment concepts that can be implemented consistently.

Scope-wise, this deliverable focuses on road vehicle ADAS/AD functions whose safety performance is sensitive to AWC, with particular attention to scenarios identified as critical in the accidentology (e.g., stationary traffic, intersection conflicts, and loss-of-control precursors). The document emphasizes frequent and safety-relevant AWC rather than rare extremes, and it addresses three coupled assessment dimensions that repeatedly emerge across the project: perception robustness, friction awareness/estimation, and their interaction in closed-loop decision making (timing, intervention strategy, and graceful degradation outside the Operational Design Domain).

The intended audience includes technical stakeholders involved in assessment design and execution (test engineers, proving-ground and facility operators, simulation and validation specialists), as well as organizations developing or applying safety assessment schemes (e.g., consumer rating bodies, regulatory and standardization stakeholders, and OEMs/suppliers preparing evidence dossiers). Readers may use this deliverable either as (a) a basis to define or refine AWC test protocols and acceptance criteria, or (b) a reference to justify why specific AWC classes, scenarios, and metrics are prioritized.

The remainder of the document is structured as follows. Section 2 summarizes the main conclusions from previous WeatherSafe analyses that motivate the guideline choices (accidentology, sensor performance in AWC, friction, re-simulations, simulation validation, and facility reproducibility). Section 3 then proposes guideline recommendations and supportive methodologies, including approaches to prioritize AWC and to operationalize assessment (e.g., ranking concepts, minimum visibility threshold, and degraded-friction dossier guidance), concluding with a proposed overall methodology for ADAS/AD assessment under AWC.

2. Main conclusions from previous analysis

2.1 ACCIDENTOLOGY ANALYSIS

Deliverables 1.1 and 1.2 of the WeatherSafe project presents a comprehensive assessment of how adverse weather conditions (AWC) affect both the occurrence of traffic accidents and the performance of Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) technologies. The analysis combines a structured literature review, statistical evaluations of accident databases (GIDAS and IGLAD), and a comparison with Euro NCAP testing protocols. This foundational research is critical to:

- Identify safety-critical weather-related scenarios,
- Determine real-world limitations of current ADAS/AD systems, and
- Propose relevant accident scenarios for further simulation and testing in future project phases.

The growing deployment of ADAS/AD technologies in vehicles is significantly reshaping road safety strategies. However, current validation protocols, such as Euro NCAP tests, largely assume optimal environmental conditions , leaving a substantial knowledge and performance gap under adverse weather scenarios. This poses safety risks and potentially undermines public trust in automation.

The WeatherSafe project addresses this gap by investigating:

1) Which weather conditions are most frequently associated with severe or fatal accidents?
2) How do ADAS/AD systems behave in these conditions based on empirical data?
3) What improvements are required in test scenarios to enhance safety validation?

2.1.1 IMPACT OF THE AWC ON THE ACCIDENTOLOGY

Despite the dominance of dry weather conditions in general traffic accident statistics (~80%), the influence of adverse weather conditions (AWC) - although numerically smaller (~20%) is significantly disproportionate in terms of accident severity and complexity.
The analysis of the GIDAS database reveals that AWC influence traffic accidents in a multifactorial manner - see. *Figure 2-1.*, exerting their impact through varying degrees of causality. Understanding this spectrum is essential for the design of effective mitigation strategies, safety systems, and regulatory test protocols.

2.1.1.1 AWC as a Direct Cause of Accidents

While only a small fraction of accidents (approx. 0.5%) are classified as being directly caused by adverse weather (e.g., loss of control due to icy roads or blinding sun glare), these cases are often associated with severe consequences, such as vehicle run-offs, rollovers, or fatal collisions. The low statistical share may obscure their importance, but the severity and unpredictability of these events justify targeted safety measures (e.g., real-time traction control, adaptive cruise systems).

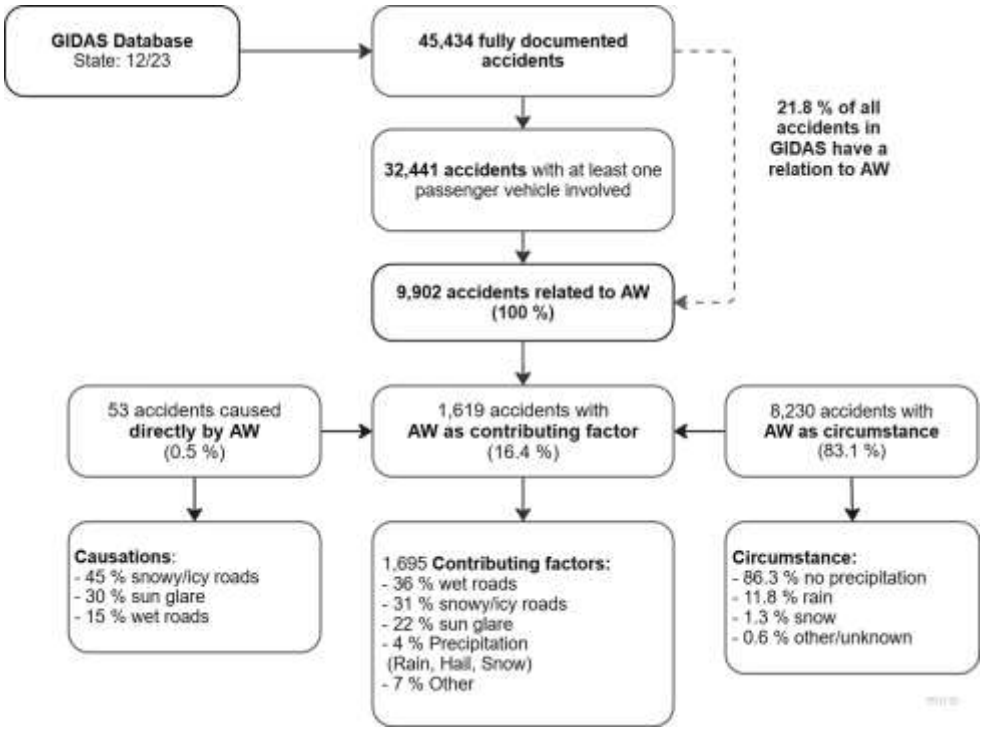


Figure 2-1: Multifactorial influence of AWC on the accidentology from GIDAS Database

2.1.1.2 AWC as a Contributing Factor

In a significantly larger share of cases (16.4%), AWC are contributing factor - not the primary cause, but influential in amplifying the danger of other driver or vehicle behaviors. For instance, reduced friction due to wet roads may not directly cause a crash but may exacerbate braking distances or destabilize evasive maneuvers. Likewise, glare may delay driver perception and contribute to reaction-time failures.

This category demonstrates that AWC often interact with human error, system limitations, or environmental features, increasing the likelihood of an accident. Therefore, safety systems and driver models must be designed not only to detect and compensate for AWC but to understand their interactive role in accident dynamics.

2.1.1.3 AWC as a Circumstance

In the majority of accidents (~83%), AWC are recorded merely as circumstantial elements - resent at the time of the crash but not necessarily causative or contributing in a coded sense. However, this does not negate their potential influence. For example, the presence of light rain or low temperatures may not be coded as a cause, but they could influence driver behavior (e.g., cautious driving) or sensor performance, especially in AD systems.

The prevalence of AWC as contextual variables implies a baseline risk exposure. Even when not causative, weather conditions modify the operational context of both human and automated drivers. This reinforces the need for ADAS/AD systems to account for environmental awareness as part of their Operational Design Domain (ODD).

This tiered impact model (cause – contributor – circumstance) underlines that AWC are not binary risk factors, but rather context-sensitive modifiers of accident risk and system performance. Treating AWC solely as primary causes underestimates their systemic relevance. A nuanced understanding of these distinctions is essential for:

- Designing robust ADAS/AD sensor systems

- Developing realistic test scenarios
- Informing policy and regulatory frameworks
- Improving driver training and warnings

By integrating this layered causation model into future development and evaluation methodologies, the WeatherSafe project can ensure a more resilient and adaptive approach to road safety under real-world weather conditions.

2.2 Sensor Performance in AWC

Deliverable in WP2 (Cerema, CARISSMA, Université Gustave Eiffel , 2024) provides a comprehensive analysis of main weather phenomena present in the word and the performance limitations of perception sensors used in ADAS and AD systems under various AWC.

2.2.1 Phenomena Characterization

This part of the project focuses on the characterization of adverse weather phenomena, their measurable parameters, and their impact on perception sensors and ADAS/ADS performance. The objective is to establish a technically robust basis to support harmonized testing, simulation, and assessment methodologies under adverse weather conditions (AWC). A structured framework of environmental indicators was defined to describe adverse weather conditions in a quantifiable and reproducible manner. The indicators cover both primary weather phenomena and secondary effects, including:

- Rain: rainfall intensity, droplet size distribution, droplet velocity, spatial distribution, wind influence, pH
- Fog: visibility range, liquid water content, droplet size distribution
- Snow: snow type, density, accumulation, visibility impact
- Temperature and humidity: ambient temperature, relative humidity
- Illumination: luminance, contrast, sun glare occurrence
- Road surface state: dry, wet, icy, contaminated surfaces

These indicators enable a multi-dimensional description of AWC, necessary for both physical testing and simulation environments.

The scope focuses on high-impact and high-occurrence phenomena in the European context, with particular emphasis on rain, fog, glare, wet road conditions, and spray, while maintaining traceability to established meteorological standards and measurement practices.

The characterization is based on a multi-layered scientific methodology combining:

- Meteorological theory (formation mechanisms, microphysics, optical effects),
- Quantitative parameterization of phenomena using measurable physical indicators,
- Statistical occurrence analysis using European climate and weather data,
- Review and harmonization of standards and literature (WMO, national meteorological services, aeronautical and road standards),
- Measurement technology review, assessing the feasibility of observing relevant parameters in real-world and test environments.

This approach ensures that the selected parameters are not only physically meaningful but also practically measurable and suitable for test scenario generation.

2.2.2 Key Environmental Phenomena and Characterization Parameters

2.2.2.1 Primary Weather Phenomena

The deliverable identifies rain, fog, and glare as the most safety-relevant primary phenomena for road traffic and perception systems.
Rain is characterized by precipitation intensity, droplet size distribution (DSD), droplet shape, fall velocity, and wind interaction. Particular attention is paid to microphysical modeling (lognormal, Weibull, Marshall–Palmer, and gamma distributions) to enable realistic sensor degradation and spray formation modeling.
Fog is primarily characterized through Meteorological Optical Range (MOR), fog water content, and droplet size distribution, directly linking atmospheric conditions to visibility degradation and sensor performance loss.
Glare is addressed through illuminance, luminance, spectral composition, glare angle, and light source geometry, reflecting its strong dependence on sun position, road geometry, and reflective surfaces.

2.2.2.2 Secondary Weather Phenomena (Road Conditions)

Secondary effects arising from primary weather events are shown to be equally critical for safety:

- wet road surfaces are characterized by water film thickness, surface texture, friction coefficient, and temperature.
- Spray and splash are identified as emergent phenomena resulting from wet roads and traffic interaction, with droplet size distribution and spatial extent being key parameters.
- Changes in road friction are highlighted as a dominant factor influencing braking distance and accident risk during weather transitions.

2.2.2.3 Occurrence and Relevance in Europe

The analysis demonstrates that:

- Moderate rainfall is common across Europe, while extreme rain intensities (>50–100 mm/h) occur infrequently but are regionally concentrated (e.g. Alpine regions).
- Fog frequency has decreased over recent decades due to improved air quality, yet low-visibility events remain recurrent, especially in Central, Eastern, and Northern Europe.
- Wet road conditions are among the most frequent adverse conditions, making them a key contributor to accident risk through spray formation and friction reduction.

This statistical grounding ensures that subsequent testing focuses on high-probability, high-impact scenarios, rather than rare or non-representative extremes.

2.2.3 Impact of Adverse Weather on Perception Sensors

This part of the deliverable provides a direct scientific basis for:

- defining weather-aware test cases for ADAS and automated driving validation;
- delecting physically meaningful test parameters rather than qualitative weather descriptors;
- supporting sensor robustness assessments under realistic degradation mechanisms;
- enabling harmonized scenario definitions aligned with meteorological standards.

By linking environmental physics to measurable indicators and occurrence probabilities, the work bridges the gap between atmospheric science and automotive safety engineering.
The main scientific contribution of this deliverable lies in:

- the systematic prioritization of adverse weather phenomena based on safety relevance and occurrence,
- the consolidation of meteorological microphysics into an engineering-oriented framework,
- the translation of weather complexity into testable parameters suitable for simulation, proving grounds, and laboratory environments.

This synthesis establishes a robust foundation for subsequent project tasks addressing scenario generation, sensor testing, and system validation under adverse environmental conditions.

The analysis highlights that adverse weather primarily affects sensor performance through signal degradation mechanisms, which vary by sensor type:

- cameras: reduced contrast and visibility due to rain, fog, low illumination, and sun glare
- radar: signal attenuation and clutter effects under heavy precipitation
- LiDAR: backscattering and range reduction caused by rain and fog droplets

The impact is not binary but progressive, depending on the severity and combination of environmental parameters (e.g. rain + wet road + low illumination). This underlines the necessity to consider compound weather scenarios rather than isolated phenomena.

Based on accidentology and environmental analysis, the project confirms that the most safety-relevant AWC scenarios are not extreme or rare events but rather frequent, moderate conditions, such as:

- Wet road surfaces with light to moderate rain
- Sun glare under otherwise clear weather
- Reduced visibility during dusk, dawn, or night-time

These conditions are highly representative of real-world driving exposure and therefore critical for meaningful safety assessment.
The results show that current standard testing conditions (typically dry, clear weather) do not sufficiently cover the operational conditions where ADAS/ADS performance degradation is most likely to occur.
Key implications include:

- the need for controlled and measurable AWC conditions on test tracks;
- the importance of accurate ground truth measurement of weather and surface states;
- the complementarity between physical testing, opportunistic/on-road observations, and numerical simulation.

Simulation plays a key role in extending coverage to rare or complex combinations of weather parameters, provided that sensor and environment models are adequately validated.

The work conducted supports the development of test and assessment guidelines by:

- identifying relevant weather parameters and thresholds;
- linking environmental conditions to sensor degradation mechanisms;
- providing a basis for scenario selection and test case prioritization.

These elements are essential to move toward harmonized and reproducible assessment protocols for ADAS/ADS under adverse weather conditions, while maintaining relevance to real-world safety challenges.

The objective is to support the development of robust, all-weather-capable driving systems by identifying critical sensor vulnerabilities and recommending effective sensor configurations and test scenarios.

Key findings from this deliverable include:

- Radar is the most resilient sensor type under adverse weather. It remains effective in fog, rain, snow, and low visibility, with minor degradation only in very severe conditions (e.g., tropical rainfall or wet snow).
- Cameras are highly sensitive to weather, especially to water droplets, low light, glare, and occlusion from snow or fog. Variants such as HDR and polarized cameras provide marginal improvements but do not fully overcome these limitations.
- LiDAR performance is significantly reduced in fog, rain, and snow due to light scattering. FMCW-based LiDARs offer improved resilience and velocity detection but remain less weather-tolerant than radar.
- Thermal cameras are largely unaffected by lighting conditions and moderately resilient to weather. They provide added value for detecting heat-emitting objects (e.g., pedestrians) in low-visibility scenarios but may be impacted by surface conditions and sensor contamination.
- Ultrasonic sensors are limited to short-range, low-speed applications (e.g., parking) and are highly affected by wet surfaces and noise.
- Proprioceptive sensors (GNSS, IMU) are not impacted by weather and remain essential for estimating vehicle dynamics but do not contribute to environmental perception.

A qualitative synthesis of these performances can be seen in Table 1-2, where the impact has been classified in

- (1) severe
- (2) moderate
- (3) negligible

AWC	Radar	Camera	LiDAR	Thermal camera	Ultrasonic
Fog	3	1	1	2	3
Rain - Light and moderate	3	2	2	2	3
Rain - Heavy	2	1	1	1	2
Snow	3	1	1	1	2
Spray/Splash effect	3	1	1	2	3
Lighting effects	3	1	2	3	3
Temperature	3	3	3	1	2
Object surface state	3	2	2	1	3
Sensor surface state	2	1	1	1	1
Sensor weather capacity	**3**	**1**	**1**	**2**	**2**

Table 2-1 Qualitative evaluation of sensors performance under AWC

No single sensor type can ensure safe operation under all weather conditions. A multi-sensor fusion approach - combining radar, camera, LiDAR, and thermal imaging - offers the best compromise between robustness and perception quality. Radar and thermal cameras are particularly valuable in ensuring continuity of perception in degraded environments. Sensor

performance must be evaluated in test scenarios that reflect the full range of operational design domain (ODD) weather conditions.
This deliverable contributes to the definition of robust sensor suites and test methodologies essential for certifying weather-resilient ADAS and ADS functionalities.

2.3 Safety on Wet Roads: Impact of Friction Estimation

This deliverable investigates the fundamental role of tire–road friction in road safety, with a particular focus on wet and degraded surface conditions.
The document establishes a clear link between reduced friction, increased crash risk, and the need for reliable friction estimation methods at both infrastructure and vehicle levels.

2.3.1 Role of Friction in Road Safety

Tire–road friction represents the critical interface between the vehicle and its environment. All longitudinal and lateral forces required for acceleration, braking, trajectory control, and vehicle stability are generated at this interface. Any degradation of this contact—caused by water, snow, ice, or surface contaminants—directly reduces vehicle dynamic capabilities and increases accident risk.
The report draws on a wide range of international accidentology studies demonstrating a strong and consistent correlation between reduced pavement friction and higher crash rates, particularly on wet roads. Historical analyses from Europe and North America show that road sections with low friction levels systematically exhibit increased wet-weather crash frequencies. Conversely, surface improvement measures (such as resurfacing and retexturing) that restore or enhance friction result in substantial accident reductions, with the largest benefits observed in wet conditions.

2.3.2 Accidentology and Friction Thresholds

The synthesis confirms the existence of critical friction thresholds below which crash risk rises sharply. Several studies indicate that when friction values fall below typical limits in the range of 0.40 to 0.50 (depending on the measurement method), braking- and loss-of-control-related crashes increase non-linearly. The report also highlights that **minimum friction levels**, rather than mean values, are more strongly correlated with accident occurrence, stressing the importance of identifying and treating locally degraded road sections.

2.3.3 Physical Mechanisms of Tire–Road Friction

The deliverable provides a detailed explanation of the physical principles governing tire–road friction, distinguishing longitudinal and lateral force components. Friction is expressed through the coefficient of friction μ, defined as the ratio between tangential force and normal load. Two primary mechanisms contribute to friction generation:

- Adhesion, resulting from microscopic bonding and interlocking between tire rubber and fine surface asperities;
- Hysteresis, associated with viscoelastic energy losses due to tire deformation over macro-texture irregularities.

On dry and relatively smooth surfaces, adhesion dominates. Under wet conditions, water acts as a lubricant that significantly reduces adhesion, making hysteresis the dominant contributor.

Consequently, pavement macro-texture and tire water evacuation capability become decisive factors in maintaining grip.

2.3.4 Longitudinal and Lateral Forces and Friction Sharing

The document describes longitudinal forces (acceleration and braking) and lateral forces (cornering and stability control), as well as their interaction. The **friction circle** concept illustrates the limited friction budget shared between longitudinal and lateral forces: increasing one component reduces the available capacity for the other. Under low-friction conditions, this trade-off becomes critical and explains many loss-of-control scenarios during braking in curves or avoidance maneuvers on wet roads.
The dependence of friction on slip ratio is also addressed. Maximum friction typically occurs at slip ratios between 5 % and 15 %, which forms the operational basis of Anti-lock Braking Systems (ABS).

2.3.5 Factors Affecting Available Friction

The report emphasizes that friction is not an inherent property of the pavement alone but the result of a complex interaction between multiple factors:

- pavement surface characteristics (micro- and macro-texture, materials, drainage);
- vehicle operating parameters (mass, speed, maneuvers);
- tire properties (rubber compound, tread pattern, wear, inflation pressure);
- environmental conditions (water, temperature, snow, ice, contaminants).

Water film thickness, vehicle speed, and tire wear are identified as key contributors to friction loss on wet surfaces.

2.3.6 Impact of Friction Estimation on Vehicle Control Systems

A significant part of the deliverable focuses on the role of friction estimation in vehicle control and safety systems. ABS, Electronic Stability Control (ESC), Traction Control Systems (TCS), Autonomous Emergency Braking (AEB), and more advanced ADAS and AD functions rely on assumptions or estimations of available friction to adapt braking, stability, and trajectory planning strategies.
Various estimation approaches are reviewed, including onboard sensors (wheel-speed, inertial, force sensors), perception systems (camera, radar, lidar), physics-based models, artificial intelligence techniques, and connected vehicle solutions (V2X and fleet data). The report highlights that current methods face a trade-off between accurate local measurement and reliable prediction of upcoming friction conditions and concludes that hybrid approaches combining multiple data sources offer the greatest potential.

2.3.7 Conclusion

Deliverable D3.4 clearly demonstrates that improving road safety in wet conditions requires a combined infrastructure- and vehicle-oriented approach. Optimizing pavement surface properties (texture, drainage, maintenance) and advancing friction estimation technologies are essential for reducing accident rates. In the context of increasing vehicle automation, robust and reliable friction understanding and estimation emerge as key prerequisites for

ensuring the safety and performance of ADAS and automated driving systems under adverse weather conditions.

2.4 KEY INSIGHTS FROM RE-SIMULATIONS

WP3 has focused on the re-simulation of the accidentology scenarios. Among the key factors linked to the AWC that can be easily identified with an impact on accidentology, focus has been given to

- sensor perception degradation because of AWC;
- reduced road surface friction;
- a combination of the 2 factors.

2.4.1 SELECTED SCENARIOS FOR RESIMULATION

The comprehensive analysis of GIDAS accident data has led to the identification of the five most prevalent accident scenarios occurring under AWC. These scenarios account for a significant portion of weather-related incidents and offer clear guidance for future system evaluation, scenario simulation, and regulatory adaptation. Among the top 5 Real-World AWC (see Figure 2-2), we can find:



Figure 2-2 Top 5 real-world AWC critically scenarios

Please note that the selection of these scenarios has been done, by excluding the loss of control scenarios, because of the poor relevance for EURO NCAP testing, as described into the Deliverable 3.0.

2.4.1.1 Intersection conflicts involving a target from the right (scenario 321)

Intersection conflict scenarios are inherently complex and become especially high-risk under adverse weather conditions due to:

- Degraded visibility and sensor perception: rain, fog, snow, or sun glare can obstruct a driver's or ADAS system's ability to detect cross traffic, pedestrians, or cyclists in time. Occlusions caused by parked vehicles, vegetation, or infrastructure are worsened under poor weather conditions, leading to delayed detection. In addition, cameras and LiDAR can fail to recognize approaching vehicles or vulnerable road users (VRUs) from side streets due to weather-induced occlusion or reflection. Misidentification or late detection can cause inaccurate gap assessment or failure to apply emergency braking, because of a bad estimation of the TTC (time to collision). AWC can make road markings, yield signs, and lane indicators less visible, increasing the likelihood of priority rule violations.
- Reduced surface traction: as in the previous scenario, wet, icy, or dirty roads at intersections reduce tire traction, leading to longer stopping distances and increased risk of rear-end or side-impact collisions.
- Compressed decision-making timeframes, due to multiple factors:
    - drivers may misjudge the speed of cross-traffic, particularly in low-visibility conditions, leading to unsafe turns or failed yield behavior.
    - Intersection conflicts often occur within a short decision window (e.g., during left turns or when crossing priority roads) and ADAS systems like AEB (lateral),

intersection assist, or turn assist may not trigger fast enough in degraded conditions.
  - Complex Traffic Configurations, like multi-leg intersections, roundabouts, or intersections, without clear signage increase cognitive and sensor complexity.

2.4.1.2 Turning left into on-coming traffic (scenario 211)

Turning left into on-coming traffic is among the most complex and high-risk manoeuvres, and under adverse weather conditions, the associated risks are significantly elevated. Among them, we can find a combination of:

- reduced visibility, due to the obscuration of the view of approaching vehicles caused by AWC or due to the poor perception of lane markers, traffic signals, or median curbs under AWC may confuse both drivers and automated systems, resulting in incorrect positioning or path planning.
- Degraded perception: in AWC, cameras, radars or lidars, commonly used to asses the intersection, can be obstructed by water droplets, snow, or fog, or blinded by glare or low-angle sunlight. These limitations lead to late or missed detection of oncoming traffic, especially motorcycles or smaller vehicles.
- Slippery surfaces: on wet or icy roads, the vehicle's turning radius may be compromised, leading to understeer, lane deviation, or failure to complete the turn safely. This is especially dangerous when crossing multiple lanes of traffic, as in multilane intersections.
- Shortened reaction windows: in conditions of limited visibility, drivers may either hesitate mid-turn, creating a stalled vehicle hazard in the intersection or turn at the wrong moment (too early or too late), causing side-impact collisions. In addition, turning left into cross traffic requires multiphase decisions: checking gaps, controlling vehicle dynamics, and reacting to cross-traffic speed – all of which are hindered by weather induced stress and uncertainty.

2.4.1.3 Turning left to a priority road when the opponent is coming from the left (scenario 302) and Crossing priority roads where the opponent is coming from the left (scenario 301)

Turning left or crossing priority roads scenarios are high-risk manoeuvres, made substantially more dangerous under AWC, because of their impact on:

- Visibility in the same case of the turning scenarios but also because of the presence of obstacles (e.g. buildings, parked vehicles, vegetation), that often obstruct the line of the sight, especially at unregulated or semi-regulated intersections.
- Traction: wet or icy road surfaces affect acceleration and stopping, making it harder to safely clear the intersection in the available time window. Vehicles may skid or fail to accelerate adequately, especially when crossing multilane roads.
- Driver's maneuvers: in uncertain weather conditions, drivers may hesitate mid-crossing, creating a dangerous stall in the intersection. This indecision can result in T-bone or side-impact collisions, particularly if the vehicle on the priority road is traveling at high speed.

When the scenario happens on the left some slight variations in conflict angles and timing shall be taken into account.

2.4.1.4 Stationary traffic scenario (scenario 611)

One of the critical safety scenarios in both urban and interurban contexts involves the need for emergency braking in response to stationary traffic. This occurs when a vehicle—human-driven or automated—approaches a queue, obstruction, or stalled vehicle and must come to a full stop to avoid a collision. Among the key risk factors directly linked to AWC, it is possible to find:

- Sensor detection limitations: cameras may suffer from glare or occlusion, radar may be scattered by precipitation, and LiDAR can be distorted by reflective surfaces. In addition, stationary objects are often harder to detect than moving ones. In poor weather, the system may misclassify the stationary object as a non-threatening feature or background artifact.
- Reduced Tire-Road Friction: wet, icy, or snowy surfaces result in longer stopping distances, especially when braking must be sudden and full. AEB systems are calibrated to respond within a certain braking distance; if friction is reduced, even timely system activation may not prevent a collision.
- Driver Overreliance or Delayed Reaction: in vehicles equipped with ADAS, drivers may become less vigilant and react later than needed, assuming the system will intervene. In AWC, where system performance may be degraded or misaligned with real conditions, this delay increases crash risk substantially.
- False Positives and System Deactivation: some AEB systems, especially in early-generation vehicles, deactivate or reduce sensitivity in low-visibility conditions to avoid false positives. This behavior can leave drivers unaware that emergency support is unavailable precisely when it is most needed.

These scenarios frequently involve non-ideal weather, reduced driver/sensor visibility, and dynamic road interactions, making them representative of high-risk AWC contexts that are currently underrepresented in testing protocols. A synthetic view can be found in Table 3-1.

Causes induced by AWC / Scenario	Sensor Perception Degradation	Reduced Road Surface Friction	Inadequate or Late Driver Input	Driver Overreliance on Automation	Road Geometry / Infrastructure Deficiencies / Complex Traffic Configurations	Excessive or Inappropriate Speed
Intersection conflicts involving a target from the right (n° 321)	delayed detection of cross traffic or VRUs / inaccurate gap assessment or failure to apply emergency braking / bad estimation of TTC	longer stopping distances / increased risk of rear-end or side-impact collisions	unsafe turns / failed yield behavior		increase cognitive and sensor complexity and impact the ability to perform an efficient braking	
Turning left into on-coming traffic (n°211)	incorrect positioning or path planning / late or missed detection on on-coming traffic (mainly VRUs)	understeer, lane deviation, or failure to complete the turn safely	stalled vehicle hazard in the intersection or turn at the wrong moment (too early or too late) may cause side-impact collisions			
Turning left to a priority road when the opponent is coming from the left (scenario 302) and Crossing priority roads where the opponent is coming from the left (scenario 301)	risk idem turning scenario with additional use-cases linked to the presence of obstacle at the intersections (e.g. buildings, parked vehicles, vegetation)	bad acceleration profile in the available window of the intersection	dangerous stall at the intersection			
Stationary traffic scenario (n° 611)	misclassification of stationary object as a non-threatening feature or background artifact	longer stopping distances	higher risk of crash	delayed manual intervention when the system deactivates in low visibility conditions to avoid false positive.		

Table 2-2 Cross-correlation matrix of the risks associated to AWC

The identification of the top five real-world accident scenarios under AWC provides a data-driven foundation for prioritizing which scenarios should be integrated into ADAS evaluation and regulatory frameworks. These high-risk, weather-dependent events challenge current system capabilities and demand a more realistic and standardized testing approach.
Incorporating these insights into future system design and validation processes will be essential for ensuring ADAS/AD systems are robust, trustworthy, and aligned with real-world safety needs—particularly as weather variability becomes increasingly relevant in the context of climate change and expanded vehicle automation.

2.4.2 RELEVANT AWC IMPACTING THE ACCIDENTOLOGY

The analysis of European and German accident data clearly identifies rain as the most statistically relevant AWC across the continent. Accounting for approximately 10% of fatal accidents, rain ranks as the second most common environmental condition present in crashes, following dry weather. Its frequent occurrence, combined with its hazardous nature, makes rain a critical safety risk in both manual and automated driving contexts.
The safety implications of rain extend beyond its prevalence. Rainfall directly reduces driver visibility, degrades tire-road friction, and negatively affects sensor perception and reliability - particularly for camera-based and LiDAR systems used in ADAS and automated driving platforms. These effects compound the risk of loss-of-control incidents, especially on curves, in intersections, and at high speeds.
In Germany, granular insights from DESTATIS and GIDAS confirm that wet and icy road surfaces, as well as sun glare, are recurrent and significant contributing factors in accident causation. Icy roads, although less frequent than rain, are strongly correlated with high-severity loss-of-control crashes. The dynamic between road surface condition and reduced traction underlines the need for more responsive and weather-aware driving assistance systems.
Notably, sun glare is a frequently overlooked hazard in accidentology and safety testing frameworks. Despite its omission from many standard test protocols, glare was shown in the GIDAS dataset to be a direct or contributing factor in over 30% of AWC-coded accidents. Its impact is twofold: it compromises human visual perception and impairs the effectiveness of camera-based systems integral to ADAS and AD technologies. These findings strongly support the inclusion of sun glare as a high-priority AWC in both safety assessment models and technical evaluations.
A direct link has been made between the 5 most critical scenarios and the presence of the most relevant AW conditions, impacting the accidentology. This is visible in the table below:

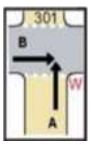
	Intersection	Turning left on-coming traffic	Turning left to a priority road	Crossing priority	Stationary Traffic
					
Low friction (%)	83,95%	76,65%	90,70%	89,02%	85,53%
Rain precipitation (%)	33,78%	36,74%	40,93%	49,13%	40,13%
Sun glare (%)	18,73%	24,24%	10,70%	11,56%	17,11%

Table 1: rate of most common AW effects for each accidentology scenario.

As expected, the references speeds for these scenarios are mostly at low or average speeds.

These findings challenge the current paradigm in which AWC are often treated as secondary variables or edge cases. While adverse weather may be less frequent in aggregate statistics, it is disproportionately represented in high-severity and single-vehicle crashes - scenarios where both human drivers and automated systems are most vulnerable.
This underscores the need to:

- reframe AWC definitions to include frequently overlooked conditions such as sun glare and road surface moisture;
- prioritize AWC scenarios (e.g., rain, glare, icy roads) in both virtual and physical testing of ADAS and AD systems;
- integrate environmental perception limitations into ODDs and system performance ratings;
- adapt regulatory and consumer test protocols to include realistic weather-driven risks.

2.4.3 Sensor Perception Degradation because of AWC

While enhancing perception in ADAS systems - through improved sensors, sensor fusion, or algorithmic refinement - can marginally increase accident-avoidance capabilities, re-simulations show that even with optimal perception, the additional benefit over standard ADAS is limited. Specifically, only 0.8% more accidents are avoided when using an ADAS with ideal perception compared to a typical production-grade ADAS.
This modest improvement highlights a key insight: perception alone is no longer the primary bottleneck in ADAS performance. Most current systems already possess sufficient perceptual fidelity to detect and classify critical objects and events in typical driving environments. Instead, the limiting factors now lie in contextual decision-making, planning under uncertainty, and the inability to adapt to dynamic physical constraints—such as road friction, driver intent, or complex scenarios involving occlusions or non-normative behavior.
This finding justifies a shift in focus from simply improving perception quality to developing higher-level reasoning, better vehicle-to-environment modeling, and dynamic decision-making systems. It also suggests that future safety improvements will come not from additional sensors or marginal perception gains, but from intelligent systems that can act more appropriately based on the real-world driving context.
In short, the deliverable demonstrates that perception performance in ADAS has reached a point of diminishing returns, and that unlocking significant safety gains requires innovation in other areas of the driving stack.

2.4.4 Reduced Road Surface Friction

Re-simulation has been proven that Integrating an advanced ADAS capable of detecting the road-tire coefficient of friction provides a significant improvement in accident prevention beyond what standard ADAS systems offer. According to simulation data, in scenarios representing low (e.g., scenario 302: 13.1%) and medium-to-high (e.g., scenario 611: 69.0%) friction conditions, a notable share of additional accidents can be avoided—accidents that would still occur even with conventional ADAS.
Standard ADAS typically assumes a nominal friction level when planning braking and evasive maneuvers, which can result in either overly cautious or insufficient responses in real-world conditions where friction varies drastically (e.g., wet, icy, or gravel roads). A system that adapts to actual friction conditions in real-time enables more accurate and effective intervention strategies, such as optimized emergency braking, lane keeping, and collision avoidance maneuvers.

This capability leads to smarter decision-making under critical conditions, enhancing safety margins. Therefore, enabling friction estimation within ADAS expands its effective range, allowing the system to handle complex scenarios where friction misjudgment often results in loss of control or failure to stop in time. Quantitatively, the potential to avoid an additional 13.1% to 69.0% of accidents in specific scenarios demonstrates a substantial safety benefit and strongly supports the development and integration of this deliverable.

2.4.5 COMBINATION OF SENSOR PERCEPTION DEGRADATION AND REDUCED FRICTION

The analysis shows that even when equipped with optimal perception, an ADAS can avoid only up to 1.6% more accidents compared to an *already advanced ADAS* that incorporates friction estimation capabilities. This finding is significant because it highlights the diminishing returns of further improving perception alone, and it validates the major impact of including real-time friction estimation in ADAS performance.
Friction estimation directly enhances the system's ability to plan and execute safe maneuvers under varying road conditions, such as rain, snow, or ice scenarios where perception alone cannot infer the vehicle's actual physical limits. In contrast, optimal perception mainly enhances object detection and classification but does not fundamentally improve how the vehicle responds to surface-level challenges.
The marginal additional benefit of 1.6% shows that an advanced ADAS with friction awareness already addresses the major causes of residual accidents, and that closing the remaining safety gap through perception-only upgrades is increasingly inefficient. This validates the decision to prioritize friction estimation as a key component of advanced ADAS deliverables, offering a high return on complexity and cost relative to further perception improvements.
In conclusion, the deliverable demonstrates that systems integrating real-world physical modeling—like friction estimation—approach the performance ceiling of optimal perception systems, but with more practical and impactful safety gains.

2.4.6 CONTRIBUTION OF THE V2X

Annexes studies realized during the project have shown how the connectivity can be considered as an additional sensor to be used to prevent accidentology in AWC. Today, the use of V2X messages does not constitute sufficient conditions for the deployment of an AEB system. Indeed, the functional safety requirements are not yet incorporated into the standards governing the use of these messages.
There is already a large body of research on the use of onboard sensors (camera, radar, or lidar) for triggering AEB systems. A few studies explore the potential use of V2X for rear-end scenarios, but very few address intersection scenarios - which are the most promising for V2X. Benefits from V2X have also been proven by the re-simulation of the accidentology data: scenario simulations show that V2V communication enables the avoidance of an additional 12.5% to 13.8% of accidents compared to a standard ADAS alone.
This added value stems from V2V's ability to extend situational awareness beyond the line-of-sight and sensor range, especially in complex traffic scenarios like intersections, occluded environments, and multi-vehicle interactions. V2V communication enables vehicles to exchange intent, position, speed, and maneuver data in real-time - well before such events become visible or interpretable by onboard sensors.
Standard ADAS is inherently limited by sensor field of view, environmental conditions, and latency in perception. V2V overcomes these limitations by creating a shared perception layer,

which allows the system to anticipate hazards earlier and respond more effectively, particularly in high-risk, fast-developing scenarios.
The deliverable demonstrates that adding V2V capabilities unlocks a new class of preventable accidents, offering a meaningful safety enhancement with relatively modest infrastructure impact, especially as V2X deployments continue to grow. This position the V2V as a key enabler for the next generation of cooperative ADAS functionalities.

2.5 Simulation of Adverse Weather Effects on Perception Sensors

2.5.1 State of the Art, Measurement Evidence and Validation Guidelines

The Simulation Work Package of the WeatherSafe project addresses a critical challenge for automated and assisted driving systems: ensuring credible assessment of perception sensor performance under adverse weather conditions. Rain, fog, snow, hail and variable illumination fundamentally interact with camera, lidar and radar sensing through complex physical and signal-processing effects, which cannot be sufficiently explored through field testing alone. Simulation therefore plays a central role in scalability, safety validation and homologation-oriented assessment. However, the credibility of simulation hinges on its ability to reproduce measurable sensor behavior, not merely visually plausible weather effects.
The three Simulation deliverables form a structured and progressive body of work. Deliverable D_Simu.1 establishes the state of the art in adverse-weather simulation means and highlights key gaps. Deliverable D_Simu.2 provides measurement-driven evidence of how real sensors degrade under quantified weather conditions and translates these findings into performance-oriented modelling principles. Deliverable D_Simu.3 consolidates these insights into practical guidelines for sensor model validation, including reference data requirements, prioritization of weather effects, and uncertainty-aware metrics. Together, they define a coherent methodology that links experimental evidence, simulation modelling and validation practice.

2.5.2 State of the Art and Identified Gaps

The state-of-the-art review shows that significant progress has been made in representing weather phenomena within simulation environments. Academic research provides detailed physical models for scattering, attenuation and illumination effects, while open-source and commercial tools increasingly offer configurable rain, fog, snow and lighting conditions. ASAM OpenX standards already include descriptive parameters for weather and environment.
However, a consistent limitation emerges across these approaches: weather is predominantly represented at a descriptive or phenomenological level, with weak links to *quantitative sensor performance degradation*. Many simulation tools focus on visual realism or scene appearance, while the actual impact on sensor-level key performance indicators (KPIs) - such as detection probability, effective range, noise, uncertainty or false detections—remains insufficiently addressed. Validation of weather simulation is rarely demonstrated, and when it is, it often relies on visual comparison rather than metric-based evaluation against measured sensor data.
The review also highlights strong sensor-modality differences. Cameras, lidars and radars respond to adverse weather through fundamentally different mechanisms, making "generic" weather models inappropriate for perception validation. Recent standardization efforts, such

as DIN SAE SPEC 91571 for lidar testing in adverse conditions, signal an industrial shift toward performance-oriented evaluation, but these standards are not yet systematically integrated into simulation workflows. D_Simu.1 therefore concludes that future progress depends on tighter coupling between experimental testing, performance characterization, simulation modelling and standards.

2.5.3 Measurement-Based Performance Characterization

Deliverable D_Simu.2 addresses this gap by anchoring simulation modelling in measured sensor behaviour. Using the Persival Weather Test Bench, long-term stationary measurements were conducted during winter 2025/2026, capturing synchronized camera and four lidar sensors together with quantitative weather reference sensing (precipitation rate, illumination, meteorological optical range and extinction coefficient). The experimental design enables replay-to-sim validation and the derivation of performance curves linking sensor KPIs directly to weather severity.

The results reveal distinct degradation signatures depending on both weather type and sensor modality. For cameras, fog acts as a global visibility limiter: increasing extinction leads to a consistent reduction of image contrast across all targets, accompanied by increased mean intensity due to veiling luminance (air light). This behavior is monotonic and physically interpretable. In contrast, precipitation conditions (rain, snow and hail) do not show a comparable monotonic attenuation in the evaluated KPIs. Instead, they primarily increase variability, reflecting transient and spatially inhomogeneous effects such as streaks, occlusions, glare and reflections. Brightness further emerges as a confounding factor, as camera internal adaptation (e.g. auto-exposure and tone mapping) strongly influences contrasts involving dark references.

For lidar, degradation is strongly configuration-dependent, influenced by field of view, range class and operating wavelength. Fog again represents the dominant object-independent effect: with increasing extinction, target detection probability and intensity decrease at long range, while rotating lidars produce substantial atmospheric backscatter detections. Directional long-range lidars are robust in homogeneous fog but become susceptible in patchy fog, where clustered atmospheric detections can appear. Precipitation effects within the measured intensity ranges are more limited: rain and snow introduce little atmospheric backscatter and largely preserve target detections, while hail generates measurable atmospheric detections above roughly 10 mm/h without causing systematic range collapse. Across precipitation types, the defining signature is stochastic fluctuation rather than deterministic attenuation.

These findings motivate a performance-driven modelling approach. Fog should be parameterized by physically meaningful descriptors such as extinction coefficient or MOR and modelled through explicit attenuation and veiling or backscatter effects. Precipitation intensity in mm/h is shown to be an imperfect proxy and should be treated cautiously; precipitation effects are better represented as stochastic disturbance processes that increase variance and generate outliers rather than as simple attenuation curves. Importantly, the results underline that validation should focus on trend agreement and variability envelopes, not frame-by-frame equality.

2.5.4 Validation Methodology and Guidelines

Deliverable D_Simu.3 integrates the state of the art and experimental evidence into practical validation guidelines for weather-affected sensor models. Validation is framed as a lifecycle

activity embedded in continuous verification and validation (V&V), rather than a one-time comparison. Building on established VV&UQ literature and recent developments for active perception sensors, the deliverable proposes an iterative, staged validation methodology that explicitly separates potential failure causes.

A key contribution is the separation of validation levels: reference data validation, measurement and simulation data validation, scenario and parameter validation, and finally model validation. This structure avoids misattributing reference sensor errors or data-processing issues to model deficiencies. Validation is explicitly use-case dependent: a sensor model suitable for trend analysis may not be sufficient for safety argumentation, and this distinction must be documented.

To keep validation effort focused on WeatherSafe-relevant phenomena, the deliverable introduces a structured workflow based on PerCollECT and CEPRA. PerCollECT provides a comprehensive catalogue of perception sensor cause-effect chains, while CEPRA prioritizes these chains according to occurrence in the operational design domain and impact on the system under test. This ensures traceability from weather phenomena to concrete validation requirements and test cases and supports transparent scoping decisions.

Reference data quality is treated as a central prerequisite for credible replay-to-sim validation. D_Simu.3 consolidates minimum data categories—synchronized sensor outputs, scene and target geometry, quantitative weather reference sensing, timing and transforms, and structured metadata—and proposes practical plausibility and completeness checks before any comparison is performed. This addresses a frequent weakness in validation studies, where uncertainty in reference data dominates conclusions but remains undocumented.

For quantitative assessment, the deliverable adopts uncertainty-aware metrics from the Double Validation Metric (DVM) family, including the DVM map. These metrics explicitly separate systematic bias from scattering errors and make the influence of uncertain reference inputs visible. Complementing this metric-first perspective, D_Simu.3 also integrates a role-model-based environmental influence approach, where expectation-value KPIs derived from measurements (e.g. atmospheric detection probability per beam, attenuation curves) are used to calibrate and sanity-check individual weather effect modules before full metric-based validation.

2.5.5 Consolidated Conclusions and Outlook

Across the three deliverables, a consistent message emerges. Credible simulation of adverse weather effects on perception sensors requires a shift from descriptive weather rendering to performance-oriented, measurement-anchored modelling and validation. Fog, precipitation and illumination must be treated as quantitatively parameterized influences, with acceptance criteria based on trends, envelopes and uncertainty rather than deterministic equality. Sensor-specific and configuration-specific behavior is essential and cannot be abstracted away without loss of realism.

The WeatherSafe Simulation Work Package provides a structured blueprint for this transformation: a clear understanding of current capabilities and gaps, experimentally grounded performance characterization, and practical validation guidelines rooted in VV&UQ best practices. While limitations remain—such as limited coverage of extreme precipitation regimes and spatial mismatch between weather reference sensors and sensor fields of view—the methodology is explicitly designed to support iterative extension.

As additional measurement data and weather effects become available, the same framework can be applied to expand cause-effect coverage, refine prioritization, and strengthen acceptance criteria. In this way, the combined results of D_Simu.1, D_Simu.2 and D_Simu.3 lay a robust foundation for Weather Safe's final simulation assessment guidelines and

for future safety-oriented validation of perception systems operating under adverse weather conditions.

2.6 Reproducibility Study

2.6.1 Objectives and Context

The development and deployment of robust Advanced Driver Assistance Systems (ADAS) and Automated Driving (AD) functions critically depend on their ability to operate safely under adverse weather conditions. Rain, fog, glare, spray, and reduced road friction have been identified in previous WeatherSafe work packages as major contributors to accident risk and sensor performance degradation. Despite this, no harmonized or standardized framework currently exists for testing ADAS/AD systems under such conditions.
Deliverable D4.1–D4.2 addresses this gap by providing a comprehensive benchmark of existing testing infrastructures and tools capable of reproducing adverse weather phenomena. The primary objective is to assess what can currently be tested, where and how these tests can be conducted, and to what extent the results are repeatable and reproducible across facilities. The findings are intended to directly support the development of testing means specifications and assessment guidelines in subsequent WP4 tasks, and ultimately contribute to regulation- and NCAP-ready adverse weather test protocols.

2.6.2 Scope and Methodology

The study evaluates indoor and outdoor testing facilities within the WeatherSafe consortium and beyond, across Europe and Asia. It focuses on weather phenomena identified as critical in previous work packages: rain, fog, glare, spray, and related environmental side effects such as wet-road reflectivity and reduced friction.
The methodology combines several complementary approaches:

- Benchmarking through site visits and workshops at key facilities (UNIV-EIFFEL Sense-City, CARISSMA, CEREMA PAVIN, AstaZero).
- Analysis of partner testing campaigns involving multiple OEMs and suppliers (including Aptiv, Nissan, Denso).
- Review of published technical literature and publicly available facility specifications.
- Cross-correlation of test requirements against facility capabilities using a structured evaluation framework.

Facilities were assessed according to common criteria, including weather reproduction capabilities, controllable intensity ranges, stability and uniformity of phenomena, test speeds, measurement and ground-truth systems, availability of spray tools, and low-friction surfaces. A cross-correlation matrix was used to identify coverage, gaps, and overlaps between facilities.

2.6.3 Benchmark of Testing Facilities and Tools

The benchmark highlights a diverse ecosystem of testing infrastructures, each with specific strengths and limitations.
Indoor facilities (e.g. UNIV-EIFFEL, CARISSMA, CEREMA, MHI) provide the highest level of control over weather phenomena. They enable reproducible rain intensity, stabilized fog visibility, controlled glare illumination, and instrumented measurement of environmental parameters. These characteristics make them particularly suitable for sensor-level studies, comparison of

sensor degradation mechanisms, and repeatable testing under well-defined conditions. However, their physical dimensions impose strong constraints on achievable test speeds and scenario representativeness.
Outdoor proving grounds (e.g. AstaZero, IDIADA, UTAC, Michelin) offer high-speed driving capability, realistic vehicle dynamics, and natural spray and friction effects. They are indispensable for studying dynamic scenarios and real-world vehicle behavior, but they lack precise control over weather conditions and therefore offer limited reproducibility.
Dedicated spray tools (such as the Messring SprayMaker and the AstaZero Spray Rig) complement facilities by enabling artificial generation of water spray phenomena. These tools highlight that spray is not equivalent to rain and must be treated as a distinct test condition with its own parameters.

2.6.4 Sensor Performance Findings under Adverse Weather

The workshops and testing campaigns provide extensive experimental evidence of how adverse weather affects perception sensors.

Camera systems are consistently identified as the most vulnerable modality. Rain induces non-linear degradation: light rain has limited impact, medium rain leads to measurable distance and classification errors, and heavy rain can cause complete detection collapse, primarily due to water film formation on lenses and windscreens rather than rainfall in the air. Fog produces extremely severe degradation, with rapid contrast loss (often exceeding 90–99%) and extended periods of near-blindness. Glare frequently causes complete sensor saturation, rendering collected data unusable. Additionally, wet-road mirror effects generate false detections and misclassifications, especially for machine-learning-based algorithms.

Radar systems generally show robustness to illumination changes and fog, but the study demonstrates that this robustness is conditional. Medium rain intensities can generate more severe issues than heavy rain, including ghost detections and multipath reflections from wet surfaces. Radar performance is strongly influenced by the test environment itself; metallic walls, ceilings, and structural elements in indoor facilities introduce artefacts that are not representative of open-road conditions, highlighting the need for facility design adaptations such as radio-wave absorbers.

LiDAR systems are particularly sensitive to particle-based phenomena. Rain causes parasitic echoes from falling droplets, while fog generates characteristic "reflection rings" near the sensor, reducing usable detection range and distorting spatial distributions. LiDAR degradation depends not only on macroscopic parameters such as rain rate or fog visibility, but also on microphysical properties such as droplet size distribution.

Spray effects emerge as a distinct and under-characterized phenomenon. Heavy spray can render distance estimation unreliable for both radar and camera systems. Importantly, current ADAS functions often fail to classify spray correctly as rain or fog, exposing gaps in weather detection logic.

2.6.5 Reproducibility, Repeatability, and Key Limitations

The central focus of the deliverable is the distinction between repeatability and reproducibility. Repeatability - obtaining consistent results within the same facility using the same setup - is generally good for controlled rain and fog tests in indoor environments. By

contrast, reproducibility—achieving comparable results across different facilities—is currently not guaranteed.
Several factors limit reproducibility:

- Differences in rain generation systems and droplet size distributions (DSD).
- Variations in spray generation mechanisms and droplet dynamics.
- Facility-dependent infrastructure effects radar performance.
- Heterogeneous measurement tools and ground-truth systems.
- Limited availability of indoor positioning and control solutions for dynamic testing without GPS.

Space constraints in indoor facilities further reduce scenario representativeness, restricting dynamic tests mostly to low city speeds (typically below 30 km/h). This affects the validity of results for highway-relevant scenarios such as high-speed spray, glare at speed, or radar multipath effects on wet pavements.

2.6.6 Environmental Side Effects and the Role of Friction

Beyond direct sensor degradation, environmental side effects play a crucial role. Reduced road friction under wet conditions significantly affects vehicle dynamics and ADAS functions such as ABS, ESC, and traction control. Literature and project results confirm that wet surfaces can reduce friction by up to 60%, dramatically increasing accident risk.
While outdoor facilities provide realistic low-friction testing, indoor friction characterization remains underdeveloped. Combined testing of weather, perception, and vehicle dynamics is rare and lacks standardization, yet is essential for holistic ADAS validation.

2.6.7 Complementary Testing: Opportunistic Weather Measurements

To overcome limitations of facility-based testing, the deliverable introduces opportunistic weather testing as a complementary approach. Weather-station-based setups, such as the Persival system, enable simultaneous measurement of environmental parameters (rain intensity, DSD, fog visibility, illumination) and sensor performance during naturally occurring weather events.
This approach provides highly realistic validation data, capturing heterogeneity and combined phenomena that are difficult to reproduce artificially. Opportunistic testing is therefore positioned as a necessary bridge between controlled laboratory experiments and real-world operational conditions.

2.6.8 Key Recommendations

Based on the benchmark and testing results, the deliverable formulates several critical recommendations:

1. Define standardized rain classes that combine intensity ranges with droplet size distribution requirements.
2. Establish fog testing protocols based on measurable visibility (MOR) and droplet characteristics.
3. Redesign glare testing methods to remain realistic while avoiding complete camera saturation.
4. Integrate quantifiable friction characterization into adverse weather testing.
5. Standardize measurement variables and ground-truth systems across facilities.

6. Improve indoor radar test environments through infrastructure treatment (e.g. absorbers).
7. Use objective image-quality metrics such as camera MTF to assess performance degradation.
8. Combine controlled facility testing with opportunistic real-world validation.

2.6.9 Overall Conclusion and Path Forward

The reproducibility study demonstrates that current adverse weather testing capabilities are technically advanced but fragmented. While repeatable testing is achievable within individual facilities, cross-facility reproducibility and regulation-ready validation remain out of reach without harmonization.
No single facility can cover the full spectrum of adverse weather scenarios, sensor behaviors, and vehicle dynamics needs. A coordinated, multi-facility testing strategy supported by standardized weather definitions, measurement protocols, and complementary real-world testing is therefore essential.
The deliverable concludes that WeatherSafe provides a strong technical foundation for future standardization efforts. Moving forward, aligning facility capabilities, grounding test protocols in measurable physical parameters, and integrating perception and vehicle dynamics are key steps toward robust, reproducible, and certifiable ADAS testing under adverse weather conditions.

3. Define test protocol guidelines

3.1 Addressing the AWC Gap in Euro NCAP Safety Testing

Euro NCAP's current testing protocols, widely regarded as the benchmark for consumer vehicle safety evaluations, present a significant limitation in their ability to reflect real-world driving conditions. The standardized scenarios used to assess ADAS and AD functions are predominantly conducted in idealized environments—clear visibility, dry roads, and controlled settings. This methodology diverges sharply from the environmental complexity encountered on public roads, particularly AWC.
Empirical accident data from GIDAS and IGLAD clearly demonstrate that AWC—such as rain, wet / icy surfaces, and sun glare - are critical factors in both the causation and severity of crashes. Yet, for the sake of repeatability and comparability, current testing protocols are primarily conducted under optimal conditions. However, WeatherSafe provides new opportunities to evaluate and compare vehicle performance under non-nominal, real-world weather conditions. Euro NCAP nevertheless requires clear evidence of system performance in degraded environmental conditions. To address this, we propose a structured methodology that both refines these requirements and enables the implementation of dedicated verification tests under adverse weather conditions. In particular:

- Rain and wet surfaces, which account for a significant share of loss-of-control and rear-end collisions, are not systematically tested in emergency braking or lane-keeping assessments.
- Sun glare, identified as a contributing factor in 30% of AWC-coded crashes, is not replicated in visibility or perception tests, despite its strong impact on both human vision and sensor reliability.
- Snow and icy road surfaces, common in northern and central European countries, are completely absent from mainstream safety validation protocols.

- Non-urban loss-of-control scenarios—frequent in rural crashes under AWC—are underrepresented, despite being some of the most severe and technically challenging scenarios for both drivers and ADAS/AD systems.

This gap in testing introduces a systematic overestimation of vehicle safety performance under real-world driving conditions. Consumers are led to believe that highly rated vehicles are equally safe across all operational environments—an assumption not currently supported by testing evidence. As vehicle automation advances, and reliance on ADAS increases, this false sense of security becomes even more problematic.
From a regulatory standpoint, the absence of AWC in test scenarios represents a critical blind spot. Without accounting for weather-induced risks, existing safety frameworks cannot reliably certify system robustness or guide improvement priorities.
The current exclusion of AWC from Euro NCAP testing protocols undermines the credibility and completeness of consumer safety ratings. Given the substantial role that AWC play in serious crashes, integrating these variables is not a technical luxury—it is a strategic imperative for public safety, system accountability, and consumer trust.

3.2 Recommendation and Strategic Alignment

Recommendations for integrating adverse weather conditions (AWC) into future Euro NCAP protocols should be formulated and validated through a single, coherent argument: if consumer ratings are intended to represent safety in everyday driving exposure, then AWC must be addressed not as marginal "edge cases," but as systematic stressors that simultaneously degrade what the vehicle can perceive and what it can physically achieve.

Accidentology results in this report show that frequent, moderate conditions—wet road surfaces, rain-induced spray, low illumination, and sun glare—are over-represented in severe crash outcomes and in the scenarios where current ADAS/AD functions approach their limits. Strategically, this creates a credibility gap: vehicles may obtain high ratings under ideal test conditions while delivering materially different safety margins when visibility is reduced, road friction is degraded, or both occur together. The recommendation therefore aligns with Euro NCAP's mission by strengthening the external validity of the protocol (i.e., closeness to real-world risk drivers), improving transparency for consumers, and providing an incentive structure for manufacturers to invest in robustness rather than optimization to "clear-weather" test artefacts.

To make this alignment operational and auditable, validation should be structured along three complementary dimensions that map directly to the causal chain of weather-related crashes

- perception system robustness
- friction awareness and monitoring
- and the coupled performance of perception and friction in closed-loop decision-making.

First, for perception systems, the goal is not only to confirm that sensors continue to output detections, but to quantify how detection, classification, tracking stability and uncertainty evolve as a function of measurable and reproducible environmental parameters. This implies defining weather and illumination classes using physical descriptors already highlighted in the document (e.g., rain intensity and droplet-related proxies, fog expressed through visibility/MOR or extinction, and glare expressed through geometry and luminance/contrast conditions), and then linking them to perception KPIs that are meaningful for safety functions (probability of detection for relevant targets, false-positive/false-negative balance, range

and field-of-view reduction, latency to first detection, track drop-out rate, and calibrated uncertainty estimates). Such KPIs should be evaluated in scenario families that are accidentology-driven (e.g., intersection conflicts, stationary traffic, curve loss-of-control precursors where lane/edge perception is stressed) rather than being generic sensor benchmarks, because the strategic value of Euro NCAP testing lies in mapping performance to risk-relevant situations. Importantly, validation should capture not only mean performance but also variance and failure modes under compound influences (e.g., rain plus wet-road reflectivity plus low sun), since AWC frequently produce stochastic degradations (occlusion bursts, reflections, and clutter) that challenge decision thresholds.

Second, for friction monitoring and estimation systems, validation should recognize that road friction is a safety-critical state variable that governs the feasibility of any intervention. Re-simulation results summarized earlier indicate that, compared with perception-only improvements, friction awareness can deliver larger safety gains in representative scenarios because it directly constrains stopping distance, stability margins, and the friction-sharing trade-off between braking and steering. Therefore, the protocol should explicitly test whether the vehicle can detect, estimate, and appropriately react to reduced friction conditions—both current friction and, where feasible, upcoming friction changes—using measurable road-surface states (dry/wet/icy/contaminated), characterized through friction proxies or coefficients consistent with facility capabilities. Validation KPIs should include estimation accuracy (bias and variability versus reference), detection timeliness (how quickly a friction drop is recognized), robustness across manoeuvres (straight braking, combined braking/steering, acceleration), and—crucially—control adaptation outcomes (stopping distance relative to available friction, stability control effectiveness, and avoidance of excessive intervention that could cause secondary hazards). This dimension also supports a strategic pathway for Euro NCAP because it is technology-neutral: manufacturers may use different sensing and inference approaches (vehicle dynamics, perception-based inference, V2X/fleet data, hybrid methods), but the safety claim is judged on observable outcomes tied to physical limits.

Third, the coupling between perception and friction must be validated because the most safety-relevant AWC crashes emerge from their interaction rather than from either factor alone. In practice, degraded visibility increases uncertainty and delays hazard recognition (raising effective reaction time and inflating time-to-collision estimation error), while reduced friction simultaneously shrinks the set of achievable manoeuvres (lower deceleration, limited lateral acceleration, earlier saturation of the friction circle). A system that performs acceptably when only one dimension is stressed may still fail when both occur: for example, a late detection that is manageable on dry asphalt becomes non-recoverable on a wet or icy surface, and an aggressive evasive path that is feasible with high grip may become destabilizing when friction is low. Validation of this coupling should therefore be closed-loop and decision-centric: it should test whether the system maintains consistent, conservative-enough yet effective decision-making under combined sensing uncertainty and physical-limit constraints. Suitable KPIs include end-to-end safety outcomes (collision avoidance rate and residual impact speed), decision quality (intervention timing relative to evolving uncertainty, inappropriate late braking, oscillatory control), and "graceful degradation" behaviours (clear system fallback strategies, stable performance envelopes rather than abrupt cliff-edge failures). Methodologically, this implies designing test cases where the same conflict geometry is exercised across combinations of visibility and friction classes, allowing the protocol to identify interaction effects and to prevent optimization toward single-factor conditions.

Overall, validating recommendations through these three aspects creates a defensible roadmap for Euro NCAP evolution: start with measurable AWC classes and perception/friction KPIs that can be reproduced in controlled environments, then progressively integrate coupled, scenario-based acceptance criteria that reflect real exposure. This approach ensures that future ratings capture not only what the vehicle can "see" in adverse conditions, but also what it can physically "do," and whether its decisions remain safe when both are constrained—thereby improving consumer trust, supporting regulatory credibility, and aligning innovation incentives with the dominant real-world crash mechanisms under AWC.

3.3 SUPPORTIVE METHODOLOGIES FROM WEATHERSAFE

To support the integration of adverse weather conditions into ADAS/AD evaluation in a way that is both operational for industry and meaningful for consumer or regulatory assessment, WeatherSafe proposes a set of complementary methodologies that translate the project's accidentology and technical findings into actionable evaluation tools.

First, a WeatherSafe Ranking Method provides a safety-oriented analysis concept for ADAS/AD by structuring the assessment around the two dominant weather-driven limiters—perception and friction—and by assigning explicit weights to phenomena (e.g., rain, fog, glare, wet/icy surface) and to severity levels within each phenomenon, enabling transparent prioritisation of what should be tested first and with which relative importance.

Second, the WeatherSafe Minimum Visibility Threshold introduces a calibrated concept—primarily targeting ACC/LCA and other perception-driven functions—aimed at ensuring that the system can warn the driver whenever its expected performance may be insufficient for the current driving situation; this threshold is designed to be usable across the development cycle (system development and calibration), for HMI design, for the technical dossier, and for defining or justifying the ODD in L3 contexts, while being complemented by guidelines to assess vehicle behaviour under degraded friction using calibrated tracks and documented evidence.

Third, WeatherSafe proposes a guideline to assess vehicle behaviour in degraded friction that complements visibility-based criteria by addressing the physical limits of braking and lateral control on wet, icy, or otherwise contaminated surfaces. The guideline is intended to be documented in a dedicated dossier that makes the safety argument traceable and auditable: it records the assumed friction classes and their measurement method, the system's friction-detection or estimation logic (including limitations and confidence handling), the resulting adaptations in control and decision strategies (e.g., modified target deceleration, earlier interventions, stability protections and fallback strategies), and the verification evidence supporting these claims. To ensure repeatability, the guideline relies on calibrated tracks and controlled surface preparation, so that the achieved friction level is characterized before and during tests and can be reproduced across campaigns. This provides a practical "evidence chain" from friction characterization to expected system behaviour, to on-track verification outcomes, enabling consistent assessment of robustness when available grip is reduced and ensuring that performance claims remain valid beyond nominal dry conditions.

Lastly, an overall methodology for ADAS/AD assessment is proposed as an "open way of testing", combining a prediction dossier (expected performance and limitations under defined weather and surface conditions) with targeted verification testing, so that claims about robustness are systematically checked against measurable outcomes across both perception and friction dimensions.

Together, these methodologies form a coherent bridge between scenario selection, calibration and documentation, and on-track verification, thereby enabling traceable, repeatable and safety-relevant assessment of ADAS/AD performance under adverse weather.

3.3.1 WeatherSafe Ranking Method

The WeatherSafe Ranking Method adopts a risk-ranking logic inspired by the Functional Safety standard *ISO 26262* and the Safety of the Intended Functionality standard *ISO 21448*, transferring the notion of exposure-based prioritisation to adverse weather conditions.
In this approach, the relevance of a given weather phenomenon and severity level is quantified by combining (see Figure 4-1)

- Exposure to a weather condition category, i.e., the probability that a vehicle is operating in a broad AWC class such as rain, derived from European and national meteorological datasets;
- the Probability of condition, which refines the assessment to a specific intensity band within the category (e.g., precipitation between 2 and 6 mm/h), again estimated from weather statistics;
- a Correction factor capturing the disproportional safety impact of that condition, defined as the ratio of accident occurrence under adverse weather relative to benign conditions and informed by national crash statistics and in-depth accident studies;
- a Driver attentiveness and special care factor, accounting for behavioural adaptation under AWC (drivers tend to reduce speed and increase caution as conditions worsen), which can be estimated from naturalistic driving studies and applied as a multiplicative moderation (e.g., normal = 1, beyond normal = 0.5, severe = 0.2 based on how drivers perceive the conditions).

By integrating these four elements, the method provides a transparent, data-grounded way to weight phenomena and their severity levels, ensuring that testing priorities and assessment criteria reflect not only how often conditions occur, but also how strongly they amplify crash risk and how human behaviour changes in response.



Figure 3-1 WeatherSafe Ranking Method Application

Figure 4-2 illustrates how the method applies to ADAS perception features. Statistical weather data determined exposure and probability of AWC conditions, while KSI correction factors were based on accidentology studies. The analysis identifies sun glare, rain up to 6 mm/h, and fog with visibility under 20 m as the most critical scenarios.

	Exposure to weather condition	Probability of AWC condition	KSI Correction factor due to adverse weather condition based on Accidentology	Driver become careful/special treatment due to adverse weather condition especially under severe exposure None Special Care (SC): 1, Medium Care 0.5, SC 0.2	Evaluation (KPI) Limit TBD
Perception related					
benign (no rain no fog... good)					
Glare					
Sun glare	0.935	0.083	2	0.5	0.078
None glare	0.935	0.917	1	1	0.857
Rain					
<2 mm/h	0.04	0.6239	2	1	0.050
2<x<6 mm/h	0.04	0.3258	2	1	0.026
6<x<10 mm/h	0.04	0.0288	3	0.5	0.002
10<x<20 mm/h	0.04	0.014	4	0.2	0.000
20<x<40 mm/h	0.04	0.0052	5	0.2	0.000
>40 mm/h	0.04	0.0023	10	0.2	0.000
Fog (visibility) entire duration - cumulative					
No road affection above 400 m by visibility	0.015	0.4	2	1	0
400<x<201 m	0.015	0.4	1.5	1	0.009
200<x<101 m	0.015	0.31	3	1	0.0140
100<x<21 m	0.015	0.24	8	0.5	0.0144
<=20 m	0.015	0.05	10	0.2	0.0015
Snow (melted snow equivalent) (~15d/yr exposed to snow)				1	
< 1mm/h (light) ~ 1-2cm/h	0.01	0.8	2	0.5	0.008
1<x< 5 mm/h (medium) 1- 20 cm/h	0.01	0.1	5	0.2	0.001
>5mm/h (strong) >20 cm/h	0.01	0.1	10	0.2	0.002

Most critical use-case: KPI inside the percentage area

Figure 3-2 Application of the method to ADAS feature - perception

If we conduct the exercise to assess the visibility of AD features, the "driver careless" case can be omitted since it does not affect the activation of these features, as illustrated in Figure 4-3. However, the conclusions regarding the most critical use cases remain largely unchanged.

	Exposure to weather condition	Probability of AWC condition	KSI Correction factor due to adverse weather condition based on Accidentology	Evaluation (KPI) Limit TBD
Perception related				
benign (no rain no fog... good)	0,935			
Glare				
Sun glare	0,935	0,083	1,2	0,0935
None glare	0,935	0,917	1	0,8571
Rain	0,04			
<2 mm/h	0,04	0,6239	1	0,02496
2<x<6 mm/h	0,04	0,3258	1	0,01303
6<x<10 mm/h	0,04	0,0288	1,2	0,00138
10<x<20 mm/h	0,04	0,014	1,2	0,00067
20<x<40 mm/h	0,04	0,0052	1,2	0,00025
>40 mm/h	0,04	0,0023	1,2	0,00011
Fog (visibility) entire duration - cumulative	0,015			0,00000
No road affection above 400 m by visibility	0,015		1	0,00000
400<x<201 m	0,015	0,4	1	0,00600
200<x<101 m	0,015	0,31	1,3	0,00605
100<x<21 m	0,015	0,24	1,4	0,00504
<=20 m	0,015	0,05	2	0,00150
Snow (melted snow equivalent) (~15d/yr exposed to snow)	0,03			
< 1mm/h (light) ~ 1-2cm/h	0,03	0,8	1,2	0,00960
1<x< 5 mm/h (medium) 1- 20 cm/h	0,03	0,1	1,2	0,0012
>5mm/h (strong) >20 cm/h	0,03	0,1	1,3	0,0013

Most critical use-case: KPI inside the percentage area

Figure 3-3 Application of the method to AD feature - perception

A unified friction-impact approach is used for both ADAS and AD, with system-specific risk mitigation shown at the KSI level. Results must be based on consistent data, as shown in Figure 4-4.

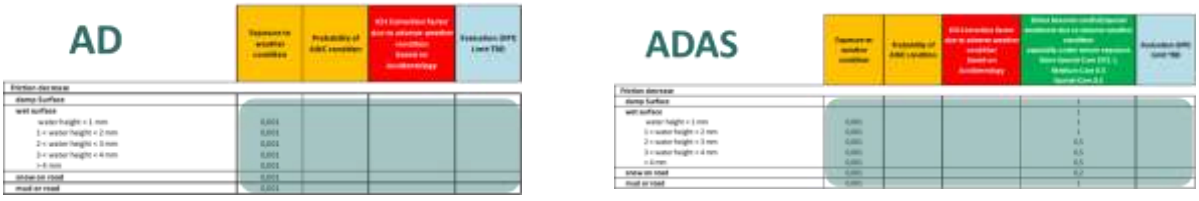


Figure 3-4 Application of the method for friction

In conclusion, the proposed WeatherSafe Ranking Method operationalizes these concepts through a KPI-based framework intended to support consistent assessment across weather phenomena, with a remaining key step being the definition of the final acceptance threshold. Based on current calibration work, a value on the order of 0.01 is proposed as an initial reference to distinguish acceptable from insufficient performance under the considered conditions.
When the KPI is applied outside the system ODD, the evaluation should not be limited to the KPI value alone: the expected safety response (e.g., a driver take-over request for automated functions, deactivation strategies, or other risk-mitigation means) should be explicitly assessed and, importantly, documented in the corresponding dossier so that system limitations and fallback behaviours are transparent and traceable.
Finally, the KPI decomposition can be used not only for scoring but also for diagnosis, since dedicated KPI factors may indicate proximity to, or exceedance of, physical limits—for instance when available surface friction is insufficient to achieve the demanded braking or lateral manoeuvre—thereby helping distinguish perception-driven degradation from controllability-driven constraints and guiding targeted improvements.

3.3.2 WeatherSafe Minimum Visibility Threshold

The Minimum Visibility Threshold (MVT) assessment is proposed as a standardized verification method for ADAS/ADS to prevent critical "false negative" situations in which automated driving continues even though environmental perception is no longer sufficient for safe operation.
The objective is to ensure that the system can detect and declare its own perception degradation *before* reaching the physical limits of the sensors and thereby operating outside the vehicle's Operational Design Domain (ODD).
Practically, the test can be performed in a controlled environment (e.g., rain/fog chamber) to maximize repeatability: the system is initialized under nominal clear conditions and the visibility is progressively reduced—typically by increasing fog density (g/m³) to lower the effective visibility range—until the system triggers a sensor-failure state, issues a limitation warning, or disengages.
The key measurement is the distance (or range) at which this transition occurs. Pass/fail criteria are then defined relative to the current speed and the associated minimal stopping distance:

- 4the assessment is passed if the system initiates a timely transition (e.g., take-over request/driver handover or automated disengagement) while the sensors still provide functional perception at a distance greater than the minimal stopping distance;
- it is failed if the system remains active despite perception degradation such that the remaining functional detection range falls below the minimal stopping distance.

Overall, robust ADAS/ADS should be able to identify when perception falls below the MVT, recognize that it is outside its ODD, and trigger an appropriate, verifiable fallback—providing a clear and reproducible way to test and document this safety-critical capability.

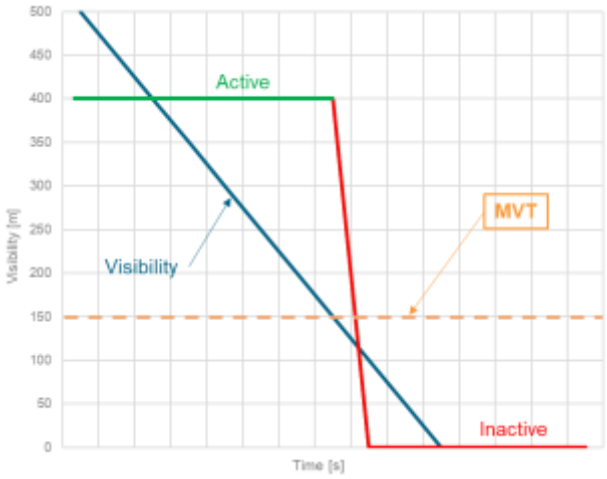


Figure 3-5 Principle of the MVT method

Example of the application of the method is shown in Figure 4-6.
Determining whether a "System Unavailable" situation is safe or unsafe can be challenging. For ADAS, it typically means lower consumer value but increased technical safety. In contrast, for ADS, it may signify failure to meet the required operational design domain (ODD).

Safety Level	Category	Behavior Description	Evaluation / Assessment
5	**Robust & Safe**	Brake initiation is **earlier** than Dry (Baseline). Behavior is **smooth/stable**.	Indicates system correctly accounts for reduced friction [μ] and sensor noise.
4	**False Positive (Unstable)**	Brake initiation is **earlier** than Dry (Baseline). Behavior is **erratic**. (e.g., Brake → Release → Brake...)	Unpredictable behavior creates secondary risks.
3	**Physics Failure**	Brake initiation is **same** as Dry (Baseline), but collision occurs.	Sensor is robust, but control logic failed to account for reduced friction [μ].
2	**System Unavailable**	System disengages ("Gives up") before or during test.	Functionality is lost. Equivalent to having no ADAS.
1	**False Negative**	Brake initiation is **later** than Dry (Baseline).	Indicates sensor failure or lack of safety margin.

3.3.3 GUIDELINE TO ASSESS VEHICLE IN DEGRADED FRICTION CONDITIONS

3.3.3.1 Dossier

Under the degraded-friction guideline, the dossier should comprehensively articulate how systems dedicated to monitoring and estimating tire–road friction constitutes a foundational enabler for the continuous adaptation of longitudinal support functions to the effectively available grip, thereby ensuring that automated interventions remain both timely and proportionate to prevailing surface conditions. In real-world operation, accurate and up-to-date friction awareness is not a theoretical enhancement but a practical necessity, as it directly conditions the effectiveness of Automatic Emergency Braking (AEB) and Adaptive Cruise Control (ACC) functions. Specifically, reliable friction estimation supports optimized AEB triggering thresholds and intervention timing, reducing the risk of delayed or insufficient braking responses under low-μ conditions, while simultaneously enabling ACC to adopt more conservative, stable time-gap and inter-distance strategies when stopping distances increase on wet, icy, or otherwise contaminated road surfaces.
Within this context, the dossier must present substantiated evidence addressing both the provenance and the performance of friction-related inputs, demonstrating that the system possesses a robust and validated understanding of available grip across a representative

range of environmental and operational scenarios. This includes, where technically feasible, the use of direct or quasi-direct measurements of the friction coefficient, obtained via dedicated sensing or measurement technologies, as well as indirect estimation approaches derived from vehicle dynamics and perception-based cues.
Vehicle-centric estimation methods typically rely on the continuous analysis of standard onboard sensor data—such as wheel speed differentials, longitudinal and lateral acceleration, steering angle, torque requests, and braking behaviour—to infer the tire–road interaction envelope through model-based algorithms and signal processing. In parallel, perception-driven techniques may leverage camera-derived road-state classification to identify surface conditions such as wetness, snow, ice, or contamination, which can then be mapped to friction hypotheses or used to contextualize dynamics-based estimates.
The dossier may further reference established third-party solutions that exemplify mature approaches in this domain, provided their role within the system architecture is clearly defined. For instance, Vaisala Xweather delivers high-resolution, real-time and forecasted weather intelligence by aggregating diverse data sources, including radar, satellite imagery, lightning network data, IoT sensors, and numerical weather prediction models, and applying advanced analytics and quality control to produce decision-ready datasets. When integrated appropriately, such external weather intelligence can enrich onboard friction assessment by supplying anticipatory and contextual information on precipitation, temperature, and surface contamination risks along the vehicle's route, thereby supporting proactive adaptation of longitudinal control strategies before critical manoeuvres are required.
Conversely, NIRA Dynamics represents a vehicle-centric friction estimation paradigm, in which continuous assessment of available grip is achieved solely through the interpretation of standard in-vehicle sensor signals, without reliance on additional hardware, enabling scalable deployment across vehicle fleets.
The dossier should clarify whether friction inputs are sourced from a single method or from a fusion of internal and external data, and should document the expected accuracy, latency, update rate, and operational design domain of each contributing source, as well as known limitations under edge cases such as very low excitation driving or rapidly changing surface conditions.
Equally important, the dossier must explicitly describe how these friction-related inputs are propagated into, and utilized by, the control and decision layers governing AEB and ACC functionality. This includes a clear explanation of how estimated or inferred friction values influence braking authority limits, deceleration profiles, trigger thresholds, target following distances, and fallback strategies, as well as how uncertainties in friction estimation are managed through safety margins or conservative assumptions.
By demonstrating a transparent and traceable linkage from friction sensing and estimation through to longitudinal control adaptation, supported by credible data sources and algorithms, the dossier can substantiate that the system is capable of maintaining safe and predictable behaviour under degraded-friction conditions, in alignment with the intent of the guideline and with real-world operational demands.

3.3.3.2 Calibrated test track

The use of calibrated test tracks remains a cornerstone of validation strategies for advanced driver assistance systems, particularly when assessing longitudinal control performance under degraded conditions; however, their capabilities and limitations must be explicitly acknowledged and argued within the dossier.
Calibrated tracks provide a controlled, repeatable, and instrumented environment in which key parameters—such as surface friction, vehicle speed, target positioning, and timing—can be tightly managed, thereby enabling precise benchmarking of system behaviour. This level

of control is especially valuable when introducing degraded-perception opportunities, as it allows engineers to isolate specific effects, such as reduced sensor performance due to spray, glare, or surface reflectivity, without the confounding variability inherent in open-road testing. The intentional addition of degraded-perception conditions on track, for example through artificial wetting, controlled water spray, or low-contrast target setups, can therefore be justified as an effective means to stress perception and decision-making chains in a safe and repeatable manner. Nevertheless, the dossier should argue that such conditions, while representative, are inherently simplified abstractions of real-world complexity and must be interpreted accordingly.

In practice, wet-grip tracks are commonly employed to emulate low-μ scenarios relevant to safety-critical functions such as AEB and ACC, yet their physical dimensions often impose nontrivial constraints on scenario coverage. Many dedicated wet handling or braking tracks are limited in length—on the order of a few hundred meters, such as the approximately 200 m wet-grip facilities available at sites like UTAC—which directly restricts the range of approach speeds, steady-state phases, and perception horizons that can be exercised. Consequently, while certain scenarios, such as Car-to-Car Rear stationary or braking (CCRs), can be realized with acceptable fidelity, others that require longer detection ranges, extended adaptation phases, or gradual friction transitions cannot be fully reproduced. This limitation is particularly relevant for ACC assessments, where realistic evaluation of time-gap adaptation under degraded friction would ideally involve long, steady following phases and progressive deceleration, which may exceed the available track length. The dossier should therefore argue that calibrated wet tracks are well suited for validating specific trigger points, control responses, and minimum performance thresholds, but are not sufficient on their own to demonstrate comprehensive system robustness across the full operational design domain.

Another intrinsic limitation of calibrated tracks lies in detection time and localization realism. On short tracks, the available detection window between target appearance and intervention is often compressed, resulting in scenarios that are perception- and control-critical but temporally constrained. While this can be advantageous for stressing worst-case response times, it may not accurately reflect real-world driving, where perception systems benefit from longer observation periods, richer contextual cues, and gradual buildup of confidence.

Furthermore, target positioning and ego-vehicle localization on track are typically achieved with high-precision reference systems, which, although necessary for validation accuracy, can mask uncertainties present in series-production localization and perception stacks. The dossier should therefore make the case that results obtained under such idealized positioning conditions must be interpreted with caution, particularly when extrapolating to real traffic environments where localization errors, map inaccuracies, and sensor dropouts may coexist with degraded friction.

Within this constrained yet controlled framework, the use of a reference tire—such as the Standard Reference Test Tire (SRTT)—to characterize and verify track friction is a critical methodological element that strengthens the validity of test results. Employing the SRTT allows the friction level of the wetted surface to be quantified in a standardized and reproducible manner, providing an objective baseline against which vehicle behaviour and system responses can be assessed. The dossier should argue that this practice is essential to ensure traceability and comparability across test campaigns, vehicles, and sites, particularly when degraded-friction performance is scrutinized by regulatory or assessment bodies. At the same time, it should be acknowledged that SRTT-based friction measurements represent an idealized reference condition and may not fully capture the interaction between production tires and heterogeneous real-world surfaces, where rubber compounds, tread patterns, contamination, and temperature effects introduce additional variability.

In summary, calibrated tracks with wet-grip capability offer a defensible and necessary test environment for evaluating system performance under degraded friction and perception conditions, provided their role is clearly framed within the overall validation strategy.
The dossier should argue that such tracks are best positioned as precision tools for controlled, repeatable assessments of specific scenarios—such as CCRs under low-μ conditions, AEB trigger timing, and immediate control response—while explicitly recognizing their limitations in terms of dimensional constraints, scenario diversity, detection time realism, and environmental complexity. By combining rigorous friction characterization using reference tires like the SRTT with a transparent discussion of what calibrated track testing can and cannot demonstrate, the dossier can present a balanced, technically credible argument that supports the use of these facilities without overstating their representativeness of real-world driving.

3.3.4 Overall methodology for ADAS / AD assessment

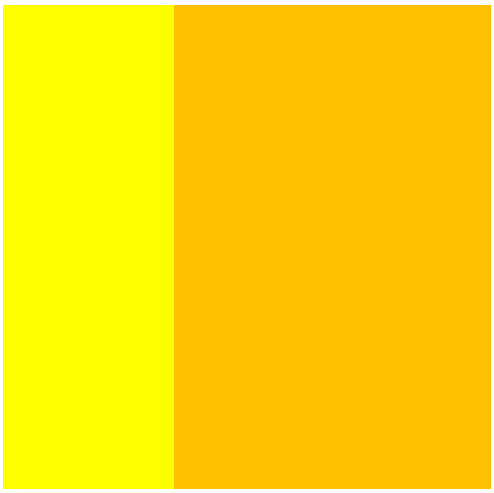
The ADAS/AD assessment methodology shall explicitly consider the compromise between system performance and robustness under varying environmental conditions.
In particular, wet-road scenarios represent a critical use case, as braking strategies calibrated for dry-road conditions are no longer sufficient: at a speed of 60 km/h, braking distances increase by approximately 6 m on wet surfaces, even with good-quality tyres, and collision avoidance requires braking to be initiated roughly 40% earlier than in dry conditions.
While adopting systematically earlier braking or warning thresholds improves robustness and safety in low-friction situations, such conservative strategies also increase the likelihood of unnecessary interventions in nominal conditions, potentially leading to driver annoyance, reduced trust, and behavioural adaptation, including system deactivation.
Therefore, the assessment shall not only verify safety performance and residual collision risk across different road friction levels, but also evaluate the operational and human-factor impacts of adaptive braking and warning strategies. The objective is to characterise and justify an acceptable balance in which sufficient safety margins are ensured in degraded conditions without disproportionate degradation of system performance or user acceptance.
The assessment of ADAS/AD performance under Adverse Weather Conditions (AWC) shall aim to demonstrate improved system capabilities in critical AWC scenarios without introducing negative impacts in nominal, non-AWC driving conditions. This requires targeted evaluation of perception and braking performance under representative AWC cases, complemented by long-term on-road data analysis to capture operational side effects such as driver annoyance and unintended system interventions.
A key challenge lies in predicting system capabilities under AWC and in objectively comparing observed AWC performance against expected behavior in normal conditions, given the inherent variability of environmental factors. Additional difficulties include the measurement and control of critical scenarios under test-track conditions, the reproducibility of on-road AWC exposure, and the consistent annotation of user annoyance and acceptance metrics.
Consequently, the methodology must combine controlled testing and real-world monitoring to ensure that robustness improvements for AWC are achieved without degrading overall system performance or user trust.
Predicting ADAS performance under Adverse Weather Conditions (AWC) requires a combination of complementary evaluation approaches, as no single method provides sufficient control, realism, and statistical coverage.
Controlled AWC testing enables repeatable and reproducible assessment of perception and braking performance under well-defined boundary conditions, supporting benchmarking and root-cause analysis, but remains limited in its ability to represent the variability and complexity of real-world AWC.

Opportunistic test-track evaluations conducted under naturally occurring adverse weather offer increased realism and allow safe execution of critical maneuvers; however, they suffer from limited availability, partial controllability, and reduced comparability across campaigns. Field operational testing on public roads provides the highest level of operational representativeness and is essential for capturing rare scenarios as well as user-related effects such as annoyance and trust, but it offers limited repeatability, constrains testing of critical situations, and requires significant effort for data annotation and performance extraction. Consequently, a robust methodology for predicting ADAS performance under AWC shall combine these approaches to balance controllability, realism, and confidence in performance assessment.

Different sources of evidence can be summarized as in the table below:

Type of performance evaluation	Description	AWC capabilities	Possible use cases	Expensive or difficult to access	Accurately measured conditions	Real world performance
Calibrated test track & facilities	Most useful and used for ADAS testing: the test track has standardized geometry and environmental conditions are mastered	Widely existing for dry/clear environmental conditions, specificities for AWC testing lead to **additional infrastructures** or mobile devices capable of generating **accurate** conditions such as water spray or damp surface with a known visibility and/or friction.	Almost all standardized situations are achievable under dry/clear conditions to test critical use cases. Though additional test means such as weather tunnels or wet grip track have a **limited space** which limits the feasibility of high speed test, multi target, crossings…			
Test track under opportunistic conditions	Widely used for ADAS assessment under nominal dry conditions but their use can be extended when naturally exposed to AWC	Most all of the test tracks are outdoor so can be naturally submitted to AWC **which have to be accurately measured** (friction, visibility)	Same standardized use cases than in dry/night condition but under "natural" AWC			
Real world / Open road testing	While testing the vehicle on road, many situations may occur with potential chance of encountering AWC. Purpose is to be capable to estimate the AWC impacts on environment and then estimate the ADAS performances under non-critical circumstances.	During ADAS on road testing, systems are exposed to real world **non-controllable AWC**.	All **non-critical** use cases can be encountered depending on the length of the drive.			

Simulation	Purpose is to generate situations based on synthetic datasets to estimate ADAS performance. The simulation toolchain must be correlated to real world on accurately measured situations	AWC can be generated but the correlation on critical cases still needs to be improved (all types of sensors)



Based on these multiple possible methods for evaluating the performance of an ADAS under AWC, several combinations of differently sourced evidence may be constitutive of an overall assessment. We can summarize how beneficial these evaluation methodologies could be in the following table:

	Assessment	
Type of performance evaluation	**Dossier / evidence of performance**	**Verification of performance**
Controlled conditions/ calibrated test tracks & facilities	Dossier from manufacturer to bring evidence of the performance under various but controlled conditions (e.g. weather tunnel) & support for synthetic dataset elaboration, including under extreme AWC. Various levels of AWC controlled disturbances may be supportive to demonstrate the maximum level of supported performances.	Generated and controlled conditions may vary from one facility to another and may be well adapted to system design but may lack repeatability for comparing systems to each other or verifying a minimum level of performance. Though, these types of evidence may be useful for spot checking some cases difficult to encounter.
Opportunistic testing on tracks	Manufacturer or system provider may verify and use the results for demonstration of the performance in critical situations (imminent collision) when AWC occurs. Such demonstration shall come with a proper measurement of the intensity of the actual AWC. Various AWC situations may be supportive to determine evolution of performance when systems face different level of intensities.	When AWC situation occurs during verification of performance, the robustness of the system may be compared to predicted behavior or a minimum expected performance. Such verification relies on an accurate measurement of the actual test conditions to properly compare to predictions, to other systems and to know how far from the nominal conditions the tested system was.
On-Road / FOT	Validation drives are part of the development cycle during which AWC are encountered. Average AWC intensity can be estimated and may be complemented by accurate on-board ground truth systems. No critical cases are expected to be encountered, therefore, mainly sensors and perception capabilities can be demonstrated.	A shortened on-road drive may support assessor for verification in non-critical cases under AWC. AS for dossier construction, the difficulty stands in the evaluation of AWC intensity, the low occurrence of heavy AWC and since no imminent collision may be encountered, only early intervention or warnings may support a check overview (e.g. sun glare on wet road…)

ADAS/AD performance in adverse weather conditions (AWC) can only be fully leveraged through a tri-dimensional approach that simultaneously considers the friction coefficient, the visibility degradation (under fog or rain), and the vehicle speed. Predictions can easily be translated following this methodology as so relevant verifications procedures associated to minimum performance thresholds. Indeed, adverse weather not only degrades sensor perception (camera, radar, LiDAR) but also alters road friction and visibility, directly impacting system reliability and decision-making. A holistic framework integrating these three dimensions enables a more accurate assessment of real-world performance, as it captures both technological limitations and contextual influences, while aligning with the systemic nature of ADAS, which inherently relies on the interaction between driver, vehicle, and surrounding environment.

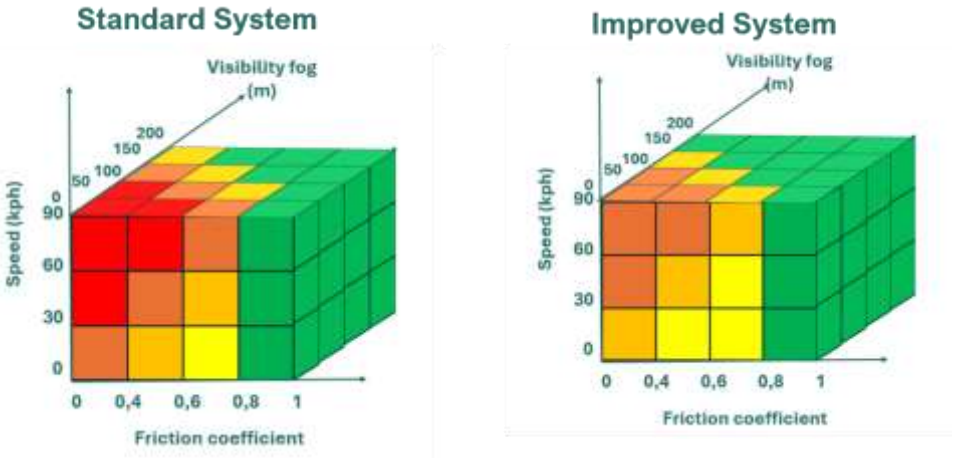


Figure 3-6 ADAS / AD performances with fog poor visibility could be fully leveraged using a such tri-dimensional approach

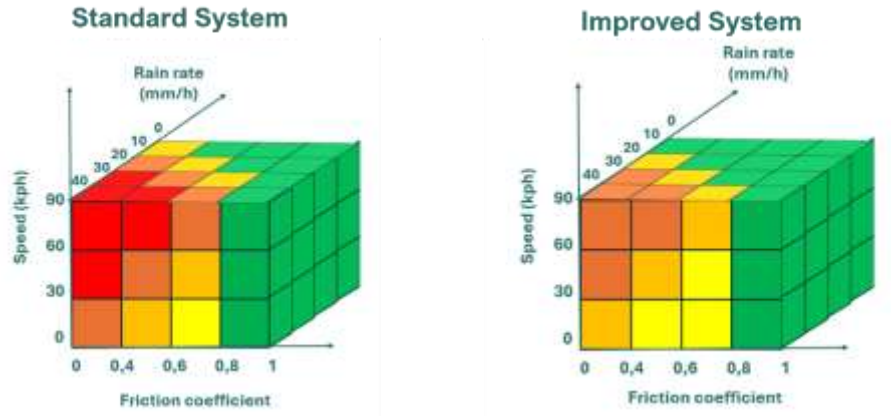


Figure 3-7 ADAS / AD performances with rain poor visibility could be fully leveraged using a such tri-dimensional approach

Conclusions

This document has established a structured and evidence-based framework for the assessment of ADAS and AD systems under Adverse Weather Conditions (AWC), addressing both technical performance and operational robustness. AWC represent a critical challenge for automated driving functions, as they directly affect perception reliability, vehicle dynamics, and system decision-making, while simultaneously increasing the safety expectations placed on these systems. As demonstrated throughout this work, performance validated solely under nominal conditions is insufficient to ensure safe and acceptable behavior in real-world operations, where degraded environmental conditions are both frequent and difficult to predict.

A central conclusion is that ADAS and AD systems must be evaluated not only for their peak performance in favorable conditions, but also for their ability to maintain adequate safety margins under degraded friction, visibility, and sensor performance. Wet-road braking has been used as a representative example to illustrate that system strategies calibrated for dry conditions can lead to insufficient deceleration margins and collision risk unless braking or warning thresholds are adapted. However, the document has also highlighted that systematically conservative strategies—such as uniformly earlier braking or warnings—may introduce negative side effects, including driver annoyance, reduced trust, and behavioural adaptation. This underlines the necessity of explicitly addressing the performance versus robustness trade-off as a core element of any ADAS/AD assessment methodology.

The analysis further demonstrates that predicting system performance under AWC cannot rely on a single evaluation method. Controlled AWC testing provides the repeatability and boundary condition control required for performance characterization, regression testing, and root-cause analysis, but it is inherently limited in its ability to reflect the diversity and variability of real-world conditions. Opportunistic test-track testing under natural adverse weather conditions offers a valuable intermediate step, enabling realistic and safety-controlled testing of critical scenarios, albeit with limited predictability and statistical coverage. Field operational testing on public roads remains indispensable for capturing operational representativeness, rare or mixed-condition scenarios, and user-related effects such as annoyance and trust, despite its low controllability and high data processing effort. The document therefore concludes that a combined and complementary use of these approaches is essential to achieve a credible and comprehensive assessment of ADAS/AD robustness under AWC.

Another key outcome of this work is the recognition that human factors must be treated as an integral part of system assessment rather than as a secondary consideration. Improvements in

robustness under AWC that lead to excessive false interventions or degraded comfort in nominal conditions risk undermining user acceptance and long-term system effectiveness. Consequently, the assessment methodology must incorporate mechanisms to observe, measure, and annotate user reactions, including annoyance, trust degradation, and potential system disengagement. Long-term on-road monitoring, supported by structured annotation frameworks, is therefore a necessary complement to technical performance testing.

From a methodological perspective, this document provides a foundation for harmonized assessment procedures that can support both development-phase validation and higher-level safety argumentation. By explicitly linking environmental conditions, system behavior, safety margins, and user acceptance, the proposed approach enables a more transparent justification of design choices and operating points. This is particularly relevant in the context of increasing automation levels, where system behavior must remain predictable and acceptable across a wide range of environmental conditions without relying on continuous driver compensation.

In conclusion, ensuring safe and acceptable ADAS/AD operation under AWC requires a shift from condition-specific performance validation toward a more holistic, environment-aware assessment paradigm. Such a paradigm must balance safety, robustness, and user acceptance, while acknowledging the inherent uncertainties of real-world weather conditions. The methodologies and arguments presented in this document contribute to this objective by outlining a structured approach to AWC assessment that is technically rigorous, operationally relevant, and aligned with the practical constraints of testing and validation. Future work should build upon this foundation by refining metrics, improving AWC detection and classification, and further integrating real-world operational data into the assessment process, thereby strengthening confidence in ADAS and AD systems deployed in all-weather conditions.

4. Acknowledgements

The WeatherSafe project would like to acknowledge for their support and work all the Partners and Third Parties involved:



5. Table of illustrations

Figure 2-1: Multifactorial influence of AWC on the accidentology from GIDAS Database..... 9
Figure 2-2 Top 5 real-world AWC critically scenarios 10
Figure 3-1 WeatherSafe Ranking Method Application 32
Figure 3-2 Application of the method to ADAS feature - perception..... 33
Figure 3-3 Application of the method to AD feature - perception 33
Figure 3-4 Application of the method for friction 33
Figure 3-5 Principle of the MVT method..... 35
Figure 3-6 Example of performance prediction..... 42
Figure 3-7 ADAS / AD performances with fog poor visibility could be fully leveraged using a such tri-dimensional approach 42
Figure 3-8 ADAS / AD performances with rain poor visibility could be fully leveraged using a such tri-dimensional approach 43