WEATHERSAFE

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

Deliverable D_Simu.1

Summary of the state of the art in simulation of adverse weather effects in perception sensors

Project Name	WeatherSafe	
Dissemination level	Consortium	
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Issue date	26/05/2026	
Reviewer	Pierre Duthon, Amine Ben-Daoued, Sebastien Liandrat, CEREMA	
Keywords	Adverse Weather, Simulation, Lidar, Radar, Camera	
Version	2.1	

EXECUTIVE SUMMARY

Report that summarizes the state of the art (T_Simu.1) and the prospect of simulation means able to reproduce adverse weather conditions.

It is a collection of the state of the art in research, in open-source and commercial simulation tools, as well as in the ASAM OpenX standards for simulation.

Overview of the whole WP Simulation and the planned tasks:

Task	***Description***
T_Simu.1	State of the art: review of existing European simulation means, studies and works dealing with adverse weather conditions in road safety based on PerCollECT.
T_Simu.2	Adverse weather conditions simulation: based on the work in WP1 and WP2, possibilities for implementing relevant weather effects in sensor simulation are demonstrated.
T_Simu.3	Validation of weather effect modelling: comparison of real and synthetic sensor data with weather influence based on a case study.
T_Simu.4	Simulations' assessment guidelines: Constitute and promote a list of recommendations to evaluate different aspects of the simulation of adverse weather, such as physical-numerical correlation and methodologies as addon for WP3.

The work package results are summarized in three deliverables:

Task	***Description***
D_Simu.1	Report that summarizes the state of the art (T_Simu.1) and the prospect of simulation means able to reproduce adverse weather conditions. Results from the comparison between real and synthetic sensor data with weather influence based on a case study.
D_Simu.2	It reviews discussions, works and outputs of T_Simu.2 and T_Simu.3. Especially the methodologies, parameters and requirements needed to simulate adverse weather conditions. It will include the description of the variables usable to play a scenario and sensor perception levels.
D_Simu.3	Guidelines for sensor model validation including the important points to consider during data collection. It concludes on project guidelines (T_Simu.4) on the assessment of simulation and the parameters to be considered.

REVISION HISTORY

Revision	Date	Description, updates and changes	Status
1.0	03/03/2025	First draft version, open for discussion	Draft
2.0	03/03/2026	Consolidated version, open for final review	Draft
2.1	26/05/2026	Consolidated version after final review	Approved

ABBREVIATIONS

Radar	***Radio Detection and Ranging***
Lidar	Light Detection and Ranging
OEM	Original Equipment Manufacturer
TIER-1	First Tier Supplier

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1. Introduction

Adverse weather conditions remain a major contributing factor to road accidents, significantly impacting vehicle perception, driver behavior, and overall traffic safety. Rain, fog, snow, and low-visibility conditions degrade sensor performance, alter road surface properties, and introduce complex environmental effects that are difficult to capture through traditional testing alone. In the context of increasingly automated and connected vehicles, the ability to accurately model and simulate such conditions has become a critical enabler for the safe development, validation, and deployment of advanced driver assistance systems (ADAS) and automated driving functions.

The WeatherSafe project addresses this challenge by advancing methods, tools, and best practices for the assessment of road safety under adverse weather conditions. Within this framework, the Simulation Work Package plays a central role by investigating how simulation technologies can be leveraged to reproduce weather-induced effects on sensors, vehicles, and driving scenarios in a realistic, scalable, and repeatable manner. Simulation is a key complement to field testing, enabling systematic exploration of rare, dangerous, or hard-to-reproduce situations while reducing cost, risk, and development time.

The Simulation Work Package is structured into four tightly connected tasks. The present deliverable corresponds to Task T_Simu.1, whose objective is to establish a comprehensive state of the art of existing simulation means relevant to adverse weather conditions in road safety. Building on the knowledge and structure provided by the participants, this task surveys current research activities, open-source and commercial simulation platforms, and relevant standardization efforts. Particular attention is given to the representation of weather phenomena and their impact on sensor modalities commonly used in automotive.

This report provides a consolidated overview of three complementary parts and a short outlook. First, it reviews academic and applied research addressing the simulation of adverse weather effects, highlighting prevailing modelling approaches, strengths, and limitations. To the knowledge of the authors, the provided report is one of the most comprehensive collections of research in this field of research. Second, it analyzes the capabilities of existing open-source and commercial simulation tools, identifying how weather effects are implemented, parameterized, and validated in practice. Third, it examines the role of ASAM OpenX standards in supporting interoperable, reproducible, and extensible weather-aware simulation workflows. Finally, a prospect towards future simulation of adverse weather is given.

By establishing this baseline, T_Simu.1 sets the foundation for the subsequent tasks of the work package. T_Simu.2 will demonstrate concrete possibilities for implementing relevant weather effects in sensor simulation, based on insights from WP1 and WP2. T_Simu.3 will focus on validation, comparing real and synthetic sensor data under weather influence through a representative case study. Finally, T_Simu.4 will synthesize these results into simulation assessment guidelines, proposing recommendations for evaluating the realism and relevance of adverse weather simulation, including physical–numerical correlation and methodological aspects. Overall, this deliverable provides a shared reference framework for WeatherSafe partners and stakeholders, clarifying the current capabilities and gaps in weather-aware simulation. It supports informed decisions on tool selection, methodological choices, and future developments, ultimately contributing to more robust safety assessment methods for road transport systems operating under adverse weather conditions.

2. State of the Art in Simulation of Weather effects in Perception Sensors

2.1 SotA in Research and Science

SotA from PhD Thesis Linnhoff (01/2023)

- Rasshofer, R. H., Spies, M., and Spies, H.: Influences of weather phenomena on automotive laser radar systems, Adv. Radio Sci., 9, 49–60, https://doi.org/10.5194/ars-9-49-2011, 2011.
- Tucker, Donna: Orographic Precipitation, in: Oliver, John E. (ed.): Encyclopedia of World Climatology, Springer Netherlands, 2005
- Tucker, Donna: Precipitation, in: Oliver, John E. (ed.): Encyclopedia of World Climatology, Springer Netherlands, 2005
- Cerro, Carlos; Codina, Bernat; Bech, Joan; Lorente, Jeroni: Modeling Raindrop Size Distribution and Z(R) Relations in the Western Mediterranean Area, in: Journal of Applied Meteorology, Vol. 36, p. 10, 1997
- Marshall, J. S.; Palmer, W. McK.: The Distribution of Raindrops with Size, in: Journal of Meteorology, Vol. 5, pp. 165–166, 1948
- Laws, J. Otis; Parsons, Donald A.: The relation of raindrop-size to intensity, in: Transactions, American Geophysical Union, Vol. 24, p. 452, 1943
- Ulbrich, Carlton W.: Natural Variations in the Analytical Form of the Raindrop Size Distribution, in: Cover Journal of Applied Meteorology and Climatology Journal of Applied Meteorology and Climatology, Vol. 22, pp. 1764–1775, 1983
- Mueller, E.: Radar Rainfall Studies, PhD Thesis, University of Illinois, 1965
- Caton, P. G. F.: A study of raindrop-size distributions in the free atmosphere, in: Quarterly Journal of the Royal Meteorological Society, Vol. 92, pp. 15–30, 1966
- Blanchard, Duncan C.: Raindrop Size-Distribution in Hawaiian Rains, in: Journal of Atmospheric Sciences, Vol. 10, pp. 457–473, 1953
- Uplinger, C. W.: A new formula for raindrop terminal velocity, in: pp. 389–391, 1981
- Uijlenhoet, Remko: Raindrop size distributions and radar reflectivity–rain rate relationships for radar hydrology, in: Hydrology and Earth System Sciences, Vol. 5, pp. 615–628, 2001
- Atlas, David; Ulbrich, Carlton W.: Path- and Area-Integrated Rainfall Measurement by Microwave Attenuation, in: Journal of Applied Meteorology and Climatology, Vol. 16, pp. 1322–1331, 1977
- Day, John A.: Fog and Mist, in: Oliver, John E. (ed.): Encyclopedia of World Climatology, Springer Netherlands, 2005
- World Meteorological Organization: Guide to meteorological instruments and methods of observation. World Meteorological Organization, 2008
- Best, A. C.: Drop-size distribution in cloud and fog, in: Quarterly Journal of the Royal Meteorological Society, Vol. 77, pp. 418–426, 1951
- Junge, Christian: The Size Distribution and Aging of Natural Aerosols as Determined from Electrical and Optical Data on the Atmosphere, in: Journal of the Atmospheric Sciences, Vol. 12, pp. 13–25, 1955
- International Telecommuncation Union: Recommendation ITU-R P.1817-1 - Propagation data required for the design of terrestrial free-space optical links, 2012
- Liu, Qing; Bingui, wu; Wang, Zhaoyu; Hao, Tianyi: Fog Droplet Size Distribution and the Interaction between Fog Droplets and Fine Particles during Dense Fog in Tianjin, China, in: Atmosphere, Vol. 11, p. 258, 2020

- Mazoyer, Marie; Burnet, Frédéric; Denjean, Cyrielle: Experimental study on the evolution of droplets size distribution during the fog life cycle, in: Atmospheric Chemistry and Physics [PrePrint], 2022
- Iqbal, Muhammad: An Introduction To Solar Radiation, Elsevier, 2012
- Wald, Lucien: Fundamentals of Solar Radiation, CRC Press, 2021
- Ouster: OS1, URL: https://data.ouster.io/downloads/datasheets/datasheet-rev06-v2p3-os1.pdf, 2022, visited on 05/31/2022
- Gallaway, Bob M.; Schiller, Robert E.; Rose, Jerry G.: Effects of Rainfall Intensity, Pavement Cross Slope, Surface Texture, and Drainage Length on Pavement Water Depths, 1971
- Viner, H.; Dunford, A; Coyle, F.; Nesnas, K.; Hargreaves, D.; Parry, T.; Flintsch, G.: Development of a Prediction Model for Splash and Spray, in: 7th Symposium on Pavement Surface Characteristics, 2012
- Chesterton, John; Nancekivell, Noel; Tunnicliffe, Noel: The Use of the Gallaway Formula for Aquaplaning Evaluation in New Zealand, in: Transit New Zealand and New Zealand Institute of Highway Technology 8th Annual Conference, 2006
- Weir, David H.; Strange, Jay F.; Heffley, Robert K.: Reduction of adverse aerodynamic effects of large trucks, URL: https://rosap.ntl.bts.gov/view/dot/753/dot_753_DS1.pdf, 1978, visited on 04/02/2022
- Paschkewitz, John: Simulation of spray dispersion in a simplified heavy vehicle wake, URL: https://www.osti.gov/servlets/purl/895085/, 2006, visited on 11/26/2021
- Hu, Xingjun; Liao, Lei; Lei, Yulong; Yang, Hanbo; Fan, Qingyin; Yang, Bo; Chang, Jing; Wang, Jingyu: A numerical simulation of wheel spray for simplified vehicle model based on discrete phase method, in: Advances in Mechanical Engineering, Vol. 7, p. 1687814015597190, 2015
- Jilesen, Jonathan; Alajbegovic, Ales; Duncan, Brad: Soiling and Rain Simulation for Ground Transportation Vehicles, in: 7th European-Japanese Two-Phase Flow Group Meeting, 2015
- Kabanovs, Anton; Garmory, Andrew; Passmore, Martin; Gaylard, Adrian: Computational simulations of unsteady flow field and spray impingement on a simplified automotive geometry, in: Journal of Wind Engineering and Industrial Aerodynamics, Vol. 171, pp. 178–195, 2017
- Strohbücker, Veith; Niesner, Reinholf; Joos, Franz: Simulation method for vehicle tire water spraying behavior, in: 18. Internationales Stuttgarter Symposium, pp. 1393–1409, 2018
- Colomb, Michele; Hirech, Khaled; André, Philippe; Boreux, Jean-Jacques; Lacôte, P.; Dufour, Joseph: An innovative artificial fog production device improved in the European project "FOG", in: Atmospheric Research, Vol. 87, pp. 242–251, 2008
- Shepard, Frank D.; Transportation Research Board; National Cooperative Highway Research Program: Reduced visibility due to fog on the highway, 1996
- Duthon, Pierre; Colomb, Michèle; Bernardin, Frédéric: Light Transmission in Fog: The Influence of Wavelength on the Extinction Coefficient, in: MDPI Applied Sciences, Vol. 9, p. 2843, 2019
- Ryde, Julian; Hillier, Nick: Performance of laser and radar ranging devices in adverse environmental conditions: Ryde & Hillier: Comparison of Laser and Radar in Adverse Environmental Conditions, in: Journal of Field Robotics, Vol. 26, pp. 712–727, 2009
- Kutila, Matti; Pyykonen, Pasi; Holzhüter, Hanno; Colomb, Michele; Duthon, Pierre: Automotive LiDAR performance verification in fog and rain, in: 2018 IEEE 21st International Conference on Intelligent Transportation Systems (ITSC), pp. 1695–1701, 2018

- Bijelic, Mario; Gruber, Tobias; Ritter, Werner: A Benchmark for Lidar Sensors in Fog: Is Detection Breaking Down?, in: 2018 IEEE Intelligent Vehicles Symposium (IV), pp. 760–767, 2018
- Jokela, Maria; Kutila, Matti; Pyykönen, Pasi: Testing and Validation of Automotive Point-Cloud Sensors in Adverse Weather Conditions, in: MDPI Applied Sciences, Vol. 9, 2019
- Heinzler, Robin; Schindler, Philipp; Seekircher, Jurgen; Ritter, Werner; Stork, Wilhelm: Weather Influence and Classification with Automotive Lidar Sensors, in: 2019 IEEE Intelligent Vehicles Symposium (IV), pp. 1527–1534, 2019
- Li, You; Duthon, Pierre; Colomb, Michèle; Ibanez-Guzman, Javier: What happens for a ToF LiDAR in fog?, in: arXiv:2003.06660 [cs, eess], 2020
- Hasirlioglu, Sinan; Doric, Igor; Kamann, Alexander; Riener, Andreas: Reproducible Fog Simulation for Testing Automotive Surround Sensors, in: 2017 IEEE 85th Vehicular Technology Conference (VTC Spring), pp. 1–7, 2017
- Hasirlioglu, Sinan; Riener, Andreas: Challenges in Object Detection Under Rainy Weather Conditions, in: Ferreira, Joao Carlos; Martins, Ana Lúcia; Monteiro, Vitor (ed.): Intelligent Transport Systems, From Research and Development to the Market Uptake, Springer International Publishing, 2019
- Carballo, Alexander; Lambert, Jacob; Monrroy-Cano, Abraham; Wong, David Robert; Narksri, Patiphon; Kitsukawa, Yuki; Takeuchi, Eijiro; Kato, Shinpei; Takeda, Kazuya: LIBRE: The Multiple 3D LiDAR Dataset, in: arXiv:2003.06129 [cs], 2020
- Hasirlioglu, Sinan: A Novel Method for Simulation-based Testing and Validation of Automotive Surround Sensors under Adverse Weather Conditions, PhD Thesis, Universität Linz, 2020
- AFNOR: NF P99-329: Road meteorology. Gathering of meteorological and road data. Terminology. 1998
- VDI: VDI 3786: Umweltmeteorologie Meteorologische Messungen Trübung der bodennahen Atmosphäre Meteorologische Sichtweite, URL: https://aproxy.ulb.tu-darmstadt.de:2203/perinorm/fulltext.ashx, 2017, visited on 05/12/2022
- Mercedes-Benz: Introducing DRIVE PILOT: An Automated Driving System for the Highway, URL: https://www.daimler.com/documents/innovation/other/2019-02-20-vssa-mercedes-benzdrive-pilot-a.pdf, 2019, visited on 05/17/2022
- Casselgren, Johan; Sjödahl, Mikael; Leblanc, James: Angular spectral response from covered asphalt, in: Applied optics, Vol. 46, pp. 4277–4288, 2007
- Peynot, Thierry; Underwood, James; Scheding, Steven: Towards reliable perception for Unmanned Ground Vehicles in challenging conditions, in: 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1170–1176, 2009
- Guo, Jing; Zhang, He; Zhang, Xiang-jin: Propagating Characteristics of Pulsed Laser in Rain, in: International Journal of Antennas and Propagation, Vol. 2015, 2015
- Hasirlioglu, Sinan; Kamann, Alexander; Doric, Igor; Brandmeier, Thomas: Test methodology for rain influence on automotive surround sensors, in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), pp. 2242–2247, 2016
- Walz, Stefanie; Bijelic, Mario; Kraus, Florian; Ritter, Werner; Simon, Martin; Doric, Igor: A Benchmark for Spray from Nearby Cutting Vehicles, in: 2021 IEEE 24th International Conference on Intelligent Transportation Systems (ITSC), 2021
- Doric, Igor; Ritter, Werner: "Wassersprühsystem zur Erzeugung eines Sprühnebels für die Erprobung von Fahrerassistenzsystemen und Prüfkörper mit einem Wassersprühsystem", DE102019131642B4, 2022
- Caesar, Holger; Bankiti, Varun; Lang, Alex H.; Vora, Sourabh; Liong, Venice Erin; Xu, Qiang; Krishnan, Anush; Pan, Yu; Baldan, Giancarlo; Beijbom, Oscar: nuScenes: A

Multimodal Dataset for Autonomous Driving, in: 2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), pp. 11618–11628, 2020
- Sun, Pei; Kretzschmar, Henrik; Dotiwalla, Xerxes; Chouard, Aurelien; Patnaik, Vijaysai; Tsui, Paul; Guo, James; Zhou, Yin; Chai, Yuning; Caine, Benjamin; Vasudevan, Vijay; Han, Wei; Ngiam, Jiquan; Zhao, Hang; Timofeev, Aleksei; Ettinger, Scott; Krivokon, Maxim; Gao, Amy; Joshi, Aditya; Zhang, Yu; Shlens, Jonathon; Chen, Zhifeng; Anguelov, Dragomir: Scalability in Perception for Autonomous Driving: Waymo Open Dataset, in: 2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), pp. 2443–2451, 2020
- Geyer, Jakob; Kassahun, Yohannes; Mahmudi, Mentar; Ricou, Xavier; Durgesh, Rupesh; Chung, Andrew S.; Hauswald, Lorenz; Pham, Viet Hoang; Mühlegg, Maximilian; Dorn, Sebastian; Fernandez, Tiffany; Jänicke, Martin; Mirashi, Sudesh; Savani, Chiragkumar; Sturm, Martin; Vorobiov, Oleksandr; Oelker, Martin; Garreis, Sebastian; Schuberth, Peter: A2D2: Audi Autonomous Driving Dataset, in: arXiv:2004.06320 [cs, eess], 2020
- Bijelic, Mario; Gruber, Tobias; Mannan, Fahim; Kraus, Florian; Ritter, Werner; Dietmayer, Klaus; Heide, Felix: Seeing Through Fog Without Seeing Fog: Deep Multimodal Sensor Fusion in Unseen Adverse Weather, in: 2020 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), pp. 11679–11689, 2020
- Sheeny, Marcel; De Pellegrin, Emanuele; Mukherjee, Saptarshi; Ahrabian, Alireza; Wang, Sen; Wallace, Andrew: RADIATE: A Radar Dataset for Automotive Perception in Bad Weather, in: 2021 IEEE International Conference on Robotics and Automation (ICRA), pp. 1–7, 2021
- Burnett, Keenan; Yoon, David J.; Wu, Yuchen; Li, Andrew Zou; Zhang, Haowei; Lu, Shichen; Qian, Jingxing; Tseng, Wei-Kang; Lambert, Andrew; Leung, Keith Y. K.; Schoellig, Angela P.; Barfoot, Timothy D.: Boreas: A Multi-Season Autonomous Driving Dataset, in: arXiv:2203.10168 [cs], 2022
- Sebastian, George; Vattem, Teja; Lukic, Luka; Bürgy, Christian; Schumann, Thomas: RangeWeatherNet for LiDAR-Only Weather and Road Condition Classification, in: 2021 IEEE Intelligent Vehicles Symposium (IV), p. 8, 2021
- Michaud, Sebastien; Lalonde, Jean-Francois; Giguere, Philippe: Towards Characterizing the Behavior of LiDARs in Snowy Conditions, in: International Conference on Intelligent Robots and Systems, p. 6, 2015
- Kutila, Matti; Pyykonen, Pasi; Ritter, Werner; Sawade, Oliver; Schaufele, Bernd: Automotive LIDAR sensor development scenarios for harsh weather conditions, in: 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), pp. 265–270, 2016
- Piroli, Aldi; Dallabetta, Vinzenz; Walessa, Marc; Meissner, Daniel; Kopp, Johannes; Dietmayer, Klaus: Robust 3D Object Detection in Cold Weather Conditions, URL: http://arxiv.org/abs/2205. 11925, 2022, visited on 05/28/2022
- Wojtanowski, Jacek; Zygmunt, Marek; Kaszczuk, Miroslawa; Mierczyk, Zygmunt; Muzal, Michal: Comparison of 905 nm and 1550 nm semiconductor laser rangefinders' performance deterioration due to adverse environmental conditions, in: Opto-Electronics Review, Vol. 22, pp. 183–190, 2014
- Shin, Jungil; Park, Hyunsuk; Kim, Taejung: Characteristics of Laser Backscattering Intensity to Detect Frozen and Wet Surfaces on Roads, in: Journal of Sensors, Vol. 2019, pp. 1–9, 2019
- Shih, Yi-Chien; Liao, Wei-Hsiang; Lin, Wen-Chieh; Wong, Sai-Keung; Wang, Chieh-Chih: Reconstruction and Synthesis of Lidar Point Clouds of Spray, in: IEEE Robotics and Automation Letters, Vol. 7, pp. 3765–3772, 2022
- Grantham, Jeffrey W.; Meidunas, Eduardo C.: Laser radar in adverse weather, in: Aerospace/Defense Sensing and Controls, p. 303, 1998

- Filgueira, Alexandre; González-Jorge, Higinio; Lagüela, Susana; Díaz-Vilariño, Lucia; Arias, Pedro: Quantifying the influence of rain in LiDAR performance, in: Measurement, Vol. 95, pp. 143–148, 2017
- Vargas Rivero, Jose Roberto; Gerbich, Thiemo; Teiluf, Valentina; Buschardt, Boris; Chen, Jia: Weather Classification Using an Automotive LIDAR Sensor Based on Detections on Asphalt and Atmosphere, in: MDPI Sensors, Vol. 20, 2020
- Hofrichter, Kristof: Sammlung und Aufbereitung der Einflüsse von Wetterbedingungen auf Radar und Lidar für die Modellbildung, Bachelor's Thesis, Technische Universität Darmstadt, 2020
- Wichmann, Matthias; Kamil, Mustafa; Frederiksen, Annette; Kotzur, Sebastian; Scherl, Michael: Long-term investigations of weather influence on direct time-of-flight Lidar at 905nm, in: IEEE Sensors Journal, Vol. 22, pp. 2024–2036, 2021
- Hasirlioglu, Sinan; Riener, Andreas; Huber, Werner; Wintersberger, Philipp: Effects of exhaust gases on laser scanner data quality at low ambient temperatures, in: 2017 IEEE Intelligent Vehicles Symposium (IV), pp. 1708–1713, 2017
- Hahner, Martin; Sakaridis, Christos; Bijelic, Mario; Heide, Felix; Yu, Fisher; Dai, Dengxin; Gool, Luc Van: LiDAR Snowfall Simulation for Robust 3D Object Detection (Supplementary Materials), p. 14, 2022
- Shearman, Edwin Douglas Ramsey; Hoare, Edward G.; Hutton, A.: Trials of automotive radar and lidar performance in road spray, in: IEE Colloquium on Automotive Radar and Navigation Techniques, vol. 1998, 1998
- Vargas Rivero, Jose Roberto; Gerbich, Thiemo; Buschardt, Boris; Chen, Jia: The Effect of Spray Water on an Automotive LIDAR Sensor: A Real-Time Simulation Study, in: IEEE Transactions on Intelligent Vehicles, Vol. 7, pp. 57–72, 2021
- Shah, Shahnawaz; Mughal, Samreen; Memon, Shahzad: Theoretical and empirical based extinction coefficients for fog attenuation in terms of visibility at 850 nm, in: 2015 International Conference on Emerging Technologies (ICET), pp. 1–4, 2015
- Kruse, Paul W.; MacGlauchlin, Laurence D.; MacQuistan, Richmond B.: Elements of infrared technology: generation, transmission, and detection, Wiley, 1962
- International Telecommuncation Union: Recommendation ITU-R P.1814 - Prediction methods required for the design of terrestrial free-space optical links, URL: https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.1814-0-200708-I!!PDF-E.pdf, 2007, visited on 06/22/2022
- Kim, Isaac I.; McArthur, Bruce; Korevaar, Eric J.: Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications, in: pp. 26–37, 2001
- Bohren, Craig F.; Huffman, Donald R.: Absorption and Scattering of Light by Small Particles, 1. Edition, John Wiley & Sons, Ltd, 1998
- Hadj-Bachir, Mokrane; De Souza, Philippe: LIDAR sensor simulation in adverse weather condition for driving assistance development, in: hal-01998668, 2019
- Goodin, Christopher; Carruth, Daniel; Doude, Matthew; Hudson, Christopher: Predicting the Influence of Rain on LIDAR in ADAS, in: MDPI Electronics, Vol. 8, p. 89, 2019
- Hahner, Martin; Sakaridis, Christos; Dai, Dengxin; Gool, Luc Van: Fog Simulation on Real LiDAR Point Clouds for 3D Object Detection in Adverse Weather, in: International Conference on Computer Vision (ICCV), p. 10, 2021
- Fersch, Thomas; Buhmann, Alexander; Koelpin, Alexander; Weigel, Robert: The influence of rain on small aperture LiDAR sensors, in: 2016 German Microwave Conference (GeMiC), pp. 84–87, 2016
- Velodyne LiDAR, Inc.: VLP-16 User Manual, URL: https://velodynelidar.com/wp-content/uploads/2019/12/63-9243-Rev-E-VLP-16-User-Manual.pdf, 2019, visited on 06/15/2022

- Berk, Mario; Dura, Michael; Rivero, Jose Vargas; Schubert, Olaf; Kroll, Hans-Martin; Buschardt, Boris; Straub, Daniel: A Stochastic Physical Simulation Framework to Quantify the Effect of Rainfall on Automotive Lidar, in: SAE International Journal of Advances and Current Practices in Mobility, Vol. 1, pp. 531–538, 2019
- Hasirlioglu, Sinan; Riener, Andreas: A General Approach for Simulating Rain Effects on Sensor Data in Real and Virtual Environments, in: IEEE Transactions on Intelligent Vehicles, Vol. 5, pp. 426–438, 2020
- Byeon, Mijung; Yoon, Sang Won: Analysis of Automotive Lidar Sensor Model Considering Scattering Effects in Regional Rain Environments, in: IEEE Access, Vol. 8, pp. 102669–102679, 2020
- Kilic, Velat; Hegde, Deepti; Sindagi, Vishwanath; Cooper, A. Brinton; Foster, Mark A.; Patel, Vishal M.: Lidar Light Scattering Augmentation (LISA): Physics-based Simulation of Adverse Weather Conditions for 3D Object Detection, in: arXiv:2107.07004 [physics], 2021
- Espineira, Juan P.; Robinson, Jonathan; Groenewald, Jakobus; Chan, Pak Hung; Donzella, Valentina: Realistic LiDAR With Noise Model for Real-Time Testing of Automated Vehicles in a Virtual Environment, in: IEEE Sensors Journal, Vol. 21, pp. 9919–9926, 2021
- Nebuloni, Roberto; Capsoni, Carlo: Laser attenuation by falling snow, in: 2008 6th International Symposium on Communication Systems, Networks and Digital Signal Processing, pp. 265–269, 2008
- Gunn, K. L. S.; Marshall, J. S.: The Distribution with Size of Aggregate Snowflakes, in: Journal of the Atmospheric Sciences, Vol. 15, pp. 452–461, 1958
- Hahner, Martin; Sakaridis, Christos; Bijelic, Mario; Heide, Felix; Yu, Fisher; Dai, Dengxin; Gool, Luc Van: LiDAR Snowfall Simulation for Robust 3D Object Detection, in: IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), p. 11, 2022
- Vargas Rivero, Jose Roberto; Gerbich, Thiemo; Buschardt, Boris; Chen, Jia: Data Augmentation of Automotive LIDAR Point Clouds under Adverse Weather Situations, in: MDPI Sensors, Vol. 21, p. 4503, 2021

Additional SotA from ROADVIEW Project (05/2024)

- L. A. Gatys, A. S. Ecker and M. Bethge, "Image style transfer using convolutional neural networks," in Proceedings of the IEEE conference on computer vision and pattern recognition, 2016.
- P. Isola, J.-Y. Zhu, T. Zhou and A. A. Efros, "Image-to-image translation with conditional adversarial networks(1 paired supervised)," in Proceedings of the IEEE conference on computer vision and pattern recognition, 2017.
- J.-Y. Zhu, T. Park, P. Isola and A. A. Efros, "Unpaired Image-to-Image Translation using Cycle-Consistent Adversarial Networks," 2017
- T. Park, A. A. Efros, R. Zhang and J.-Y. Zhu, "Contrastive learning for unpaired image-to-image translation," in Computer Vision–ECCV 2020: 16th European Conference, Glasgow, UK, August 23–28, 2020, Proceedings, Part IX 16, 2020.
- X. Li, K. Kou and B. Zhao, "Weather GAN: Multi-domain weather translation using generative adversarial networks," arXiv preprint arXiv:2103.05422, 2021.
- Y. Zhang, N. Huang, F. Tang, H. Huang, C. Ma, W. Dong and C. Xu, "Inversion-based style transfer with diffusion models," in Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition, 2023.
- C. H. Wu and F. De la Torre, "Unifying Diffusion Models' Latent Space, with Applications to CycleDiffusion and Guidance," arXiv preprint arXiv:2210.05559, 2022.
- S. Yang, H. Hwang and J. C. Ye, "Zero-shot contrastive loss for text-guided diffusion image style transfer," arXiv preprint arXiv:2303.08622, 2023.
- Y. Jia, L. Hoyer, S. Huang, T. Wang, L. Van Gool, K. Schindler and A. Obukhov, "DGInStyle: DomainGeneralizable Semantic Segmentation with Image Diffusion Models and Stylized Semantic Control," arXiv preprint arXiv:2312.03048, 2023.
- S. Zheng, C. Lu and S. G. Narasimhan, TPSeNCE: Towards Artifact-Free Realistic Rain Generation for Deraining and Object Detection in Rain, 2023.
- X. Mao, Q. Li, H. Xie, R. Y. K. Lau, Z. Wang and S. Paul Smolley, "Least squares generative adversarial networks," in Proceedings of the IEEE international conference on computer vision, 2017.
- W.-T. Chu, X.-Y. Zheng and D.-S. Ding, "Image2weather: A large-scale image dataset for weather property estimation," in 2016 IEEE Second International Conference on Multimedia Big Data (BigMM), 2016
- J. C. V. Guerra, Z. Khanam, S. Ehsan, R. Stolkin and K. McDonald-Maier, "Weather Classification: A new multi-class dataset, data augmentation approach and comprehensive evaluations of Convolutional Neural Networks," in 2018 NASA/ESA Conference on Adaptive Hardware and Systems (AHS), 2018.
- D. Yang, Z. Liu, W. Jiang, G. Yan, X. Gao, B. Shi, S. Liu and X. Cai, "Realistic Rainy Weather Simulation for LiDARs in CARLA Simulator," December 2023.
- Haider, A., Pigniczki, M., Koyama, S., Köhler, M. H., Haas, L., Fink, M., Schardt, M., Nagase, K., Zeh, T., Eryildirim, A., Poguntke, T., Inoue, H., Jakobi, M., & Koch, A. W. (2023). A Methodology to Model the Rain and Fog Effect on the Performance of Automotive LiDAR Sensors. *Sensors*, *23*(15), 6891. https://doi.org/10.3390/s23156891
- M. Dreissig, D. Scheuble, F. Piewak and J. Boedecker, "Survey on LiDAR Perception in Adverse Weather Conditions," April 2023.
- K. Montalban, C. Reymann, D. Atchuthan, P.-E. Dupouy, N. Riviere and S. Lacroix, "A Quantitative Analysis of Point Clouds from Automotive Lidars Exposed to Artificial Rain and Fog," Atmosphere, vol. 12,
- J. Lee, D. Shiotsuka, T. Nishimori, K. Nakao and S. Kamijo, "GAN-Based LiDAR Translation between Sunny and Adverse Weather for Autonomous Driving and Driving Simulation," Sensors, vol. 22, p. 5287, July 2022

- M. Colomb, P. Duthon and S. Laukkanen, Deliverable D 2.1 : Characteristics of Adverse Weather Conditions, 2017, p. 73.
- A. S. Mohammed, A. Amamou, F. K. Ayevide, S. Kelouwani, K. Agbossou and N. Zioui, "The Perception System of Intelligent Ground Vehicles in All Weather Conditions: A Systematic Literature Review," Sensors, MDPI, 2020.
- X. Gao, S. Roy, G. Xing and S. Jin, "Perception Through 2D-MIMO FMCW Automotive Radar Under Adverse Weather," in 2021 IEEE International Conference on Autonomous Systems (ICAS), 2021.
- Y. Zhou, L. Liu, H. Zhao, M. Lopez-Benitez, L. Yu and Y. Yue, "Towards deep radar perception for autonomous driving: Datasets, Methods, and Challenges," 2022.
- M. Bijelic, T. Gruber and W. Ritter, "Benchmarking Image Sensors under Adverse Weather Conditions for Autonomous Driving," IEEE Intelligent Vehicles Symposium, Proceedings, Vols. 2018-June, no. Iv, pp. 1773- 1779, 2018.
- S. Zang, M. Ding, D. Smith, P. Tyler, T. Rakotoarivelo and M. A. Kaafar, "The Impact of Adversary Weather Conditions on Autonomous Vehicles," IEEE Vehicular Technology Magazine, 2019.
- Y. Zhang, A. Carballo, H. Yang and K. Takeda, "Perception and sensing for autonomous vehicles under adverse weather conditions: A survey," ISPRS Journal of Photogrammetry and Remote Sensing, vol. 196, p. 146–177, February 2023.
- J.-G. Wang, S. Chen, L.-B. Zhou, K. Wan and W.-Y. Yau, "Vehicle Detection and Width Estimation in Rain by Fusing Radar and Vision," 2018.
- R. Yu, X. Li and T. Bi, "Modelling and validation of LiDAR noise distribution in fog and rain," Measurement, vol. 229, p. 114472, April 2024.
- K. Wang, T. Zhou, X. Li and F. Ren, "Performance and Challenges of 3D Object Detection Methods in Complex Scenes for Autonomous Driving," IEEE Transactions on Intelligent Vehicles, vol. 8, p. 1699–1716, February 2023.
- Y. H. T. D. Reddy Nagarjun and B. V. Arem, "Operational Design Domain Requirements for Improved Performance of Lane Assistance Systems: A Field Test Study in The Netherlands," IEEE Open Journal of Intelligent Transportation Systems, vol. 1, p. 237–252, 2020.
- M. Kutila, P. Pyykönen, H. Holzhüter, M. Colomb and P. Duthon, "Automotive LiDAR performance verification in fog and rain," 2018.

Latest findings during project

- Ben-Daoued, A., Duthon, P., & Bernardin, F. (2023). SWEET: A Realistic Multiwavelength 3D Simulator for Automotive Perceptive Sensors in Foggy Conditions. *Journal of Imaging*, *9*(2), 54. https://doi.org/10.3390/jimaging9020054
- Ben-Daoued, A., Bernardin, F., & Duthon, P. (2024). A Comparative Review of the SWEET Simulator: Theoretical Verification Against Other Simulators. *Journal of Imaging*, *10*(12), 306. https://doi.org/10.3390/jimaging10120306
- Sylvestre Prabakaran, Youri Mikhail Noutatiem Guiafaing, Ammar Ridzuan, Tchoya Florence Koné, Otmane Attou. Simulation of weather conditions perturbation for an automotive LIDAR sensor. *Driving Simulation Conference (DSC)*, Sep 2024, Strasbourg, France. ⟨hal-04720367⟩
- D. Wachtel Granado, H. D. Trevisol, T. Rothmeier, B. T. Nassu and W. Huber, "Navigating on Adverse Weather: Enhancing LiDAR-Based Detection with the DBSPRY Dataset," *2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC)*, Edmonton, AB, Canada, 2024, pp. 4034-4039, doi: 10.1109/ITSC58415.2024.10920224.
- D. Wachtel Granado, T. Rothmeier, L. Cristofoli, M. Vossiek and W. Huber, "Simulation and Validation of Automotive Radar Performance with Water Spray Over Radome," *2024 IEEE SENSORS*, Kobe, Japan, 2024, pp. 1-4, doi: 10.1109/SENSORS60989.2024.10784774.
- S. Teufel, G. Volk, A. Von Bernuth and O. Bringmann, "Simulating Realistic Rain, Snow, and Fog Variations For Comprehensive Performance Characterization of LiDAR Perception," 2022 IEEE 95th Vehicular Technology Conference: (VTC2022-Spring), Helsinki, Finland, 2022, pp. 1-7, doi: 10.1109/VTC2022-Spring54318.2022.9860868.
- S. Hasirlioglu and A. Riener, "A Model-Based Approach to Simulate Rain Effects on Automotive Surround Sensor Data," *2018 21st International Conference on Intelligent Transportation Systems (ITSC)*, Maui, HI, USA, 2018, pp. 2609-2615, doi: 10.1109/ITSC.2018.8569907.
- Ozarkar, S., Gely, S., and Zhou, K., "Physics-Based Simulation Solutions for Testing Performance of Sensors and Perception Algorithm under Adverse Weather Conditions," *SAE Intl. J CAV* 5(4):297-312, 2022, https://doi.org/10.4271/12-05-04-0024.
- Graf, Michael, Dagmar Steinhauser, Ondřej Vaculín, and Thomas Brandmeier. "Impact of Adverse Weather on Road Safety: A Survey of Test Methods for Enhancing Safety of Automated Vehicles and Sensor Robustness in Challenging Environmental Conditions." *IEEE Access*, 2025, 1–1. https://doi.org/10.1109/ACCESS.2025.3622501.
- Pao, Wing Yi. "Methodology Development and Evaluation of Automotive LiDAR Performance in Rain." Ph.D. Thesis, Ontario Tech University, 2024.

2.2 SOTA OF RESEARCH/OPEN-SOURCE TOOLS

2.2.1 CARLA: WEATHER EFFECTS IN SENSOR SIMULATIONS

- **CARLA Overview**
  - Open-source simulator for autonomous driving research
  - Supports development, training, and validation of vehicle systems
  - Allows flexible specification of sensor suites and environmental conditions, including weather effects
  - Official sources:
    CARLA Website
    GitHub Repository
    Technical Documentation
- **Weather Effects in CARLA**
  - Various weather conditions can be simulated, impacting sensor performance
  - Includes effects like rain, fog, and different lighting conditions
  - Enables robustness and accuracy testing of sensor systems under realistic conditions
- **Examples**
  - **Rain Simulation for Lidar Sensors**
    - CARLA supports rain simulation for Lidar sensors
    - A study developed a physical model to augment Lidar data in rainy conditions
    - Enhances object detection system performance under rain scenarios
    - Study reference: arXiv:2312.12772
  - **CARLA-Loc Dataset**
    - Integrates multiple sensors: cameras, event cameras, Lidar, radar, and IMU
    - Developed to test SLAM (Simultaneous Localization and Mapping) algorithms
    - Designed for challenging and dynamic environments, including varying weather conditions
    - Dataset reference: arXiv:2309.08909
- **Conclusion**
  - CARLA enables the integration of various weather effects in sensor simulations
  - Implementation and impact vary by sensor type
  - Ongoing research aims to improve simulation realism

2.2.2 ENVITED Open Source Model & Simulation Library (OpenMSL)

- **OpenMSL Overview**
  - ENVITED stands for Environment for Virtual Test Drive encompassing all components for virtual test and validation of Advanced Driver Assistent Systems (ADAS) including but not limited to standardized data sets, e.g. digital maps, scenario data, simulation models and their respective test and validation methods.
  - OpenMSL aims to connect and demonstrate the seamless interaction of projects in the domain using elaborate test pipelines, also to assure the compliance of all simulation entities with relevant standards.
  - All repositories are organized in sub-libraries and each sub-library (SL) represents the best practices in the automotive industry on how to use, create and apply standard compliant simulation data and models.
  - The FZD Reflection Based Lidar Model based on the FZD OSI Sensor Model Packaging Framework is a highly parameterizable sensor system model including detection calculation and object tracking simulation. The model gets lidar reflection calculated in a simulation tool beforehand e.g. with ray tracing. The model outputs are lidar detections and detected moving objects.
- **Modeling of Weather Influence on Lidar Point Cloud**
  - In the "Lidar-Environmental-Effects-Strategy", several weather influences are added to the simulated point cloud. The influences are parameterizable via the sensor profiles and calibrated for certain sensors based on measurements published by Linnhoff et al.
  - The stochastically modeled weather conditions include
    - Direct Sunlight
    - Fog
    - Rain
    - Snow
  - Modeling of Road Spray in Lidar Point Cloud
    - The "Lidar-Environmental-Effects-Strategy" does not only contain weather effects, but also other environmental conditions, specifically the influence of road spray on lidar. The road spray simulation is based on a methodical data set recorded in real spray conditions on a test track covering multiple vehicle classes, different pavement watering levels and object speeds ranging from 50 km/h to 130 km/h. Modeling parameters are extracted from the recorded data and utilized to calibrate a novel stochastic road spray model. The model is focused on simulating clustering effects appearing in the lidar point cloud due to turbulences in the spray plume. More detail can be found shortly in an upcoming publication, currently under review.

2.2.3 ROADVIEW PROJECT: STATISTICAL NOISE MODELS FOR CAMERA AND LIDAR

- **ROADVIEW Overview**
  - Project about "Robust Automated Driving in Extreme Weather"
    - Provided a report and a library of validated statistical noise models for camera, lidar, and radar: https://github.com/roadview-project/data-driven-noise-models
  - Official report: https://roadview-project.eu/wp-content/uploads/sites/59/2025/11/Attachment_0-1.pdf
  - GitHub: https://github.com/roadview-project/data-driven-noise-models
- **Methodology & Implementation**
  - Data-driven noise models learn weather-induced noise by comparing natural data with and without degraded weather using machine learning.
  - Camera, lidar, and radar are handled independently due to differing data characteristics.
  - Cameras: A Cycle-GAN processes full images to model weather effects.
  - Lidar & radar: A point-by-point classification approach based on *vanishing distance* is used.
  - Training data sources:
    - Public images collected by CEREMA (cameras).
    - CEREMA-acquired data from the Puy-de-Dôme (France) site during winters 2022–2023 and 2023–2024 (Lidar/radar).
- **Outcomes**
  - Models cover 1 camera and 1 lidar and address fog, rain, and snow conditions.
  - Cameras: Cycle-GAN models support multiple weather types and intensity classes, realistically simulating complex effects (e.g., snow accumulation, vehicle tracks, leaf removal), beyond simple snowfall simulation.
  - Lidar: The vanishing-distance method accurately reproduces different weather conditions with precise control over intensity.
  - radar: Found to be insensitive to the tested adverse weather intensities.
- **Conclusion**
  - Training was performed on new, real-world data collected by CEREMA under naturally degraded weather conditions, improving realism.
  - Model outputs were visually compared with real data from CEREMA datasets and the REHEARSE database.
  - Formal validation using dedicated metrics was not included in the report.
  - Training and validation were intentionally separated across different datasets to avoid bias, following best practices.
  - Key advantages of the models:
    - Ability to control weather intensity (exact for Lidar, class-based for cameras).
    - Parallelizable and real-time capable.

        - Capture combined and secondary weather effects without explicit physical modeling.
    - Main limitations:
        - Camera models only support discrete intensity classes, not exact values.
        - Data-driven models act as black boxes and may introduce artifacts.
        - Strong dependence on training data raises generalization concerns.
        - Defining robust realism metrics remains challenging.

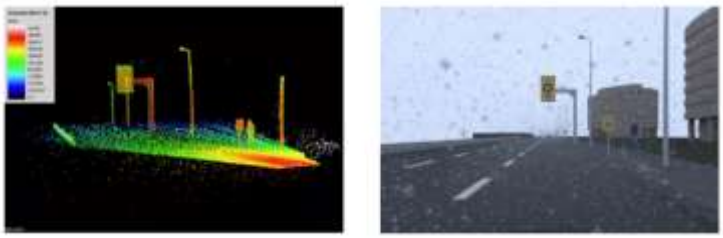
Tool name	Covered weather effects	Sensor technology
CARLA	Rain, fog, lighting conditions	Lidar; also camera, event camera, radar, and IMU in weather-varying datasets
ENVITED OpenMSL	Direct sunlight, fog, rain, snow, road spray	Lidar
ROADVIEW	Fog, rain, snow	Camera and lidar; radar considered but reported as insensitive in tested conditions

2.3 SotA of Commercial Tools

2.3.1 ANSYS: Weather effects in sensor simulations

- **Ansys Overview and Integration of Weather Effects**
    - Advanced solutions for simulating weather effects in sensor simulations
    - Focused on autonomous driving applications
    - Enables developers to evaluate sensor performance and reliability under different environmental conditions
    - Sources:
      YouTube Video
      Ansys Webinar
      Ansys Blog - Clearing the Fog
- **Examples**
    - **Weather Condition Simulation with CFD**
        - Ansys Fluent enables CFD (Computational Fluid Dynamics) simulations for wind, rain, fog, snow, and dust
        - Generates high-precision, reproducible weather data for optical simulations
        - CFD and optical simulations help analyze sensor impacts (thermal camera, visible camera, lidar) and optimize design, placement, and cleaning strategies

- Sources:
- Ansys Blog - Simulation for Autonomous Vehicles
- https://www.ansys.com/blog/self-driving-cars-sensors-snow



Long-distance, physics-based sensor simulations of lidar (left) and cameras in the snow (right).

- **Integration of fog in Sensor Simulations**
  - Ansys Speos enables realistic weather condition simulations such as fog
    - Collaboration with "FLIR Systems" (fog generation during physical testing in the lab) resulted in a virtual fog model
  - Allows developers to test and optimize e.g. thermal imaging sensors in foggy conditions
  - Sources:
    Ansys Blog - Clearing the Fog
    Ansys Webinar
    Ansys Blog - Optical Simulation
    Ansys Blog - Simulation for Autonomous Vehicles
    Thermal Analysis Simulation
    Ansys AVxcelerate Sensors
    Microsoft Report

- **Conclusion**
  - No validation of simulation results demonstrated, yet

2.3.2 IPG: WEATHER EFFECTS IN SENSOR SIMULATIONS

- **IPG Automotive Overview and Integration of Weather Effects**
  - CarMaker enables developers to test and optimize driver assistance systems and autonomous driving functions under various environmental conditions
  - Provides comprehensive weather effect integration for sensor simulations
    e.g. allows simulation of different weather conditions such as rain, fog, and atmospheric pressure (being included in the radar equations of CarMaker's radar model)
  - Source: IPG Automotive Forum
- **Examples: Specific Effects for Different Sensor Types**
  - **Radar Sensors**
    - Rain, fog, and atmospheric pressure impact radar sensor performance
    - CarMaker incorporates these factors into radar equations for realistic simulations

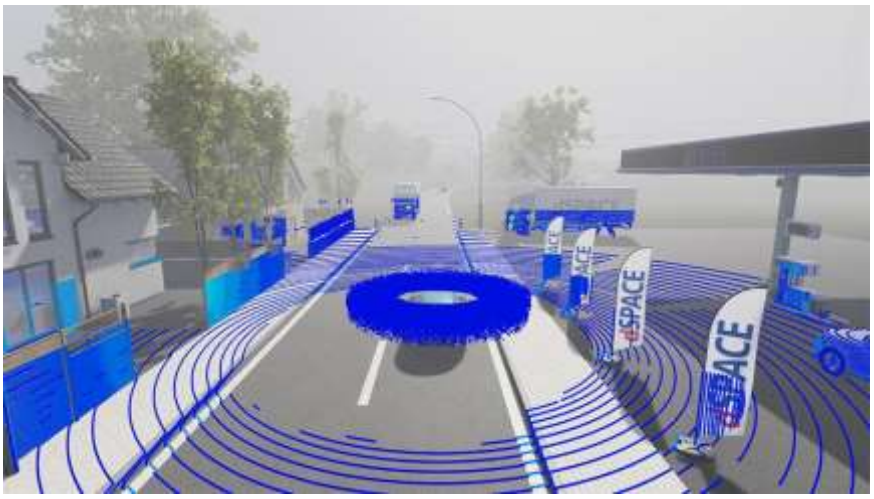
    - Source: IPG Automotive Forum
  - **Camera Sensors**
    - Since CarMaker release 13.1 rain modelling added with adjustable rain rate and wind conditions. Also Improved visibility effects like reflections, spray and raindrop impact.
    - Source: https://www.ipg-automotive.com/en/company/who-we-are/corporate-news/news/carmaker-release-131-available-now/
    - Since CarMaker release 14.0, besides rain, more weather conditions like snowing or sunset can be simulated for the testing of driving functions.
    - Source: https://www.ipg-automotive.com/en/products-solutions/software/highlights-carmaker-product-family/

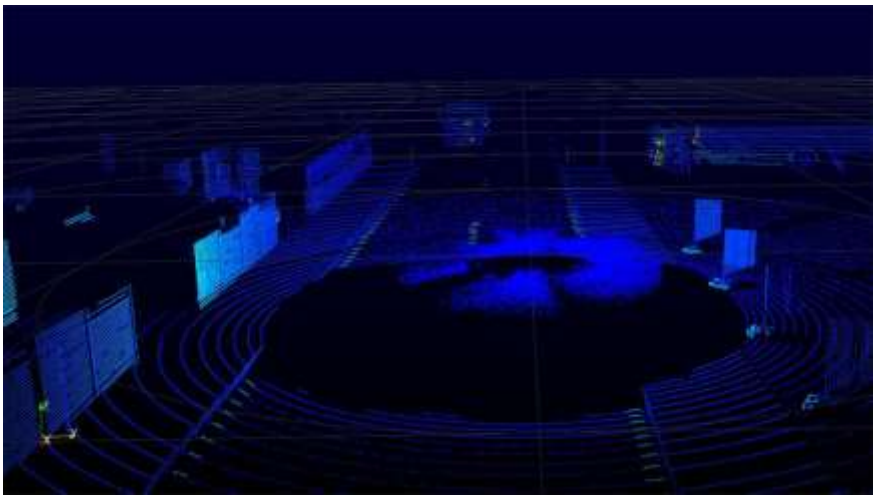
- **Conclusion**
  - No validation of simulation results demonstrated, yet

2.3.3 dSPACE: Weather effects in sensor simulations

- **dSPACE Overview and Integration of Weather Effects**
  - AURELION is an advanced simulation platform integrating variable lighting and weather effects, enabling testing and optimization of sensor systems under various environmental conditions
  - Essential for the development and validation of ADAS and autonomous driving functions
  - Source: dSPACE Digital Twins
- **Examples: Specific Effects for Different Sensor Types**
  - **Lidar Sensors**
    - Fog simulation added in AURELION 24.2 to test Lidar robustness under different weather conditions.
    - Dynamic fog configuration allows adjusting fog density and maximum view distance.
    - Lidar interaction with fog affects range, reflectivity, and accuracy in the generated point cloud.

- Source: https://www.dspace.com/de/gmb/home/news/aurelion-new-version-242.cfm





- **Radar Sensors + Camera Sensors**
  - https://sms.sae.org/articles/cloud-simulation-assists-active-safety-development-electric-refuse-truck
  - https://www.dspace.com/en/inc/home/news/engineers-insights/blogrealisticsensorsimulation.cfm
  - https://www.dspace.com/en/inc/home/news/dspace_pressroom/press/sensor_simulation_solution.cfm
  - ATTENTION: The Links above regarding Radar- and Camera-Simulation are containing information about weather-effects being simulated, but without a very "specific" relation to the sensors themselves.

- **Conclusion**
  - No validation of simulation results demonstrated, yet

2.3.4 SIEMENS

- **Siemens Overview and Integration of Weather Effects**
  - Simcenter Prescan is a simulation platform for developing and testing ADAS and autonomous vehicle systems.

- It allows the replication of real-world traffic scenarios, including the incorporation of various weather conditions, e.g. rain, fog, and snow for Camera Simulation, to assess their impact on sensor performance. https://www.youtube.com/watch?v=KOXmk5a8ukE

- **Examples: Specific Effects for Different Sensor Types**
  - **Camera Sensors**
    - Simcenter Prescan enables the simulation of camera effects influenced by weather, including reflections, varying lighting conditions, and dynamic raindrop formation on lenses, enhancing the realism of camera sensor testing.
    - General Sources:
      - https://webinars.sw.siemens.com/en-US/validation-and-verification-of-sensors/
      - https://plm.sw.siemens.com/en-US/simcenter/autonomous-vehicle-solutions/prescan/
    - Rain:
      - https://blogs.sw.siemens.com/simcenter/whats-new-in-simcenter-prescan-2302/
      - https://blogs.sw.siemens.com/simcenter/whats-new-in-simcenter-prescan-2407/
      - https://www.youtube.com/watch?v=KOXmk5a8ukE
    - Snow:
      - https://blogs.sw.siemens.com/simcenter/significantly-accelerate-verification-of-level-4-automation/
      - https://www.youtube.com/watch?v=KOXmk5a8ukE
    - Fog: https://www.youtube.com/watch?v=KOXmk5a8ukE
  - **Lidar Sensors**
    - The platform offers physics-based Lidar simulations that account for environmental factors like motion distortion and multiple reflections, crucial for evaluating Lidar performance. "We will improve our environment simulation by creating new weather models for all different type of weather and light conditions." https://blogs.sw.siemens.com/simcenter/lidar-systems-simulation-and-validation/
- **Conclusion**
  - No validation of simulation results demonstrated, yet

- **Previous official documentation / presentations**
  - In older presentations and marketing documents from Siemens (especially around 2019-2021), it was explicitly mentioned that Prescan can simulate environmental influences such as rain, fog, snow, lighting, etc. - sometimes in combination with 3rd party rendering (such as Unreal or own environment models).
  - Earlier Siemens videos/webinars mentioned "adverse weather conditions" as a simulation feature.

- Older versions of Prescan used OpenSceneGraph for rendering, which supported simple weather effects.

- **Technical Reality**
  - Prescan supports the creation of weather scenarios via its scenario parameters (e.g. light intensity, visibility, reflections, etc.), which in turn can influence sensor perception. This is often not explicitly documented as a "rain model", but has a similar effect.

Why is it not directly stated in the new sources?

Newer Siemens communication (since the integration into Simcenter) focuses more on model-based systems engineering, toolchains, and hardware-in-the-loop, rather than on individual weather effects. The sensor simulations are also often part of custom workflows in combination with other Siemens tools (e.g. Simcenter Amesim, STAR-CCM+, etc.) where weather is physically modeled.

2.3.5 APPLIED INTUITION

- **Applied Intuition Overview and Integration of Weather Effects**
  - Applied Intuition offers physics-based sensor simulation solutions, including Sensor Sim, to develop, test, and validate sensor suites and perception systems for autonomous vehicles.
  - The platform supports the simulation of diverse environmental conditions, enabling the assessment of sensor performance under various weather scenarios.
  - Sources:
    - https://www.appliedintuition.com/products/sensor-sim
    - https://www.appliedintuition.com/blog/why-3d-worlds-matter-for-adas-and-ad-development
- **No specific Sensor specified**
  - "Iteratively run sensor simulations to monitor progress across purpose-built test cases, and introduce variations across behaviors, weather, and lighting to ensure robustness." https://www.appliedintuition.com/use-cases/perception-and-localization
  - In a collaboration with Toyota's Woven Planet Group, it was noted that "Synthetic data enables the scalable generation and verification of situations by changing parameters such as weather, fog, time of day, and visibility." https://www.appliedintuition.com/case-studies/toyota
  - "ADAS and AD development teams can generate a fully featured map that supports all weather conditions."
  - "Applied Intuition's technical artistry team solves the monotony and repetition problems of 3D world generation by creating more realistic rule sets and automatically varying assets with dust, rust, weathering, weather effects, and other variations." https://www.appliedintuition.com/blog/why-3d-worlds-matter-for-adas-and-ad-development
- **Camera Sensor**
  - No validation of simulation results demonstrated, yet

2.3.6 AVSIMULATION

- **AVSimulation Overview and Integration of Weather Effects**
  - AVSimulation's SCANeR is an automotive simulation software designed for the development and validation of ADAS and autonomous vehicles.
  - The platform includes features to render (not specified, if it has impact on sensor simulation) different weather conditions, allowing for the assessment of their impact on sensor performance and vehicle behavior.
  - Sources:
    - https://www.avsimulation.com/en
    - https://www.avsimulation.com/en/scaner-2021-1-release-note/
- **Examples: Specific Effects for Different Sensor Types**

- SCANeR (Release 2021.1) integrates with Unreal Engine to provide realistic rendering, including weather effects such as atmosphere, volumetric clouds, rain and snow, fog, wind https://www.avsimulation.com/en/scaner-2021-1-release-note/
- **Light Sensor**
  - SCANeR (Release 2021.1): Simulation of sun position, cloud density, fog and shadows, tunnels https://www.avsimulation.com/en/scaner-2021-1-release-note/
- **Lidar**
  - Fog Simulation in Scientific Paper: "The aim of this paper is to present a model that has been developed and used with AVSimulation's SCANeR Studio software, with the use of a specific semi-rotative Lidar." https://hal.science/hal-04720367v1/document

2.3.7 Additional Companies that lean into Weather Effects within Sensor Simulations

2.3.7.1 Nvidia

- **Summary**
  - Nvidia mentions the importance of weather effects in sensor simulations on their homepage with no explicit information on how it is implemented
- **Sources**
  - https://www.nvidia.com/de-de/use-cases/autonomous-vehicle-simulation/?deeplink=content-tab--1
  - https://www.nvidia.com/en-us/glossary/sensor-simulation/

2.3.7.2 RoadRunner Scenario (by MathWorks)

- **Summary**
  - Integration of foggy weather in Lidar Simulations, using visible distance (*FogVisibility*) as a property
- **Source**
  - https://www.mathworks.com/help/lidar/ug/lidar-sensor-model-weather-simulation-for-roadrunner-scenario.html

2.3.7.3 Claytex

- **Summary**
  - Noise - which is originating from weather models using weather station data - is included in Lidar Simulations
- **Source**
  - https://www.claytex.com/blog/adas/lidar-modelling-with-weather/

2.3.7.4 AVL

- **Summary**
  - AVL has developed a 1,700 m² weather chamber for sensor model validation.
  - Artificial rain, fog, and various lighting conditions can be generated.
  - Enables complex dynamic scenarios (e.g., Euro NCAP, AEB, VRU).
  - Different rain intensities, fog visibility ranges, and light conditions are supported.
  - All scenarios can be simulated in a digital twin including weather effects.
  - Ensures close alignment between simulation and real-world sensor performance.
  -
- **Source**
  - https://www.autonomousvehicletechnologyexpo.com/de/conference-program.php?day=3

2.3.7.5 Further Simulation Tools (suspended or not mentioning weather effects)

- https://microsoft.github.io/AirSim/
- https://www.4d-virtualiz.com/
- https://www.opal-rt.com/fr/
- https://www.carsim.com/
- https://github.com/lgsvl
- https://www.mitsuba-renderer.org/

Tool name	Covered weather effects	Sensor technology
Ansys	Wind, rain, fog, snow, dust	Visible camera, thermal camera, lidar
IPG CarMaker	Rain, fog, atmospheric pressure, reflections, spray, snow, sunset	Radar and camera
dSPACE AURELION	Fog, variable lighting/weather effects	Lidar; weather also mentioned for radar and camera without clear sensor-specific implementation details
Siemens Simcenter Prescan	Rain, fog, snow, reflections, varying lighting conditions, raindrops on lenses	Camera; lidar weather support mentioned more generally
Applied Intuition	Weather, fog, lighting, visibility, weathering effects	No sensor explicitly specified; camera mentioned separately
AVSimulation SCANeR	Atmosphere, volumetric clouds, rain, snow, fog, wind, sun position, shadows	Light sensor and lidar
Nvidia	Weather effects mentioned, not further specified	Not specified
RoadRunner Scenario (MathWorks)	Fog	Lidar
Claytex	Weather-model-based noise in lidar simulation	Lidar
AVL	Rain, fog, lighting conditions	Sensor model validation in general; no specific sensor technology named

2.4 ASAM OpenX Standards

ASAM OpenX standards, in particular OpenSCENARIO and the Open Simulation Interface (OSI), already provide mechanisms to describe environmental conditions and to exchange sensor-level data in simulation. However, environmental influences relevant for perception sensor degradation, such as weather intensity, atmospheric attenuation, surface state changes, or sensor contamination, are currently represented only in a limited and largely superficial manner.

The existing parameters are often descriptive rather than performance-relevant and lack clear links to measurable sensor behavior. As simulation increasingly supports safety assessment and homologation-oriented use cases, there is a clear need for stronger joint efforts involving OEMs, Tier-1 suppliers, simulation tool vendors, and sensor model providers, complemented by experimental testing facilities. Such collaboration is essential to define meaningful parameters, valid ranges, and performance-oriented semantics for adverse weather effects, grounded in real sensor measurements. Extending ASAM standards in this direction would significantly improve consistency, credibility, and traceability between real-world testing and virtual validation of perception systems under adverse environmental conditions.

In the following, the current state with regard to environmental influences are listed for the two standards:

ASAM OpenSCENARIO v1.3.1

Properties				
Name	**Type**	**Cardinality**	**AppliedStereo-types**	**Description**
atmospheric Pressure	double	0..1	XSDattribute	Reference atmospheric pressure at z=0.0 in world coordinate system. Unit: [Pa]. Range: [80000..120000]. The actual atmospheric pressure around the entities of the scenario has to be calculated depending on their z position. See also the Standard Atmosphere as defined in ISO2533.
cloudState	CloudState	0..1	XSDattribute, deprecated	Definition of the cloud state, i.e. cloud state and sky visualization settings.
fractionalCloudCover	FractionalCloudCover	0..1	XSDattribute	Definition of cloud states using the fractional cloud cover in oktas.
temperature	double	0..1	XSDattribute	Outside temperature at z=0.0 in world coordinate system. Unit: [K]. Range: [170..340]. The actual outside temperature around the entities of the scenario has to be calculated depending on their z position.
sun	Sun	0..1	XSDelement	Definition of the sun, i.e. position and intensity.
fog	Fog	0..1	XSDelement	Definition of fog, i.e. visual range and bounding box.
precipitation	Precipitation	0..1	XSDelement	Definition of precipitation, i.e. type and intensity.
wind	Wind	0..1	XSDelement	Definition of the wind: direction and speed.
domeImage	DomeImage	0..1	XSDelement	Image reference to represent the sky. Mutually exclusive with "fractionalCloudCover". If the image also contains lighting

Properties	
	information (HDRi) it is also mutually exclusive with "sun".

ASAM OSI (Open Simulation Interface) V3.7.0

Enumerator	
PRECIPITATION_UNKNOWN	Intensity of precipitation is unknown (must not be used in ground truth).
PRECIPITATION_OTHER	Other (unspecified but known) intensity of precipitation.
PRECIPITATION_NONE	No precipitation, when I in [0,0.1[mm/h.
PRECIPITATION_VERY_LIGHT	Very light intensity of precipitation, when I in [0.1,0.5[mm/h.
PRECIPITATION_LIGHT	Light intensity of precipitation, when I in [0.5,1.9[mm/h.
PRECIPITATION_MODERATE	Moderate intensity of precipitation, when I in [1.9,8.1[mm/h.
PRECIPITATION_HEAVY	Heavy intensity of precipitation, when I in [8.1,34[mm/h.
PRECIPITATION_VERY_HEAVY	Very heavy intensity of precipitation, when I in [34,149[mm/h.
PRECIPITATION_EXTREME	Extreme intensity of precipitation, when I in [149,infinity[mm/h.

3. Prospect of Weather Effect Simulation

While the current state of the art shows significant progress in simulating adverse weather conditions, an important gap persists between visually or physically plausible weather rendering and the actual performance degradation of perception sensors observed in real-world conditions. Future perception sensor simulation must therefore evolve toward performance-driven models, capable of reproducing measured detection, classification, and ranging performance as a function of environmental influence.

A key enabler for this evolution is the systematic exploitation of controlled experimental infrastructures. Facilities such as the Persival weather test bench, CEREMA's and CARISSMA's large-scale testing facilities provide reproducible and well-characterized exposure of perception sensors to adverse weather phenomena, including rain, fog, snow, spray, and surface contamination. These infrastructures allow the derivation of quantitative sensor performance curves, capturing the combined effects of atmospheric disturbances, surface state changes, and sensor-internal signal processing.

Rather than explicitly modeling each physical interaction in simulation, a promising prospect lies in injecting empirically derived performance envelopes into sensor models. This performance-oriented approach enables simulation tools to directly reflect measured sensor behavior, such as range reduction, increased uncertainty, noise, or false detections under defined weather intensities. It is particularly aligned with safety assessment needs, where the magnitude and consistency of performance degradation are often more relevant than the exact physical root cause.

Camera performance is strongly affected by adverse weather through reduced visibility, contrast loss, glare, occlusions, and changes in scene appearance due to wet or snow-covered surfaces. Experimental facilities such as Persival, CARISSMA, and CEREMA enable the measurement of camera performance degradation across fog density, rainfall rate, snowfall intensity, and illumination conditions. In simulation, this supports the use of data-driven or hybrid models that modulate image quality, noise characteristics, and feature visibility according to measured performance classes or confidence envelopes. While exact intensity control remains challenging, performance-driven camera simulation can realistically reproduce downstream impacts on perception algorithms, such as object detection and lane recognition robustness.

Lidar sensors are particularly sensitive to adverse weather due to scattering, attenuation, and multi-path effects caused by rain, fog, snow, and spray. This sensitivity has led to a strong push toward standardized performance evaluation. A major milestone in this context is the publication of DIN SAE SPEC 91571:2026-04 – Test methods for Lidar Performance in adverse conditions; released in April 2026. This specification defines standardized test methodologies for evaluating Lidar performance under adverse weather, contamination, and interference conditions, building on the earlier ideal-condition assessment framework in DIN SAE SPEC 91471.

For simulation, this standard provides a critical reference for anchoring Lidar degradation models to measurable, standardized KPIs, such as effective range, detection probability, and noise behavior. Facilities like CARISSMA, CEREMA, and Persival can generate datasets aligned with these test methods, enabling the calibration and validation of Lidar simulation models that reproduce real performance curves rather than purely synthetic effects.

Radar sensors are generally more robust to adverse weather compared to optical modalities, but they are not entirely immune to environmental influences such as heavy precipitation, clutter, and multi-path reflections from wet surfaces. Controlled testing at CEREMA and CARISSMA allows the characterization of subtle performance shifts, including increased noise floors or ghost targets. In simulation, radar models can therefore benefit from lightweight performance modifiers, ensuring consistency with measured behavior while preserving their inherent robustness. This sensor-specific balance is essential to maintain realism in multi-sensor fusion scenarios.

The convergence of experimental weather testing, performance-driven modeling, and standardization efforts such as DIN SAE SPEC 91571 creates a clear prospect for next-generation perception sensor simulation. Simulation environments should enable explicit specification of weather severity levels and link them to validated sensor performance modifiers, ideally through standardized interfaces compatible with ASAM OpenX ecosystems. This would ensure reproducibility, traceability, and comparability across tools and projects.

Within the WeatherSafe project, this prospect directly informs T_Simu.2, where concrete implementations of weather effects in sensor simulation will be demonstrated, and T_Simu.3, where real and synthetic sensor data will be compared using case studies grounded in measured performance. The insights gained will ultimately be consolidated in T_Simu.4, contributing to actionable guidelines for assessing the realism and relevance of adverse weather simulation for road safety applications.

4. Conclusion

This first deliverable of the WeatherSafe Simulation Work Package has provided a comprehensive overview of the current state of the art in simulation means addressing adverse weather conditions in road safety. By reviewing existing international research activities, open-source and commercial simulation tools, and relevant standardization efforts, the report establishes a clear baseline of current capabilities and limitations in the simulation of weather effects on vehicle perception.

The analysis shows that simulation technologies have reached a high level of theoretical knowledge in terms of scenario description, traffic modeling, and sensor data generation. Many simulation environments today are able to represent adverse weather conditions at a descriptive or phenomenological level, enabling the visual depiction of rain, fog, snow, or reduced visibility. However, when it comes to perception sensor simulation, these representations remain largely insufficient to capture the quantitative performance degradation observed in real-world conditions.

This gap is particularly critical for safety-oriented applications, where understanding how sensor performance degrades under adverse weather is essential for the validation of ADAS and automated driving functions. The review of perception sensor modeling highlights strong differences between sensor modalities. Cameras, lidars, and radars are affected by environmental conditions in fundamentally different ways, requiring sensor-specific modeling approaches. While data-driven and hybrid methods are increasingly explored in research, their integration into mainstream simulation workflows remains limited. At the same time, large-scale experimental facilities such as CEREMA, and CARISSMA demonstrate that it is possible to measure sensor performance under controlled and reproducible adverse weather conditions, providing a solid empirical basis for performance-driven simulation.

From a standardization perspective, ASAM OpenX standards such as OpenSCENARIO and OSI already offer a common framework for describing environments and exchanging simulation data. Nevertheless, environmental influences relevant for perception sensors are currently modeled only in a superficial manner, with limited semantics and weak links to measurable sensor behavior. Recent initiatives such as the publication of DIN SAE SPEC 91571 for lidar performance testing in adverse conditions underline the growing industrial consensus on the need for standardized, performance-oriented evaluation methods. These efforts provide important reference points for future extensions of simulation standards.

Overall, this deliverable highlights a clear and consistent message: future progress in adverse weather simulation will depend on a closer alignment between real-world sensor testing, performance characterization, and simulation modeling. Achieving this alignment requires stronger collaboration between OEMs, TIER-1 suppliers, sensor manufacturers, simulation tool providers, and testing facilities. Only through such joint efforts can meaningful parameters, valid ranges, and credible performance models be defined and integrated into simulation environments.

5. Acknowledgements

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

