Advancing Wind Tunnel Vehicle Soiling Studies with a Realistic Dynamic Rain Simulation System

[1]Long (Tom) Li, [2]Wing Yi (Roxana) Pao, [1]Eric Villeneuve, [1,2]Keira Wilson, [1]Warren Karlson

[1]ACE Climatic Aerodynamic Wind Tunnel
[2]Faculty of Engineering and Applied Science
Ontario Tech University
2000 Simcoe St N, Oshawa, ON, Canada L1G 0C5

long.li@ontariotechu.ca
wingyi.pao@ontariotechu.net
eric.villeneuve@ontariotechu.ca
keira.wilson@ontariotechu.net
warren.karlson@ontariotechu.ca

Abstract: Rainfall is one of the most prevalent environmental challenges for road vehicles, impacting visibility and sensor performance. As automated features become standard in modern vehicles, ensuring sensor reliability in adverse weather is more critical than ever. Climatic wind tunnels provide controlled environments for vehicle soiling and sensor studies, but traditional spray nozzle systems lack independent control over rain characteristics, limiting their ability to replicate realistic rain conditions. Sensors such as cameras and LiDARs are highly sensitive to these parameters, requiring precise and repeatable testing for real-world validation. This paper presents a novel rain simulation system, the Vectorized Rain Simulation Apparatus (VeRSA), developed at Ontario Tech's ACE Climatic Aerodynamic Wind Tunnel. It employs vectorized water injection and controlled droplet dynamics to generate realistic rain conditions that can be characterized, repeated, and benchmarked. Demonstrations are provided through rain characterization, perception testing of cameras and LiDARs, and early-stage UV dye tracing for vehicle soiling analysis. By overcoming the limitations of traditional systems, VeRSA significantly enhances realism, supporting both academic research and commercial testing. This integrated approach marks a milestone in advancing weather-resilient ADAS and autonomous vehicle development.

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1 Introduction

The role of climatic wind tunnels in realistic soiling evaluation

Understanding how vehicles perform under real-world environmental conditions is critical, especially when it comes to visibility and sensor reliability. That's where climatic wind tunnel testing plays a key role. By simulating both aerodynamic forces and perceived precipitation, these facilities allow engineers and researchers to analyze how rain, spray, and dirt accumulate on vehicle surfaces – a process known as vehicle soiling.

There are three main ways soiling occurs, shown in Figure 1: primary soiling from precipitation, secondary soiling from spray generated by nearby traffic, and self-soiling from the vehicle's own tires on wet roads. Each type introduces unique challenges, particularly for ADAS and autonomous sensors that depend on clear, unobstructed views to operate effectively.

Climatic wind tunnels allow engineers to simulate and control a wide range of conditions – from droplet size and precipitation density and intensity. This capability makes it possible to evaluate vehicle and sensor performance under repeatable, realistic conditions, ultimately helping manufacturers design vehicles that stay cleaner, safer, and smarter on the road.

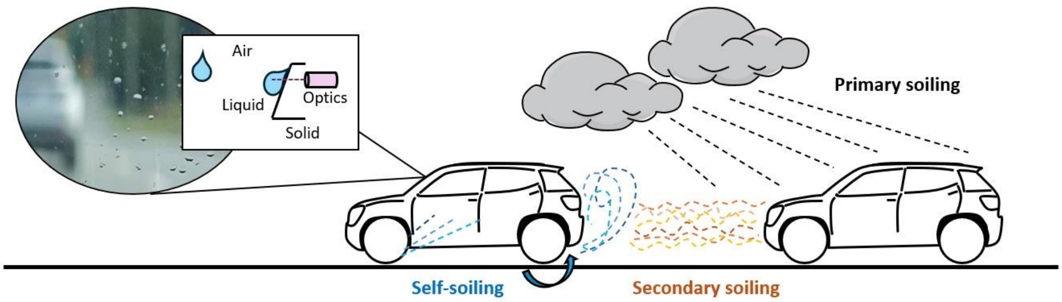

Figure 1: Schematic demonstration of vehicle and sensor soiling.

Why sensor testing in weather matters

Autonomous vehicles rely on a network of sensors to interpret their surroundings and make real-time driving decisions [1]. However, weather conditions can severely impact sensor accuracy and system performance. Cameras and LiDARs are highly sensitive to individual raindrops and water streaks; RADARs and ultrasonic sensors are more affected by snow and ice buildup. When any of these systems are impaired, so are crucial functions like collision avoidance, adaptive cruise control, lane-centering, and auto-steering. That's why it is essential to test these systems in controlled yet realistic conditions, ensuring they perform reliably, not just in perfect weather, but in rain, fog, and snow as well.

Meeting the demands of full autonomy

As industry moves closer to SAE Level 5 autonomy [2], the margin for error narrows. Weather remains one of the most complex variables to solve. To ensure consistent sensor performance, manufacturers must go beyond traditional testing approaches and adopt repeatable methodologies that replicate adverse weather scenarios.

Several testing methods have emerged, ranging from real-world driving to indoor simulation. While field testing provides valuable insights, it is time-consuming and vulnerable to unpredictable variables like wind gusts or sun glare. Outdoor proving grounds face similar limitations. This is where climatic wind tunnels offer a distinct advantage, allowing precise manipulation of wind, droplet size, and intensity, providing a faster and more consistent path toward validating autonomous systems for all-weather performance.

Evolving beyond traditional methods

Climatic wind tunnels have been in use since the mid-20th century, originally focused on simulating rain for aircraft wings, buildings, turbines, and vehicles. But today, the goal has shifted: it is no longer just about measuring water exposure, it is about understanding how rain affects sensor perception. Here, droplet size distribution becomes critical. For instance, tire spray and light rain may have similar overall intensity, but they affect visibility very differently due to the size, shape, and impact area of individual droplets. These characteristics must be captured accurately to reflect real-world driving conditions.

The challenge of creating realistic rain

Simulating rain in a climatic wind tunnel isn’t simple. Several types of rain systems are commonly used, each with strengths and limitations: spray nozzle systems can cover large areas, but often produce excessively fine droplets at higher pressures, making them better suited for secondary soiling studies. Sprinkler systems suffer from significant pressure loss and lack fine control over droplet size and flow rate, making them less ideal for consistent sensor testing. Drop former systems create larger and more realistic droplets at lower pressures but often require heavy overhead reservoirs with limited adjustability.

As the demands of autonomous vehicle development continue to grow, so does the need for greater precision and adaptability in rain simulation systems. Addressing these challenges means rethinking how rain studies should be carried out.

Advancing ADAS sensor testing – toward industry benchmarking

To meet these challenges, this paper presents advanced methodologies and improvements to rain study strategies, offering a more robust and realistic framework for testing perception systems in climatic wind tunnels. As part of this contribution, the paper benchmarks best practices for sensor testing in wind tunnels, setting a new standard for evaluating environmental impact on vehicle perception. These advancements lay the groundwork for more weather-resilient, perception-aware vehicles, accelerating progress toward safe and reliable autonomy in all driving conditions.

2 Background Work

Proven methodology for sensor testing in controlled environments

Over the past several development cycles, we have established and refined a wind tunnel-based testing methodology tailored specifically for ADAS and autonomous vehicle sensor evaluation [3]. This work has laid key milestones in the field, combining academic rigor with real-world application to address the growing need for weather-resilient perception systems. There are two core components to this methodology: (1) realistic rain simulation and (2) representative sensor evaluation. This framework has been successfully applied in a number of studies, at the ACE Climatic Aerodynamic Wind Tunnel, focused on sensor soiling, visibility degradation, and performance loss, offering a robust platform for evaluating perception systems across a broad spectrum of use cases.

Bridging outdoor rainfall and controlled testing

To effectively design wind tunnel rain testing conditions, several fundamental questions must be answered – how much rain does a moving vehicle encounter? What are the characteristics of the rain events? – These questions form the basis of what we refer to as perceived precipitation, that is the rainfall conditions experienced by the vehicle as it moves through the environment, rather than simply what falls from the sky. Recreating this perceived precipitation accurately in a controlled environment is essential to producing realistic sensor soiling and performance outcomes.

To support the design of realistic and consistent wind tunnel rain conditions, a perceived precipitation intensity model was developed. This model was built using outdoor validation experiments, combining both dynamic on-vehicle measurements and static reference data from weather towers [4]. The model helps translate real-world rainfall conditions into wind tunnel parameters, considering driving speed, surface orientation and geometry, droplet size distribution, and crosswinds, demonstrated in Figure 2. Representative rain categories – drizzle, light, moderate, heavy, and downpour – were defined based on field data.

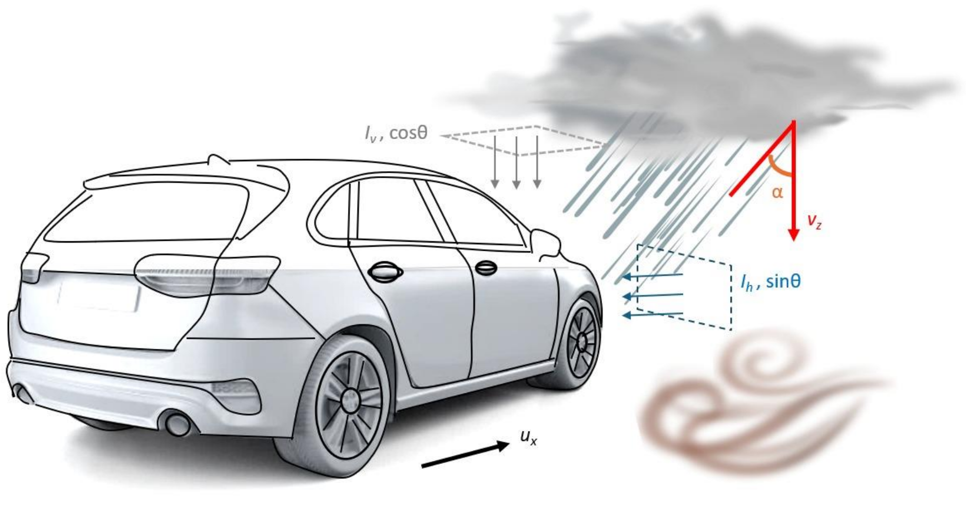

Figure 2: Schematic demonstration of perceived precipitation.

Evaluating sensor soiling and performance in wind tunnel testing

The rain testing methodology developed in our wind tunnel is designed to be scalable and flexible, ranging from sensor-level studies to full-vehicle evaluations with integrated ADAS systems. To quantify performance under rain exposure, we established a suite of objective metrics, tailored to both camera and LiDAR sensors.

A theoretical model was developed to estimate performance degradation based on incoming raindrop size distributions and surface wettability characteristics [5]. This model supports interpretation of experimental results by linking physical parameters to sensor behaviour.

With repeatable, and realistic rain testing capabilities, the test platform enables a variety of parametric studies, including the effect of surface materials on soiling [6], the evaluation of soiling mitigation strategies [7], and even sensor data training under controlled environmental variation [8]. Representative results from these studies are shown in Figure 3.

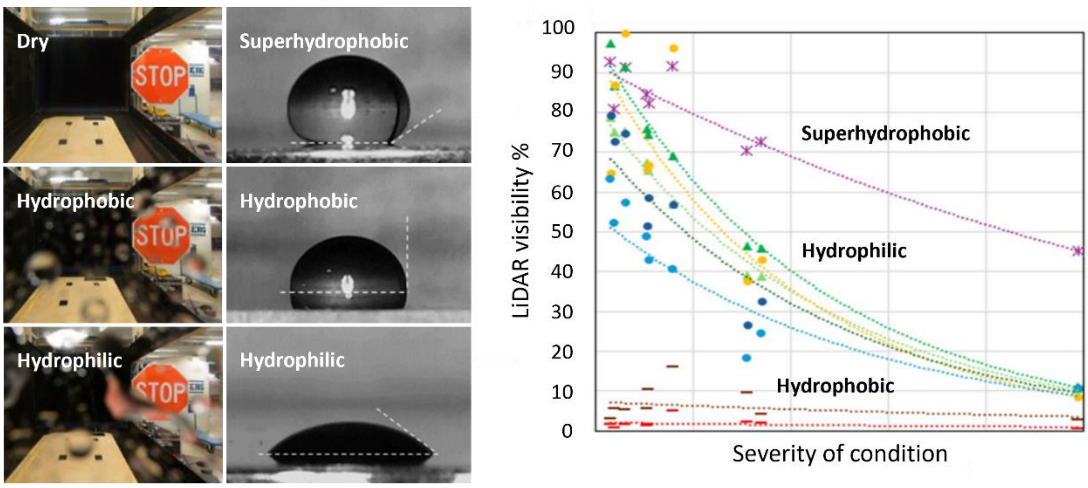

Figure 3: Sensor response varies by surface material in wet conditions.

The overall procedure for conducting ADAS sensor testing in the climatic wind tunnel includes:

1. Selection and calibration of the desired rain condition (based on perceived precipitation model);
2. Application of these calibrated rain profiles onto the vehicle or sensor setup;
3. Recording and analysis of the resulting sensor data.

Further advancements in methodology are discussed in Sections 3 and 4, including expanded rain characterization, integration with moving targets, and development of more advanced testing strategies for sensor evaluation. With growing understanding of both multiphase aerodynamics and sensor-environment interactions, we have broadened our wind tunnel testing capabilities to capture more realistic and complex driving scenarios, such as dynamic camera tracking and LiDAR target discrimination in adverse weather.

The following sections present a full-tunnel rain characterization and highlight practical examples of vehicle soiling and sensor performance evaluation for camera and LiDAR sensors under primary, secondary, and self-soiling conditions.

3 Full Tunnel Rain Characterization

The ACE Climatic Aerodynamic Wind Tunnel is equipped with the Vectorized Rain Simulation Apparatus (VeRSA), a system designed to reproduce realistic precipitation in both vertical and horizontal orientations. The “Ve” in VeRSA highlights the flexibility of this approach, where vertical rain can be combined with horizontal injection to recreate complex weather conditions that vehicles encounter on the road. Together, these systems make it possible to move beyond simplified water spray and deliver controlled, quantifiable rainfall for sensor testing and vehicle development. Figure 4 illustrates the vertical and horizontal rain system in operation, showing rainfall interaction with both the Laser Precipitation Monitor (LPM) and a vehicle positioned in the test section.

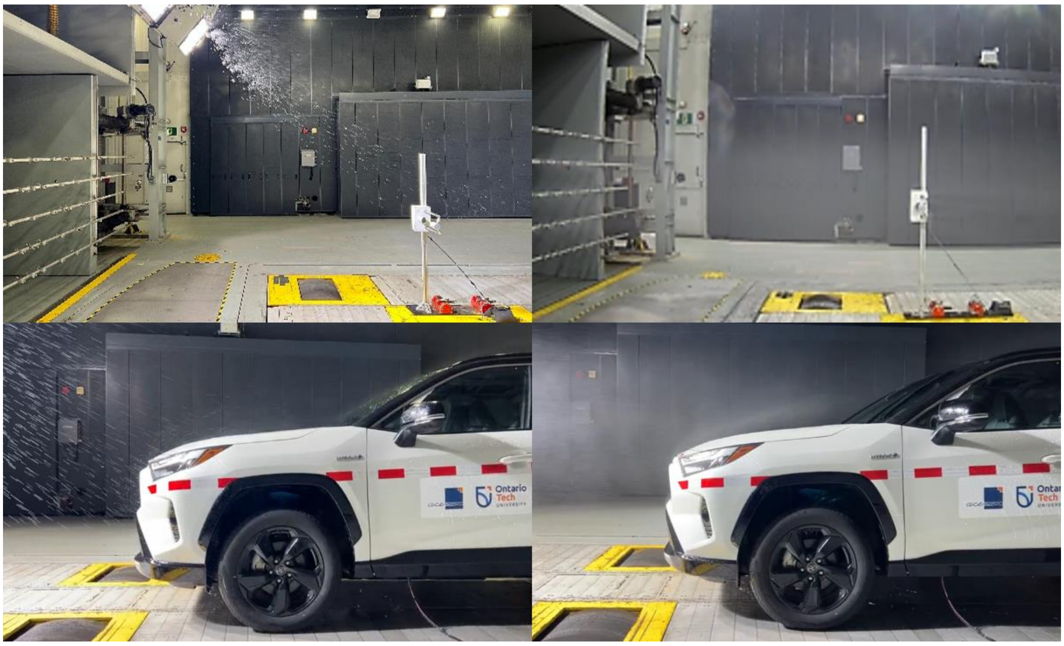

Figure 4: Vertical and horizontal rain system demonstration, with LPM and vehicle.

A full characterization of the rain system has been conducted in the jet symmetry plane, where y = 0 at the tunnel centreline. For the vertical rain configuration, parameters such as nozzle spacing, vertical and horizontal positioning, and flow rate were evaluated. For the horizontal rain configuration, nozzle selection, flow rate, and bar positioning at the nozzle exit plane were assessed. Representative results from these tests are shown in the performance envelopes of intensity and droplet size distribution at 50 km/h, providing a clear picture of how the system can be tuned to match desired conditions, presented in Figure 5.

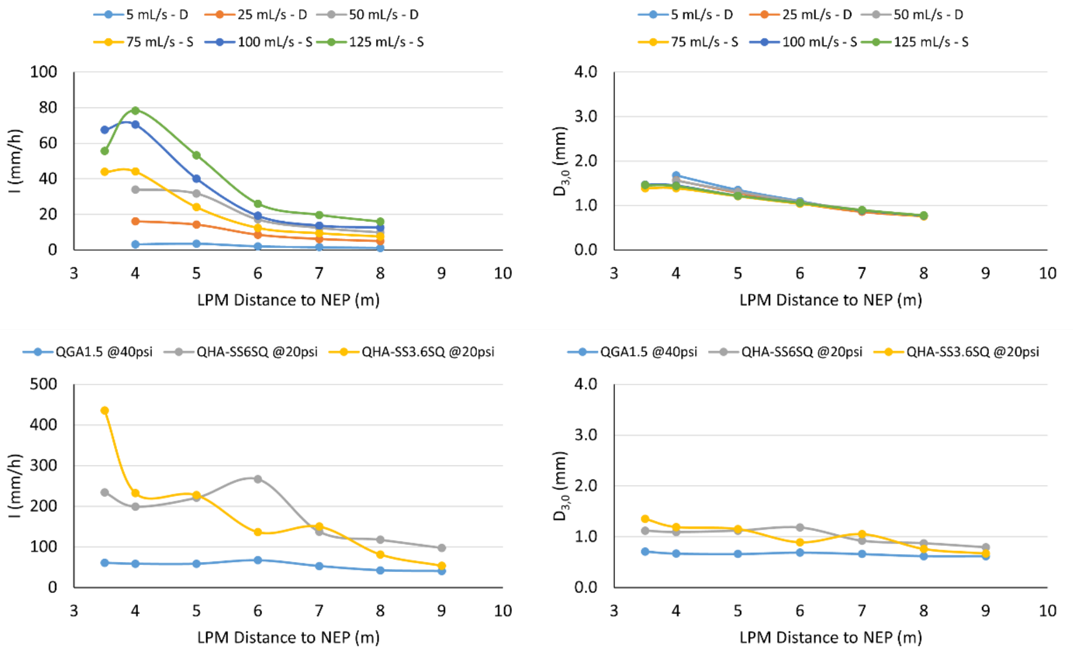

Figure 5: Rain characterization result samples at y = 0 symmetry plane, 50 km/h wind speed, presenting top left: vertical rain system intensity; top right: $D_{3,0}$ (mm); bottom left: horizontal rain system intensity; and bottom right: $D_{3,0}$ (mm).

The vertical system shows strong sensitivity to distance between the nozzle plane and the vehicle. This allows flexible positioning: shifting the vehicle one metre further downstream, for example, can be matched by moving the nozzle plane the same amount, maintaining consistent rain delivery while also opening space for additional equipment such as sensor targets. The horizontal system, in contrast, produces highly uniform droplet size characteristics across the flow field. Because the nozzles are mounted directly at the exit plane, the test vehicle can be positioned precisely where the target rainfall profile is achieved. This combination of adaptability and repeatability makes VeRSA a powerful tool for tailoring rain to different test scenarios.

Another important distinction lies in the behaviour of the two systems. Vertical rain is influenced by transient droplet breakup and coalescence as droplets travel through the air, leading to variations in distribution with distance. This sensitivity creates both challenges and opportunities. Larger droplets tend to arrive at shallower approach angles while smaller droplets follow steeper paths, which reduces uniformity across the full test section. At the same time, these dynamics make it possible to tune rain characteristics at a very specific local position, such as a sensor or windshield, broadening the range of achievable test conditions. By contrast, the horizontal system provides consistent volume mean droplet sizing ($D_{3,0}$) across the test section, enabling stable and predictable exposure conditions. Together, these complementary behaviours allow both realistic variability and highly repeatable uniformity to be recreated, depending on the testing objective.

The results shown here are only a small preview of the system's capability. VeRSA enables a wide range of realistic rain environments, from fine drizzle to heavy downpours, with droplet distributions and intensities that can be characterized, repeated, and benchmarked. In the following sections, sensor data will be presented to demonstrate why these rain characteristics matter, and how the ability to control them is critical for evaluating perception systems under adverse weather.

4 Vehicle and Sensor Soiling Evaluation

In this study, sensors were positioned inside the vehicle behind the windshield to evaluate performance under controlled rain exposure. Both cases, with and without a clearing device, were tested to represent common water management strategies. For each condition, the vehicle surface was first soaked for two minutes to reach a steady-state soiling level before sensor data collection. This ensured consistency across tests and reduced nonlinear effects caused by initial droplet accumulation. Transient performance during accumulation and clearing could also be analyzed in real time, providing a more complete picture of sensor behaviour under rain.

4.1 Camera

Camera evaluation was carried out at 50 km/h under three vertical rain conditions: drizzle at 1.7 mm/h, moderate rain at 24.0 mm/h, and downpour at 186.2 mm/h. Vertical rain was selected to avoid aerodynamic interference from horizontal nozzle bars and to maintain an unobstructed projection field. A GoPro Hero 7 was used as an open-source device to demonstrate methodology without disclosure restrictions. While not representative of commercial ADAS hardware, it provided a consistent platform to showcase the precipitation testing capabilities of the ACE Climatic Aerodynamic Wind Tunnel.

A dynamic projection technique was deployed to create a controlled driving scene within the tunnel, shown in Figure 6. The Berkeley Deep Drive Attention (BDD-A) dataset was projected onto the flow-straightening mesh screen [9], enabling repeatable perception testing under controlled rain conditions. This system is still in early prototyping, with plans for integration into the tunnel infrastructure to support broader testing scenarios.

Figure 6: Dynamic display with physical rain simulation hybrid digital twin platform. Sample object detection quality on dynamic and static targets.

Object detection was performed using YOLOv3 pretrained on the MS-COCO dataset, focusing on road-relevant targets such as a stop sign, car, pedestrian, and bicycle [10, 11]. In parallel, image quality was evaluated using four complementary metrics: mean squared error (MSE), structural similarity index (SSIM), peak signal-to-noise ratio (PSNR), and the MSU Blurring Index with sigma and delta variations. Together, these metrics provide a multidimensional perspective on how rain alters perception.

The results, summarized in Figure 7, show that without any clearing device, detection performance collapsed across all rain intensities. Detection count and model confidence remained near zero even in drizzle, and quality metrics steadily declined as droplets accumulated. With a physical mitigation device activated, perception recovered significantly. Detection count rose to nearly 50% in drizzle with confidence reaching 80%, and partial recovery was observed in moderate and downpour cases. These devices did not eliminate rain effects, but by periodically restoring visibility, they reset perception above a usable threshold and prevented the sensor from sliding into complete blindness.

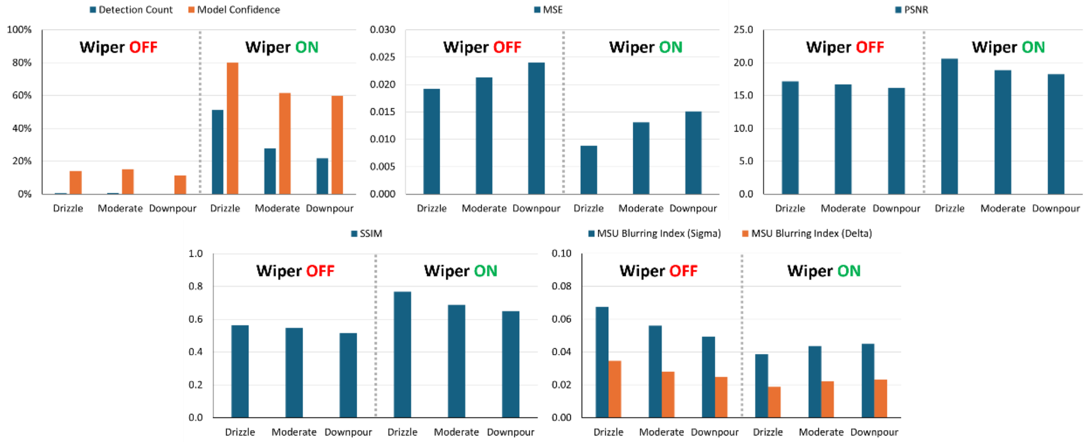

Figure 7: Object detection and image quality evaluation under drizzle, moderate rain, and downpour conditions at 50 km/h, comparing wiper off and wiper on cases.

Frame-by-frame PSNR analysis reinforces this effect. In drizzle without clearing, PSNR values hovered around 17 dB with little variation, reflecting a continuous decline in image fidelity. With clearing engaged, PSNR values reset sharply upward each cycle before gradually decaying again, creating a sawtooth pattern in values. This behaviour illustrates how mitigation works in practice: not by holding visibility constant, but by restoring it in repeated intervals so that sensor perception remains within operational limits.

Image quality metrics further highlight these dynamics. MSE and blurring indices rose quickly without clearing, while SSIM and PSNR dropped, showing degradation of both pixel fidelity and structural features. With clearing, all four metrics improved, particularly in drizzle and moderate rain. Even in downpour, where degradation was strongest, the ability to reset visibility maintained partial functionality that would otherwise have been lost.

The key lesson is that rain intensity alone is not a predictor of performance. Light drizzle without clearing caused near-total blindness, while heavy downpour with clearing allowed intermittent recovery. This underscores the importance of replicating droplet behaviour, film formation, and clearing dynamics, not simply water quantity. Controlled wind tunnel testing enables these effects to be created systematically, providing insights into both sensor limitations and mitigation strategies.

These demonstrations reflect the dual role of the ACE Climatic Aerodynamic Wind Tunnel. As the core research facility of Ontario Tech University, ACE supports academic advances in sensor evaluation and environmental testing. At the same time, ACE operates as a commercial testing facility, providing industry clients with controlled, repeatable environments to validate and improve ADAS performance. The ongoing development of precipitation capabilities, including dynamic projection and coupled perception evaluation, underscores a continuing commitment to advancing both research and industry needs in the automotive sector.

4.2 LiDAR

For LiDAR testing, the vehicle was positioned at X = 7.5 m downstream in the wind tunnel. This location provided sufficient field of view and range for stationary targets, which are necessary since LiDAR relies on reflections from solid objects and does not register projected imagery. Two groups of targets were included for analysis: a close-to-mid field set positioned between 4 and 8 m, and a far field target at 22 m. Bounding boxes were applied around each cluster of points in the point cloud to enable quantitative comparison. The target set included common road objects such as a stop sign, bicycle, pylon, dog silhouette, pedestrian mannequin, passenger car mock-up, and spray bars, presented in Figure 8. In addition, the wind tunnel flow-straightening honeycomb and mesh screens were used as far-field references. The dense mesh screen, in particular, provided a highly consistent reflective surface that served as an effective benchmark for evaluating long-range detection reliability. By combining everyday driving targets with structured reference objects, both practical and controlled scenarios could be studied without overlap in the point cloud.

Both the vertical rain system and the horizontal spray system were employed to evaluate primary rain exposure and secondary soiling. Three intensities of rain and one tire spray case were tested at 50 km/h, providing a range of realistic conditions.

The results highlight how strongly LiDAR performance depends on weather characteristics. Figure 8 illustrates the effect: in dry conditions, the point cloud captured the full set of targets clearly, while in heavy rain much of the detail was lost, leaving only partial object recognition. Quantitative analysis reinforces these visual impressions. Visibility percentages (Figure 9, left) dropped steadily with increasing severity, with tire spray producing the steepest decline. In contrast, normalized reflectivity (Figure 9, right) sometimes increased under degraded conditions, particularly for reflective objects, as droplets magnified their signal returns. These competing effects show why uncontrolled outdoor testing can be misleading: a sensor may appear to perform better in one instance and worse in another, depending on random droplet interactions rather than consistent environmental factors.

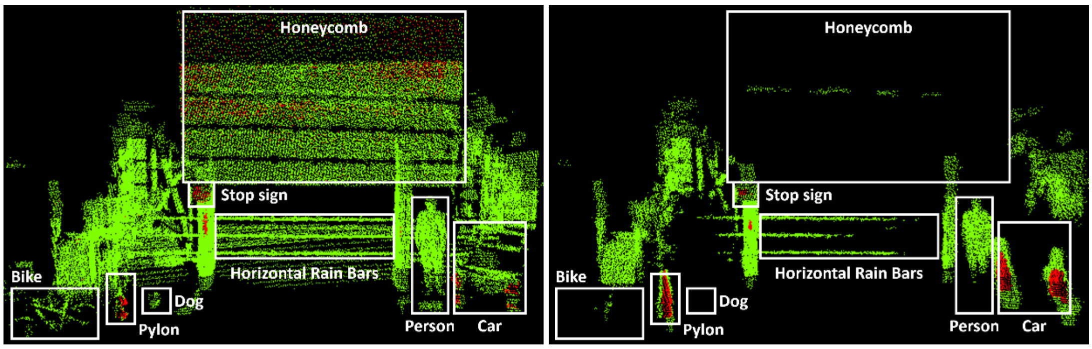

Figure 8: LiDAR point cloud comparison of detection targets in dry (left) and degraded rain conditions (right). Near-field objects include a stop sign, bicycle, pylon, dog silhouette, pedestrian mannequin, car tail gate, and spray bars, while the far-field honeycomb serves as a consistent reference target.

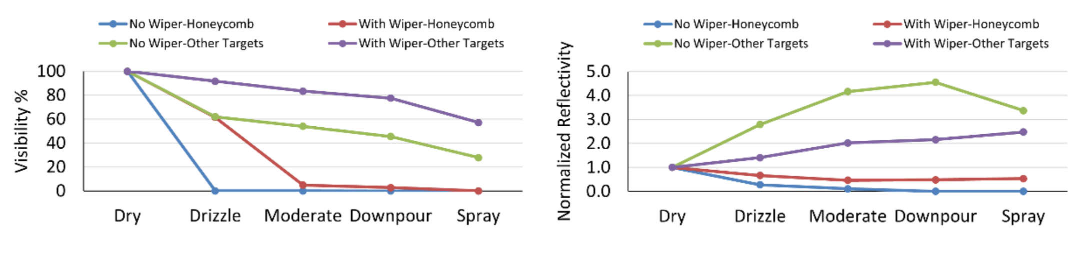

Figure 9: LiDAR visibility percentage (left) and normalized reflectivity (right) for honeycomb and other detection targets under dry, drizzle, moderate rain, downpour, and spray conditions, comparing wiper off and wiper on cases.

Rain quality and droplet dynamics were found to be central to LiDAR perception. Droplet size distribution, number density, and local trajectories each influenced how much of the beam was attenuated before reaching the target. Without control of these parameters, it becomes impossible to separate sensor limitations from environmental variability. By reproducing defined droplet distributions in the tunnel, it becomes feasible to explore practical design trade-offs. Should LiDAR be tuned to capture the broader environment at lower confidence, or accept blind zones while enhancing the detection of reflective objects? Should the sensor be positioned in the aerodynamically cleanest location, or recessed behind a protective surface that alters the field of view? These are real engineering decisions that require quantitative evidence to resolve, and they benefit most from close collaboration between academic research and commercial testing.

Physical mitigation devices add another dimension. Systems such as wipers, shutters, or protective covers can temporarily clear or shield a sensor, but they also introduce brief occlusion. In this demonstration, placing the LiDAR behind a windshield simulated such a device. The results showed that while clearing reduced long-term degradation from droplet accumulation, it also interrupted visibility in short intervals. This mirrors the broader challenge of balancing active and passive mitigation approaches, since neither fully resolves the influence of rain and spray.

Beyond visibility and reflectivity, a wide range of LiDAR behaviours can be studied in a controlled tunnel environment. Material interactions can be evaluated by mounting sensors behind different cover panels or coatings to measure how transmission changes when droplets adhere or shear across surfaces. Local droplet dynamics, including breakup, coalescence, and thin film formation, can be reproduced to study their effect on scattering. Performance can be mapped across conditions that include both uniform rainfall and complex spray patterns, allowing sensitivity to droplet size and number density to be quantified. Tunnel testing also makes it possible to examine placement strategies by shifting sensor position relative to the flow and observing how aerodynamics influence soiling and visibility. Together, these capabilities extend LiDAR evaluation well beyond simple range reduction, enabling systematic exploration of how environment, design, and materials interact to shape perception reliability.

4.3 Soiling Patterns

Ultraviolet dye tracing is a technique where water mixed with fluorescent dye is illuminated under UV lighting and recorded with a camera fitted with a green filter. Areas with greater surface soiling accumulate more dyed water, producing stronger fluorescence that can be quantified through image processing. By converting images into grayscale intensity maps, deposition patterns can be measured and compared across different vehicle regions. Previous work by Gaylard and Gulavani at the FKFS facility in Germany demonstrated the effectiveness of this method [12, 13], particularly in evaluating tire spray-induced soiling.

This capability is now being developed at the ACE Climatic Aerodynamic Wind Tunnel. As an early demonstration, dye tracing was applied to evaluate spray deposition along the side and rear of a test vehicle. Figure 10 shows the front half of the vehicle side, where tire-induced soiling is visible and captured through intensity mapping, as well as results on the tailgate, where deposition is less pronounced due to the absence of UV illumination and filtering, but still detectable through processing. These examples demonstrate how localized accumulations can be visualized and quantified for objective soiling evaluation.

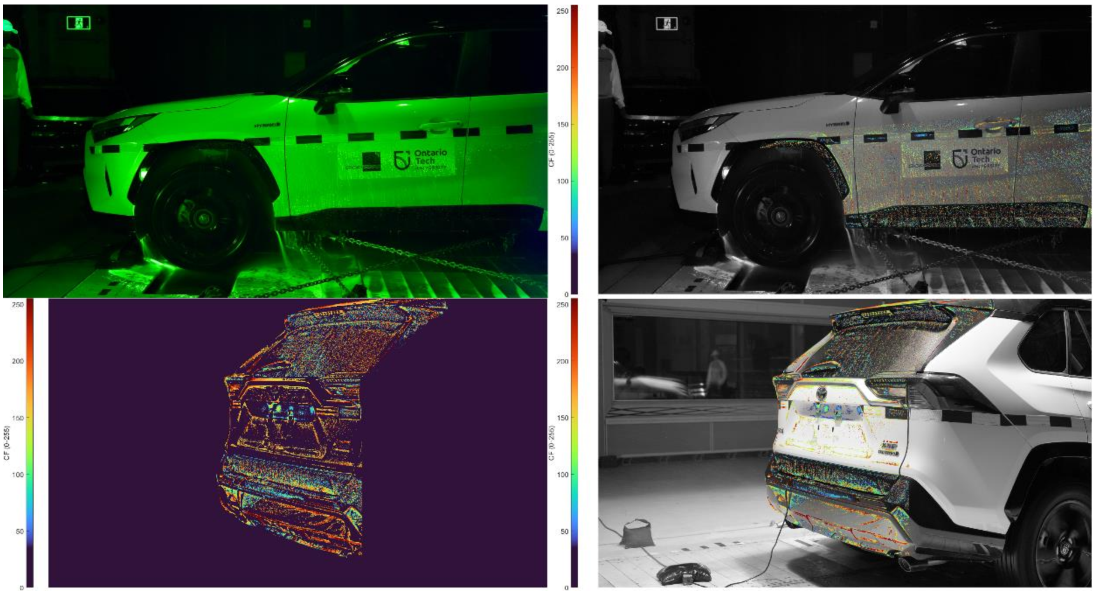

Figure 10: UV dye tracing demonstration. Top: raw side image with UV illumination and filter (left) and processed soiling intensity map (right). Bottom: rear surface overlays without UV illumination or filtering, where reflections appear alongside dyed water deposition.

Unlike FKFS's experiments, which wrapped vehicles in vinyl to reduce reflections, the demonstration was carried out directly on a production vehicle surface. Vinyl wrapping reduces background noise from UV reflections, making dyed particles easier to detect, but it does not represent how real vehicle surfaces interact with water. As shown in Pao's research on material properties, soiling behaviour depends on contact angle and surface energy. On hydrophobic surfaces, droplets may remain as particles, while on hydrophilic regions they may merge into rivulets and run off. Preserving the true surface behaviour is essential for evaluating soiling in a realistic context, even if it introduces additional noise in early-stage processing. At this stage, the results reflect an early attempt to capture vehicle surface soiling intensity, with further refinement underway. The focus is on building the foundation for more robust methods, while acknowledging the pioneering work already carried out at facilities such as FKFS.

The results presented here are preliminary, but they illustrate the potential of dye tracing as a complement to rain and spray simulation. The technique provides a direct, visual method for assessing where water accumulates and how it travels across a vehicle surface. With continued development, dye tracing will expand the range of tools available at ACE for sensor soiling and vehicle cleanliness studies, further strengthening its role as both a research facility of Ontario Tech University and a commercial testing centre for the automotive industry.

5 Conclusions and Future Work

Climatic wind tunnels provide a controlled and repeatable environment for evaluating how precipitation and spray affect vehicles and sensors. The demonstrations presented here highlight both established and emerging capabilities at the ACE Climatic Aerodynamic Wind Tunnel, from full-tunnel rain characterization to camera and LiDAR perception testing, and early-stage UV dye tracing for surface soiling. Together, these methods show how environmental factors can be recreated with precision to reveal sensor behaviours that would be unpredictable in outdoor testing.

As the core research facility of Ontario Tech University and a commercial testing centre for the automotive industry, ACE continues to advance tools and techniques for weather-resilient vehicle development. By combining environmental simulation with sensor evaluation, the facility provides a pathway toward reliable ADAS performance and lays the foundation for broader industry benchmarking in adverse weather conditions.

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