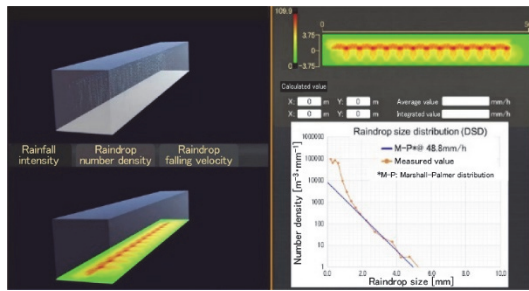


Innovation of Autonomous Mobility Safety Evaluation: Utilization of Meteorological Characteristic Data



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Autonomous driving systems are being vigorously developed worldwide and are expected to exhibit dramatic improvements in capability and widespread adoption in the future. To guarantee their safety and security, it is necessary to verify that sensors and systems function normally under diverse natural environments (rain, fog, light, snow, etc.). Anticipating the growing need for such verification, Mitsubishi Heavy Industries Machinery Systems, Ltd. has developed the indoor Adverse Weather Automated-driving Research Environment as an evaluation system for autonomous mobility. This report introduces a case where two rainfall environments with different raindrop size distributions despite having the same rainfall intensity were generated, and their impacts on LiDAR were compared; as a result, the reduction rate of reflection intensity varied depending on the rainfall environment, thereby demonstrating the importance of evaluation that considers detailed meteorological characteristic data.

1. Introduction

As the widespread adoption of autonomous mobility progresses, establishing a technological foundation to objectively and quantitatively evaluate safety and reliability has become an important challenge. Autonomous mobility systems recognize their surrounding environments by combining multiple sensors, such as cameras, LiDAR, and radar; however, weather conditions such as rain and fog exert a significant impact on the perception performance of these sensors. Here, since the scattering and attenuation characteristics of electromagnetic waves change depending on the drop size distribution (hereinafter referred to as DSD) for rain and fog, it has been reported that even under the same rainfall intensity or fog visibility, variations in the DSD cause differences in sensor outputs and perception results ⁽¹⁾.

Meanwhile, among existing weather emulation facilities used for sensor performance evaluation under adverse weather conditions, many facilities utilize an average rainfall intensity obtained by dividing the total water volume per unit time from ceiling nozzles by the area of the test region and use the time-average value of a small number of visibility meters as the representative visibility of the entire space. Consequently, it is difficult for these facilities to conduct evaluations that sufficiently reflect detailed meteorological characteristics, such as rainfall intensity, the spatial distribution and temporal variation of fog visibility, as well as the DSD, making it a constraint in grasping the response characteristics of each sensor and their quantitative correlations.

This report introduces a case evaluation of LiDAR perception performance utilizing high-resolution meteorological characteristic data, such as rainfall intensity and DSD, acquired via the Adverse Weather Automated-driving Research Environment. Furthermore, it demonstrates that by utilizing high-resolution characteristic data, it is also possible to realize the estimation of sensor signal strength attenuation and the refinement of simulation models for sensor perception functions.

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2. Meteorological characteristic data

The rainfall environment of the Adverse Weather Automated-driving Research Environment can reproduce not only rainfall intensity but also the DSD and falling velocity characteristics observed in nature, and is capable of acquiring the spatial distribution of these rainfall characteristic data. Even under the same rainfall intensity conditions, test conditions can be set taking into account differences in DSD, such as "dominated by small-diameter raindrops" or "including large-diameter raindrops," making it possible to systematically evaluate the impact of differences in DSD on sensor perception performance. Furthermore, by combining computer simulation with proprietary control technology, the fog environment can freely replicate and stably maintain visibility from 200 m to 10 m, enabling the acquisition of temporal change data for visibility. Note that for details on fog emulation, please refer to reference (2). This report focuses on the rainfall environment.

Figure 1 shows a schematic diagram of the demonstration test facility of the Adverse Weather Automated-driving Research Environment, in which a disdrometer (**Figure 2**) is installed inside the facility to acquire the DSD and falling velocity. Representative examples of the DSD and falling velocity distribution for Rain A and Rain B, which have different rainfall characteristics, are shown in **Figure 3**. The measured values are shown in orange; for reference, the Marshall-Palmer distribution (a representative model of raindrop distribution in nature) and the experimental values of Gunn–Kinzer (the relationship between the drop size and terminal velocity falling through still air) are shown by blue lines. Here, the reason the falling velocities of the measured values have not reached terminal velocity is due to constraints from the ceiling height of the demonstration test facility where the rain nozzles are installed; however, if necessary, mapping to natural rainfall is also possible by applying a correction based on the ratio to the terminal velocity for each drop size. In addition, the spatial distribution of rainfall characteristic data can be acquired by changing the installation positions of the rain gauges and the disdrometer. As a concrete example, **Figure 4** shows the spatial distribution of rainfall intensity. By changing the arrangement of the sensor and target, test systems with various rainfall intensities can be constructed efficiently, and the correlation between the spatial variations in characteristic data and sensor perception can also be analyzed.

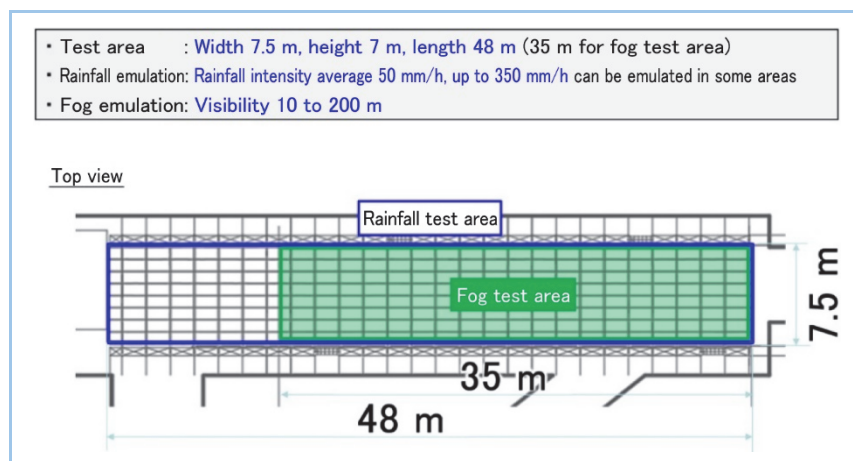
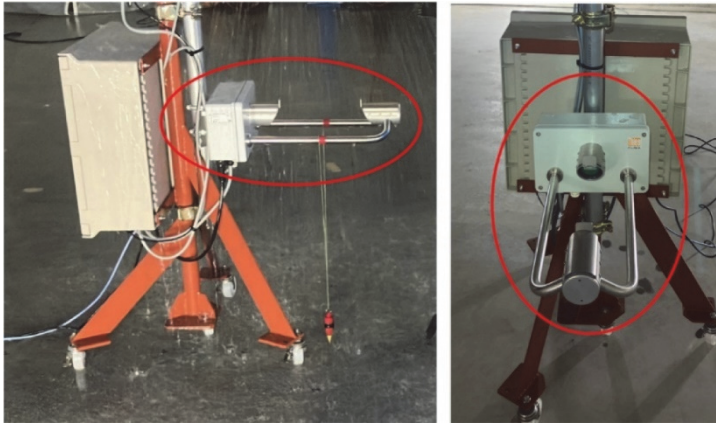
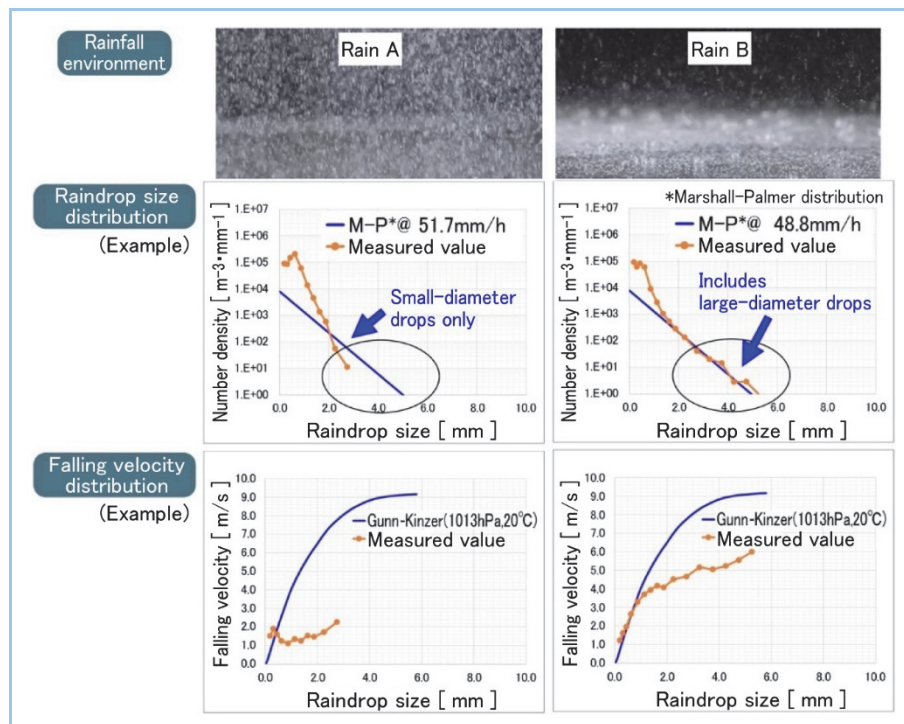
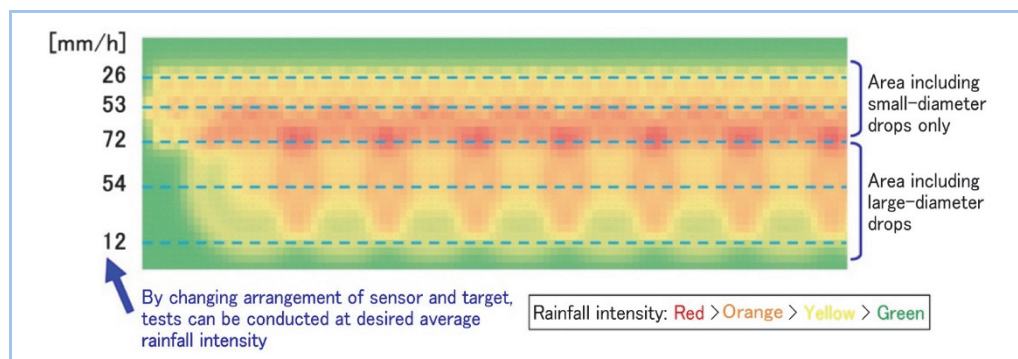


Figure 1 Demonstration test facility (Plan view)

Technical verification of rainfall and fog emulation, as well as evaluation of sensor perception performance are possible

**Figure 2 Disdrometer**

Measures drop size distribution and falling velocity

**Figure 3 Raindrop size distribution and falling velocity distribution of rain with different rainfall characteristics****Figure 4 Rainfall intensity distribution in plan view of rainfall area**

During simultaneous rainfall in small-diameter raindrop area and large-diameter raindrop area

3. Sensor signal strength attenuation under adverse weather conditions

3.1 DSD and scattering/extinction characteristics

The attenuation of sensor signal strength in adverse weather environments such as rain and fog is caused by the scattering and absorption of electromagnetic waves by water drops present in the space. When the drop size is on the same order of magnitude as the wavelength of the electromagnetic waves, this scattering phenomenon is described by the Mie scattering theory. Furthermore, even when the electromagnetic waves used differ, as in the case of cameras, LiDAR, and radar, the fundamental physical mechanism remains common. In the Mie scattering theory, the scattering and absorption characteristics of individual drops depend on the relative relationship between the drop size and the wavelength of the electromagnetic waves, and the attenuation characteristics of the drop group as a whole are determined by the DSD $N(D)$. The extinction coefficient α taking into account the DSD is expressed as the superposition of the extinction cross-sections for each drop size as follows:

$$\alpha = \int_0^{\infty} N(D) \sigma_{ext}(D, \lambda) dD$$

Here, $N(D)$ represents the DSD, and σ_{ext} is the extinction cross-section as the sum of light scattering and absorption by individual drops, which is given as a function of the drop size and wavelength based on the Mie scattering theory.

Focusing on the rainfall environment, the DSD is an index representing the microscopic structure of rainfall, and the rainfall intensity R is expressed as follows using the raindrop diameter D , the falling velocity $v(D)$, and the DSD $N(D)$:

$$R = \frac{\pi}{6} \int_0^{\infty} D^3 v(D) N(D) dD$$

From this equation, it can be understood that even under the same rainfall intensity, when the DSD differs, the same rainfall intensity is established by different combinations of drop sizes and number densities.

From the above, it can be seen that even under the same rainfall intensity R , the extinction coefficient α changes when the DSD differs, and as a result, the attenuation characteristics of the sensor signal strength also vary.

3.2 Attenuation calculation considering spatial distribution

Adverse weather environments are not spatially uniform; the DSD, rainfall intensity, and fog visibility fluctuate depending on position and time. By dividing the propagation path into microscopic intervals Δr_i and calculating the extinction coefficient α_i from the DSD in each interval i , the attenuation considering the spatial distribution is evaluated. The total attenuation rate A is expressed discretely as follows:

$$A = \exp\left(-2 \sum_i \alpha_i \Delta r_i\right)$$

Here, Δr_i represents the resolution of the spatial cell. This method enables the evaluation of sensor signal strength attenuation that reflects the spatial non-uniformity of rainfall. Note that because LiDAR perceives an object by receiving light reflected from the target, the attenuation rate is doubled (to account for the round trip). This report uses spatial coordinate data of the DSD reproduced with a spatial resolution of 1 m or less, obtained by time-averaging 3-minute rainfall characteristic data acquired via the Adverse Weather Automated-driving Research Environment.

3.3 LiDAR signal strength attenuation model

The LiDAR signal strength is described by the LiDAR equation based on radiative transfer. Focusing on the attenuation impact due to rainfall, this report utilizes the following model as a relative evaluation against a clear (no rain) condition:

$$P(r) = P_0 \exp\left(-2 \int_0^r \alpha(s) ds\right)$$

Here, $P(r)$ represents the received signal strength at a distance r , P_0 is the signal strength under the clear condition, and $\alpha(s)$ is the extinction coefficient at position s . By discretely approximating the extinction coefficient as determined in Section 3.2, the attenuation of the LiDAR signal strength under a non-uniform rainfall environment is quantitatively evaluated. In addition, the attenuation rate is evaluated as a ratio to the clear condition as follows:

$$A(r) = \frac{P(r)}{P_0}$$

Note that the attenuation model used in this report aims to evaluate the primary impact of physical phenomena, and is based on the following assumptions:

- The attenuation factors are limited to forward scattering and spatial extinction.
- The impacts of backscattering and multiple scattering are not considered.
- The impacts of internal sensor signal processing and perception algorithms are not included.

Therefore, this model is primarily applied to the evaluation of the attenuation characteristics of the sensor signal strength, and cannot be applied to the evaluation of higher-order phenomena such as false point detection or perception considering the entire point cloud.

4. LiDAR perception performance evaluation under rainfall environment

4.1 Test results

The object (target) shown in **Figure 5** was fixed 35 m in front of the LiDAR (wavelength 865 nm), and after setting the average rainfall intensity on the evaluation line to 53 mm/h, tests were conducted under rainfall environments with different DSD and falling velocity distributions (Rain A and Rain B: see **Figure 3**). For the perception performance of the LiDAR, detection points corresponding to the target were extracted from the acquired point cloud data (**Figure 6**), and their reflection intensity (received signal strength) was used as the evaluation index. The reduction rate was calculated by normalizing the value acquired under the rainfall condition against the value under the clear condition. Note that in this test, to evaluate the representative tendency of changes in the target detection status due to rainfall, measurement data of approximately 9 seconds (90 frames) were integrated, and the median value of the reflection intensity for all detection points was used as the index. As a result of the statistical evaluation with a 95% confidence interval, for Rain A, which does not include large-diameter raindrops, a significant difference compared to the clear condition was observed in both the reflection intensity originating from the object and the number of detection points. Specifically, as shown in **Figure 7**, the reflection intensity decreased by 91% compared to the clear condition. On the other hand, for Rain B, which includes large-diameter raindrops, the reflection intensity showed a reduction rate of 43% (significant difference). These results indicate that even under the same rainfall intensity condition, the degree of impact on the perception performance received by the LiDAR varies depending on the difference in the DSD. Particularly in Rain A, where small raindrops are dominant, attenuation of the LiDAR signal strength occurs due to the frequent occurrence of weak scattering. Meanwhile, in Rain B, although large raindrops cause strong scattering, the impact tends to be localized because the number of raindrops is small. Furthermore, within the raindrop size range of 0.2 mm to 2 mm, the extinction coefficient increases as the drop size decreases; therefore, it is considered that Rain A, which contains a large number of small drops, makes a larger contribution to the attenuation of signal strength. However, since a decreasing trend is observed in the extinction coefficient at 0.1 mm or less, the attenuation characteristics depend not only on the number of raindrops but also on the DSD.

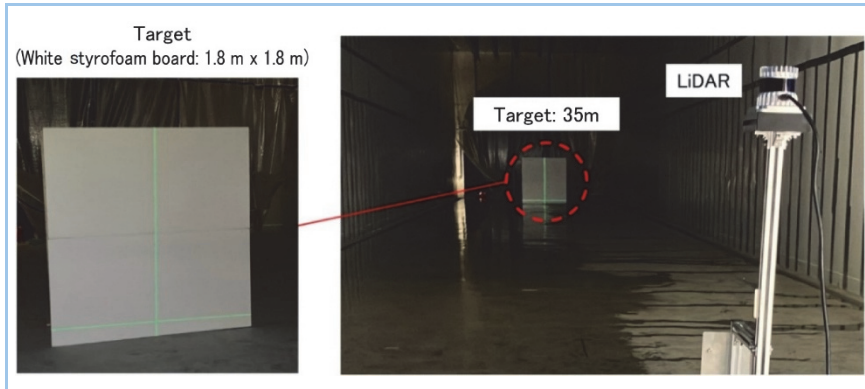


Figure 5 LiDAR perception performance evaluation test
The object (target) is fixed 35 m in front of LiDAR

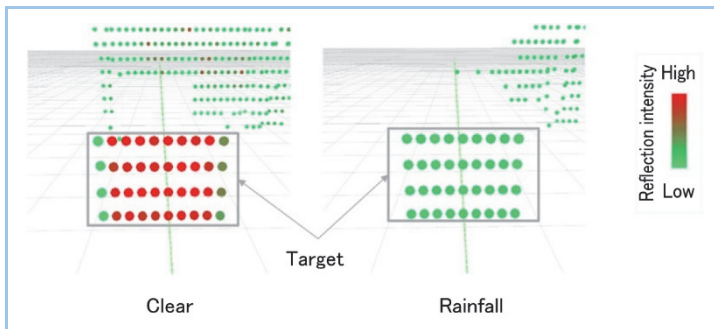


Figure 6 Point cloud processing results by LiDAR
Extracting detection point coordinates corresponding to target

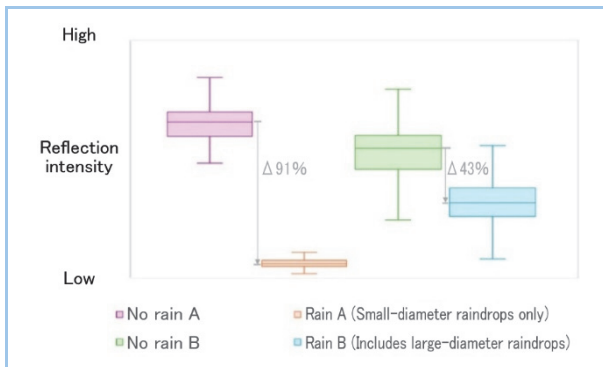


Figure 7 Impact on LiDAR perception performance under rainfall environment
Reduction rate of reflection intensity when clear condition is taken as 100%

4.2 Simulation results of signal strength attenuation

In this section, regarding the LiDAR signal strength attenuation under a rainfall environment, the test results and the estimation results by simulation were compared to verify the validity of the evaluation method utilizing the raindrop distribution for each spatial coordinate. For the simulation, the spatial attenuation model based on the extinction coefficient shown in Chapter 3 was applied. Specifically, forward scattering and attenuation by raindrops were formulated based on the Mie scattering theory, and the extinction coefficient for each drop size against the LiDAR wavelength was calculated. Furthermore, from the rainfall environment data acquired via the Adverse Weather Automated-driving Research Environment, the number density for each raindrop size obtained with a spatial resolution of 1 m or less was used as input to determine the extinction coefficient in each spatial cell. By integrating this along the optical path between the LiDAR and the target, the signal strength attenuation rate considering the round-trip attenuation was estimated.

As shown in **Table 1**, the simulation results (Rain A: 95%, Rain B: 60%) showed a similar attenuation trend to the test results (Rain A: 91%, Rain B: 43%), confirming that the attenuation trend depending on the DSD was appropriately reproduced. Particularly in Rain A, which does not include

large drops, the decrease in reflection intensity was prominent; this can be interpreted as an increase in spatial extinction accompanying an increase in drop number density, and this trend is similarly reproduced in the simulation. On the other hand, for Rain B, which includes large drops, a difference of approximately 17% was confirmed between the test results and the simulation results. As for this difference, while the simulation model primarily evaluates forward scattering and spatial attenuation, it is considered that in the actual environment, the impacts of backscattering and multiple scattering originating from large-diameter raindrops, as well as internal sensor signal processing and noise characteristics, tend to relatively manifest themselves. In addition, while large-diameter raindrops have a low number density, they have a large scattering cross-section, and the local scattering contribution becomes dominant. For this reason, signal fluctuations and statistical uncertainties originating from variations in the number of raindrops may increase, expanding the deviation from the test results.

From the above, although this method is effective for evaluating the attenuation trend based on the DSD, it was suggested that challenges remain in reproducing the angular distribution of scattering and higher-order scattering processes in environments that include large raindrops.

Table 1 Attenuation rate of LiDAR reflection intensity (median)

Environment	Rain A Small drops only	Rain B Includes large drops
Simulation	95%	60%
Test	91%	43%
Difference (Simulation - Test)	4%	17%

* Reduction rate when clear condition is taken as 100%

5. Conclusion

This report introduced a case evaluation of the perception performance of LiDAR installed in autonomous mobility systems, leveraging the rainfall characteristic data acquired via the Adverse Weather Automated-driving Research Environment. By considering the DSD, the effectiveness of a test system that cannot be evaluated solely by average rainfall intensity was demonstrated. Furthermore, the signal strength attenuation simulation utilizing high-resolution spatial distribution data is effective for test planning and result interpretation, and also contributes to improving the accuracy of advanced sensor perception simulation models. This system is capable of generating environments with high reproducibility, and its feature lies in the fact that it can be utilized for unifying test and simulation conditions as well as for analytical verification through meteorological characteristic data. On the other hand, this evaluation targets a specific LiDAR, and there is a limit to its generalization. In addition, the current simulation model is limited to forward scattering and spatial attenuation, and does not consider the impacts of backscattering or recognition algorithms. Going forward, we aim to improve the reliability and efficiency of this system through statistical expansion that takes into account the uncertainties of meteorological characteristic data, as well as through collaboration with integrated models that include cameras and radar, thereby contributing to the widespread adoption of autonomous driving.

References

- (1) Haider, A. et al., A Methodology to Model the Rain and Fog Effect on the Performance of Automotive LiDAR Sensors, *Sensors*, Vol. 23, No. 15, Article 6891, 2023
- (2) Nakayama, H. et al., Innovation of Fog Emulation Technology: Reproduction of Fog Environment by Testing and Verification System for Autonomous Vehicles, *Mitsubishi Heavy Industries Technical Review*, Vol.63 No.2 (2026)
- (3) Marshall, J. S. and Palmer, W. Mc K., The Distribution of Raindrops with Size, *Journal of Meteorology*, Vol.5, No.4 (1948), pp.165-166.
- (4) Gunn, R. and Kinzer, G. D., The Terminal Velocity of Fall for Water Droplets in Stagnant Air, *Journal of Meteorology*, Vol.6, No.4 (1949), pp.243-248.