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Test Methodology for Rain Influence on Automotive Surround Sensors

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Abstract— **Automotive safety systems aim to provide maximum protection to vehicle occupants and vulnerable road users. These safety features rely on data from surround sensors such as radar, lidar and camera, which provide detailed information about the environment of the vehicle. A minor error in the measurements of these sensors can lead to major injuries or death. Hence, the reliability and accuracy of these sensor systems is mandatory. The performance of surround sensors depends on their local environment, because of the attenuation of the ambient atmosphere. Environmental influences such as rain additionally affects the accuracy of sensor systems. Therefore, these sensors must be tested under various weather conditions. This paper presents a new test methodology for rain influence on automotive surround sensors. Therefore, a rain simulator was designed and validated. The proposed test methodology was applied to radar, lidar and camera sensors in an experimental setup.**

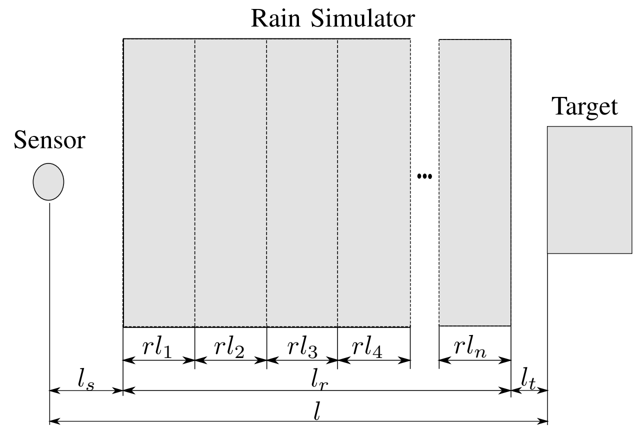

Fig. 1. Principle of the test methodology

I. Introduction

Each year over 1.2 million people die in traffic accidents. 90% of all traffic fatalities occur in low and middle income territories. This percentage is extremely high, especially considering that these countries account for only 54% of the entire worlds vehicle population. In Brazil, the estimated road traffic death rate per 100.000 inhabitants is 23.4. [1]

Due to these reasons, car manufacturers place very high priority on the development of safety systems. The main tasks of active safety systems are to prevent accidents and reduce the risk of injury to vehicle occupants and vulnerable road users. Therefore, surround sensor systems are used to detect the vehicle environment. In order to fulfill safety requirements, sensors have to achieve high robustness and the capability of real-time use. Sensors which are capable of handling these requirements are radar, lidar and camera sensors.

For testing these sensors and entire safety systems, field experiments have proven to be a good test method. This tests belong to experiments under realistic settings and allow to investigate naturalistic driving behavior. However, these tests do not cover all environmental situations and are not reproducible. In order to gather a sufficient amount of data, an experiment duration of several month is needed [2]. In field experiments it is also difficult to test and compare different sensor systems under defined conditions.

A potential solution are reproducible and deterministic indoor tests. Under defined conditions specific influences can be simulated with average or very strong characteristics. Realistic weather simulation can support test driven development and save high test effort and increase the reliability of sensor systems. Furthermore, time-efficiency is mandatory for the development and test of novel detection algorithms and sensors. Therefore, this paper presents a new test methodology for automotive surround sensors.

This paper is organized as follows. Section II describes the developed rain simulator, the used target and presents a new test methodology for automotive surround sensors under different weather conditions. In Section III the test results for radar, lidar and camera sensors are shown. Section IV summarizes the results and the scientific contribution of this paper.

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II. Materials and Methods

Transmitted electromagnetic waves traveling through the ambient atmosphere are scattered and absorbed by particles of ice, snow or water. Water with its larger dielectric constant scatters more than ice. Additionally, water has a larger dielectric loss and the attenuation due to thermal dissipation is for water particles higher than for ice particles [3]. Therefore, focus of our test methodology is the replication of realistic rain. For this, a rain simulator was developed, which replicates rain with realistic characteristics.

This enables the reproducible and deterministic test of automotive surround sensors under various weather conditions. With indoor tests, results can be achieved more rapidly and under controlled conditions [4]. Additionally, it supports test driven development in an early development stage. The following test methodology is proposed for the test of lidar, radar and camera sensors under various weather conditions.

A. Test Methodology

The test method is based on a rain simulator with length l_r. The principle is shown in figure 1. The rain simulator is separated in individual switchable rain layers with the length r_l. This layers are used to reproducible disturb the target measuring surround sensor, by varying the activated rain layers. With stepwise increasing number of activated rain layers, the disturbance to the sensor is increased. The sensor limit is reached when the sensor can not distinguish between target and rain disturbance. The surround sensor is mounted in front of the rain simulator at a distance of l_s. A target is mounted behind the rain simulator at a distance of l_t. The distance between sensor and target is l. This configuration is used to disturb the transmitted electromagnetic waves, by absorption and scattering effects. For enabling the effect of water covered sensor or target, l_s and l_t can be set to zero. First, the sensor measures the target without the influence of rain. This means the rain simulator is deactivated. Then the first rain layer rl_1 is activated. The path between sensor and object will be disturbed by rain and the measurement of the target is still running. Subsequently, the second rain layer rl_2 is activated. The disturbance based on transmission, reflection and absorption will increase through the higher quantity of rain drops. This procedure is continued stepwise until all layers, including the last layer rl_n, are activated and measured. At a specific rain layer the sensor can not distinguish between rain and target. This is the basis for our sensor benchmark methodology, in which the number of rain layers with a specific rain intensity is the assessment criterion. A sensor which can detect the target by more layers is more rain resistant.

The presented test methodology can also be used to verify and validate theoretical models. In a previous work [5], we developed a theoretical model to determine the sensor behavior of laser scanners in rain. Basic principle is the abstraction to a layer model, whose virtual layer thickness is equal to the sensor resolution. A virtual layer considers physical effects like transmission, reflection and absorption. Considering a lidar sensor, the sum of all received intensities can be described as

$$I_\kappa = I_0 \cdot \sum_{i=1}^{\frac{\kappa-1}{2}} p_i \cdot \varrho^{2i-1} \cdot \tau^{\kappa+1-2i}. \tag{1}$$

where I_κ is the received and I_0 the transmitted intensity. τ describes the transmittance and ϱ the reflectance of one single layer. κ is the number of traveled layers, which is the sum of the exponents of τ and ϱ, and p_i the number of occurrence of this path. Using p_i, which is calculated by Dyck paths using Catalan and Narayana numbers, enabled the inclusion of multiple refections. The highest received intensity from the object I_{obj} can be described as

$$I_{obj} = I_0 \cdot \varrho_{obj} \cdot \tau^{2\kappa} \tag{2}$$

where ϱ_{obj} is the reflectivity of the object. Equation 2 describes the received intensity, if the transmitted wave travels straight to the object and back without any reflections.

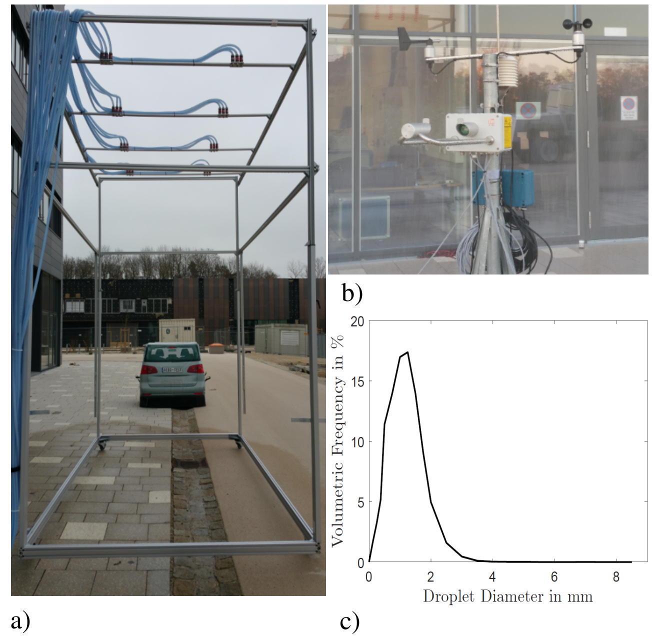

Fig. 2. a) Rain simulator with full cone nozzles, b) Disdrometer for measuring the rain characteristic, c) Drop size distribution of replicated rain

B. Test setup

Based on the presented methodology a rain simulator was designed. The height of the rain simulator can be adjusted up to 5.6 m. The watering area is 2 m x 4 m. Each rain layer has a length of 1 m, resulting in a total of four rain layers. The rain is based on the use of full cone nozzles. For one rain layer three pairs of nozzles, which produce fine, medium and large droplets for a realistic drop size distribution are used. Natural rainfall consists of drop sizes from near zero to about 7 mm in diameter. The median is between 1 and 3 mm and tends to increase with rain intensity [6]. The terminal velocity of raindrops varies from 0.1 m/s to more than 9 m/s [7]. The water flow rate of each individual nozzle can be adjusted. Thereby, a spectrum of various rain intensities can be achieved. Average rain intensities are between 12 and 120 mm/h [4]. Figure 2a shows the developed and constructed rain simulator for the test of automotive surround sensors. For the validation of the rain simulator, a laser precipitation monitor (disdrometer), which can be seen in figure 2b, is used [8]. The measured rain intensity of the designed rain simulator is 94.5 mm/h, which corresponds to stormy rain. Figure 2c shows the rain drop distribution of the rain simulator measured with the disdrometer. For realistic tests the Euro NCAP Vehicle Target (EVT) was used as standardized test object. The EVT was chosen for the test set up, based on its design which is considering current generation radar, lidar and camera sensors. The details of the EVT are presented by ADAC in [9].

In the following measurements the test configuration $l_s = 2$ m, $l_r = 4$ m, $l_t = 4$ m and $rl = 1$ m was used.

III. Automotive Surround Sensors

A. Radar

Radar (Radio detection and ranging) is an object-detection system that utilizes electromagnetic waves to determine the range, angle and velocity of obstacles. Radar sensors are widely used for comfort, (semi-)automated driving and safety systems, e.g. for applications such as automated cruise control, collision warning and mitigation systems [10]. For these systems high accuracy, confidence and reliability is required.

Environmental influences on radar sensors has been studied in [11]. In rain a reduction of the measured signal in millimeter-wave range can be observed. An electromagnetic wave traveling through rain will be absorbed, depolarized, scattered and delayed in time. In [12] the relationship between rainfall rate and a normalized rain backscatter cross section was modeled. The rain backscatter depends on the raindrop size distribution within the antenna beam. In [13] a filter was designed to enhance target detection in the presence of rain. Based on the Weibull-distribution for rain the radar cross section (RCS) value for volume reflectivity can be estimated.

The measurement setup was built as shown in figure 1. For the measurement a standard automotive long range radar with a frequency of 77 GHz was used. For each measurement with a specific number of rain layers a measurement series containing 200 single measurements is used. Measurement series were recorded under incremental activated rain layers. For evaluation of rain influence to radar sensors, a pre-processed data stream which contains the RCS values of classified and tracked objects is used.

The RCS value is the measure of an obstacles capability to reflect echo signals in the radar receivers direction. The RCS of complex targets such as vehicles and pedestrians is dependent on the size, shape, orientation and material, which has influence on a maximum detectable range, target detectability and tracking stability. Therefore, the RCS of targets is very important for detection, tracking and classification and can be calculated by

$$\sigma = \frac{(4\pi)^3 \cdot R^4}{P_t \cdot G^2 \cdot \lambda^2} \cdot P_r \tag{3}$$

where σ is the obstacles RCS value, P_t the transmitted power, P_r the received power, R the range from radar to the target, G the antenna gain and λ the transmitting wavelength [10]. Specific groups of obstacles usually vary in an object specific range of RCS values for clutter-free environment conditions (no rain), e.g. humans RCS is approximately -8 dBsm and rear of vehicles RCS is approximately 7-12 dBsm [14].

The test results can be seen in figure 3, which shows the RCS values for measurement series with increasing number of rain layers in a boxplot. The first box shows the RCS value without the influence of rain, which is 12.13 dBsm and in the typical range of vehicle RCS values.

It can be seen that the median decreases with increasing rain layers. The activation of the first rain layer leads to

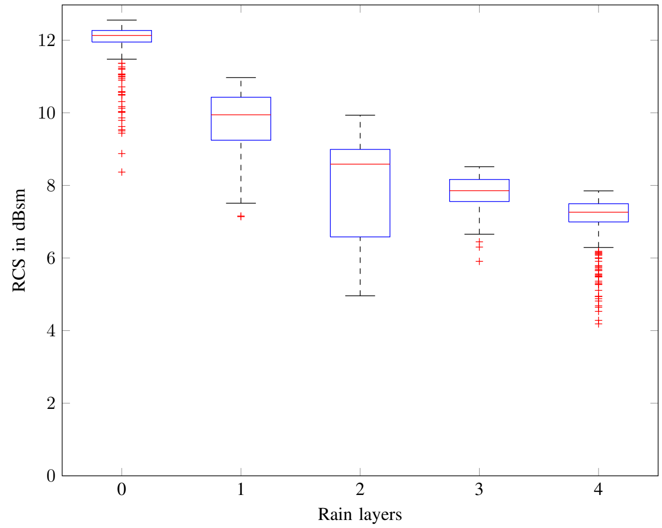

Fig. 3. RCS values with increasing number of activated rain layers

a decrease of the measured RCS to a value of 9.95 dBsm, which corresponds to a reduction by 40% of the initial value in linear scale. Two activated rain layers lead to further decrease of 56% of the initial value. If all rain layers are activated, a reduction of 67% compared to the initial value can be seen.

In [10] the RCS values of different targets like sedan, small van, bicycle, manned bicycle and pedestrian are analyzed. It can be seen that diverse target types have different RCS values. Therefore, the identification of various targets might be enabled by using these RCS values. However, during rain, the measured RCS values will drop under the typical threshold leading to a reduced performance of the radar sensors detection, tracking and classification. As presented in [14], for certain objects a corresponding RCS value range can be assumed. Due to the rain influence the characteristic RCS of a vehicle can be lowered to the characteristic RCS value range of a manned bicycle leading to incorrect object classification. The presented test methodology can be used to disturb the perception of the environment of a radar sensor under reproducible rain intensities.

The electromagnetic wave interaction with rain drops leads to attenuation and reflection depending on the particle size, the wavelength, particle density, extent and index of refraction. The complex refraction index is a common measure of an electromagnetic wave traveling through a medium, e.g. water. At 77 GHz both the real and imaginary parts of refraction index of water are relatively high, leading to a higher attenuation than lidar sensors [15].

B. Lidar

Lidar (Light detection and ranging) sensors use the time of flight principle to calculate the distance to an object. A short duration laser pulse is emitted from a laser light source which travels to the target. The laser pulse reflected by the target is captured by a receiver. The total time of flight gives a measure of the distance to the object.

Environmental influences on the lidar sensor can be found in [16], where Mie's theory is used for the calculation of extinction and backscattering efficiency for a single rain drop. It is shown that the detection range decreases with increasing rain rate. In [17] the impact of environmental water on lidar sensors has been analyzed. In [18] environmental factors have been studied with an Ibeo laser sensor, which is capable of multi target detection.

For performing the presented test methodology, the Hokuyo UTM-30LX-EW laser range finder (λ=905 nm) is used [19]. This two dimensional scanning sensor measures horizontal distances to objects in a range up to 30 m with a scan rate of 40 Hz. In the following, the results of the test methodology are presented. Figure 4 shows single scans of the Hokuyo sensor. The scan on the far left is made without any rain influence. The measurements on the right are made under stepwise increasing activated rain layers. The scan far right is made with four activated rain layers. The gray bar on the top marks the region of the target. The four static points in rectangle configuration are reflected by the structure of the rain simulator. The sensor is centered at the bottom of each plot.

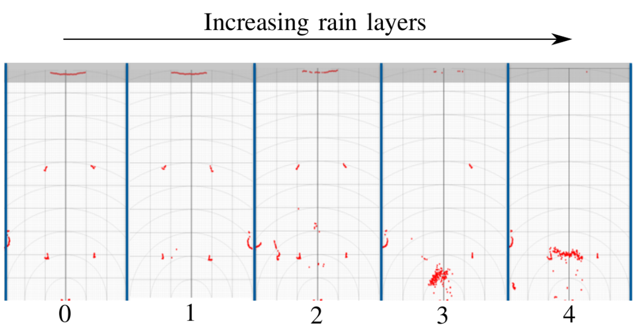

Fig. 4. Test procedure with Hokuyo sensor

In the scan without rain, the object is detected correctly, which means that there are no measurement points between sensor and target. With activated rain layers, it can be seen that reflections from rain drops occur. Using the multi echo technology, reflections from objects behind rain drops can be detected. The Hokuyo laser scanner allows the detection up to three echos in one direction. The defined object position and the static test procedure allows a simple segmentation of the target reflections using threshold values.

Figure 5 shows the relative intensity of points, which are reflected from the target and received by the laser scanner depending on the number of activated rain layers. The object reflection is ensured using multi echo. It is displayed as a boxplot with outliers and distribution and clearly shows the decrease of intensity. Each measurement (box) contains 40 consecutive points of the same angle, which results in a measurement time of one second. Without the influence of rain, the relative intensity is around 2260. This is the maximum achievable value. Activating the first layer the median intensity of the target decreases by 18%. Because

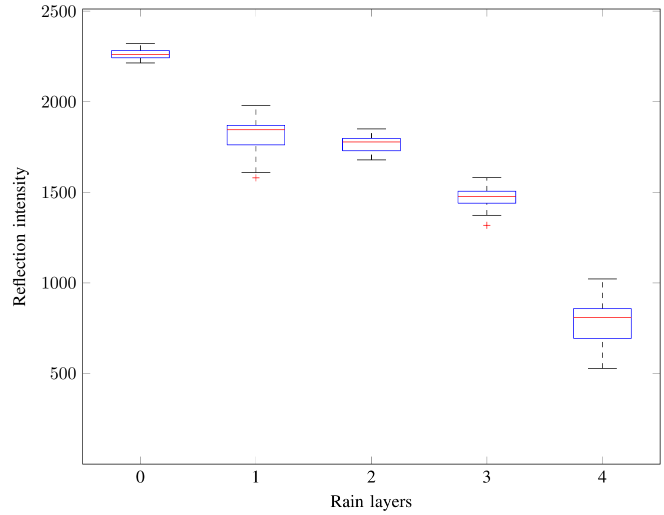

Fig. 5. Relative intensity with increasing number of activated rain layers

of the dynamic of rain, the reflected points cause the range of variation and the outliers. With activating the second and third layer, a further decrease of the median can be seen. Four activated layers lead to a median of 800 which is around 36% of the initial value. This effect results mainly from water absorption in near infrared spectral band [17].

Using the adaptive breakpoint detector, threshold values are used to classify breakpoints, marking if two measurements belong to the same or different segments. Two measurements belong to different segments if

$$||(p,\theta)_i - (p,\theta)_{i-1}|| > p_{i-1} \cdot \frac{\sin \Delta\theta}{\sin(\lambda - \Delta\theta)} + 3\sigma_r \qquad (4)$$

where $\Delta\theta$ is the angular resolution, λ is the worst case of incidence angle of the laser beam with respect to a line for which the scan points are still reliable. The statistical error in the range readings is represented by σ_r [20].

Figure 4 shows, that under rain influence the reflected points are shifted from their origin position. Hence, the distance between two points exceeds the threshold value calculated by equation 4 and leads to a breakpoint. The target will be classified as several objects and ghost objects will be generated. Consequently, rain influence disturbs the segmentation process.

The presented test methodology can be used to disturb the perception of the environment of lidar sensors. Particularly because lidar sensors have usually high angular resolution, future algorithms should be able to detect extreme weather conditions and more robust in the segmentation process. The test driven development of more robust detection algorithms can be supported by the presented test methodology.

C. Camera

Cameras are one of the most actively researched areas in the field of automotive safety. The preprocessing of image data involves the extraction of relevant features and transfer to higher level image processing. The most important image features are edges and corners.

Garg and Nayar published several works about the influence of rain on camera. In [21] a geometric and photometric model for refraction and reflection from a single rain drop was presented. It was shown that a rain drop redirects the light from a large field of view (approximately 165°). Hence, the brightness of rain drops does not depend absolutely on their background and the projection in the image is brighter than its background. Unlike a stationary rain drop, the intensities of rain streaks depend on the background scene and integration time of the camera [22]. In [23] a method that sets the camera parameters (exposure time, F-number, distance of the focal plane) in order to reduce the effects of rain without post processing was developed. In [24] a post processing method to detect and remove rain streaks from videos is presented, while [25] proposes a method to remove rain from single images. However, strong rainfall between the camera sensor and an object always leads to information reduction, which can not be restored completely and in real time.

For the development of new rain filter algorithms or testing of sensors a reproducible and deterministic environment is mandatory. In the following, the presented method was performed with a standard automotive camera sensor, which is mounted in front of the central rear view mirror of a test vehicle. Figure 6 shows the raw image of a standard automotive camera sensor in front of the rain simulator and the EVT without the influence of rain.

Fig. 6. Raw image of standard automotive camera in front of rain simulator and EVT

During the test, images are recorded continuously. The relevant part (area including rain drops and target object) of the images are extracted and converted to gray scale. Figure 8 shows a series of images under incremental increasing rain layers. The image far left is taken without rain influence. The image far right is taken with four activated rain layers. It can be seen, that with increasing rain layers the disturbance increases. The influence of rain is most visible on dark background. On bright background like the sky, the rain drops are barely visible. The edges of the EVT are more difficult to detect, because of the loss in contrast. For a better evaluation, the histograms of the images without rain, with two activated layers and with four activated layers are shown in figure 7.

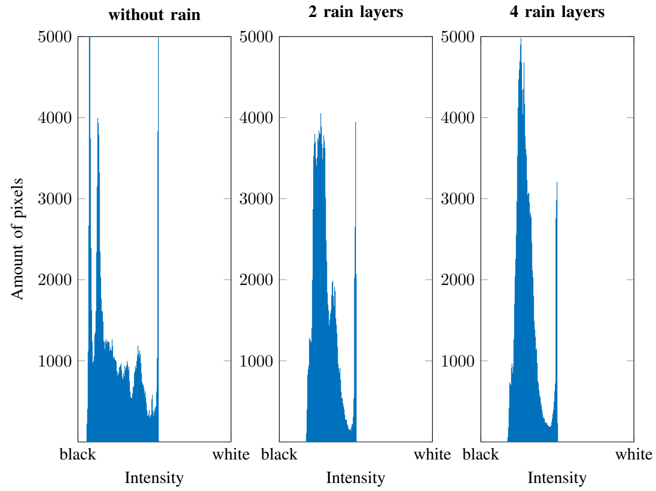

Fig. 7. Histogram of images without rain influence, with two activated rain layers and four activated rain layers

The horizontal axis of the histogram represents the gray level intensities, while the vertical axis represents the amount of pixels in the corresponding intensity. It can be seen in the histogram without rain, that most of the pixels are on the left side, which represents the dark area. Comparing with the histograms with activated rain layers, the range of intensity spectrum is smaller and shifted to the right. The mean intensity of the histogram without rain is 62, while the mean of the histogram with two activated rain layers is 74. The mean intensity value of four activated rain layers is 77. A smaller intensity range corresponds to less contrast and a shift to the right corresponds to a brighter image. Comparing the histograms with two and four activated rain layers, it can be seen that the intensity area becomes smaller but higher, which corresponds to a further decrease in contrast.

The brightening is based on rain drops reflecting light from the environment including the sky. Specular and internal reflections additionally increase the brightness of rain drops. Consequently, a rain drop tends to be brighter than its background [23]. Narasimhan and Nayar addressed in [26] the problem of restoring the contrast of atmospherically degraded images.

With increased rain intensity a lower contrast in images makes it difficult to detect objects like pedestrians or vehicles, because of the reduced amount of relevant features like edges and corners. The proposed test methodology can be used to improve and validate camera based detection algorithms under various and reproducible rain influence.

IV. Summary and Future Work

This paper presents a new methodology for the test of automotive surround sensors and object detection algorithms under various weather conditions. The test is based on a novel rain simulator with individual switchable rain layers. With stepwise increasing number of activated rain layers, the sensor disturbance is increased. The sensor or detection algorithm limit is reached, when the sensor can not distinguish

Fig. 8. Series of images of an EVT under incremental increasing rain layers; far left: no rain influence, far right: four activated rain layers

between the object and rain disturbance. The presented test methodology can be used for various sensor principles by disturbing the electromagnetic waves and allows to quantify the weather robustness of automotive surround sensors and detection algorithms. For benchmark tests, the number of activated rain layers at a specific rain intensity can be used as assessment criterion. The characteristics of artificial rain were measured with a standard disdrometer, compared with literature and validated with natural rainfall. The influence of rain is shown on standard radar, lidar and camera sensors. The activation of automotive safety systems is a time critical and responsible decision. Hence, the systematic test of sensor systems and detection algorithms under various reproducible weather conditions is mandatory. The proposed test methodology can be transfered to related environmental influences like fog, as well as snow and other weather conditions. In order to ensure comparability of test results it is mandatory that the simulated environment is deterministic. Beside benchmark tests, the proposed test methodology can also be used to support test driven development and improve sensor systems and detection algorithms at an early development stage.

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