Final Report
Sensor testing in Adverse Visibility Conditions - SUS

Public report

Authors: Peter Eriksson, Erik Ronelöv, Oscar Tullberg, Valery Chernoray

Date: 2023-04-13

Strategic Investment within FFI

1 Summary

In automotive and autonomy products, there is a clear trend to use sensor data as input for active safety systems. With improvements in technology, the use cases for such systems are constantly increasing. Hand in hand with development of new technologies that covers additional scenarios comes the challenge of developing methods of evaluating its performance and reliability in relevant and repeatable ways.

This project aims to develop test equipment that can produce the effect of road spray, the phenomenon caused by vehicles driving on wet road surfaces and generating a turbulent mix of fine water particles that reduce visibility.

Methods used in the project includes both the design of hardware, development of software to quantify visibility degradation and physical manufacturing of test equipment.

A key finding in this project has been the complexity of not having a test environment that is free from external disturbances. Factors such as light and wind condition proved to have significant effects on visibility through spray. The project concludes that controlling these factors is essential to reach repeatability between different test occasions and proposes alternative methods of doing so.

In a controlled environment, the project has repeatedly emulated water spray with a controlled contrast attenuation up to 80% and continuously kept it within ±5-15%.

2 Introduction

2.1 Background

Reduced visibility from bad weather conditions such as fog, rain, snow, and water spray on wet roads, presents a significant challenge for active safety (ADAS) and autonomous driving (AD) systems. To accurately perceive its surroundings these AD and ADAS systems use sensors such as camera, radar, and lidar but these sensors are sensitive to interference from adverse weather conditions.

To ensure the reliability and safety of ADAS and AD systems in all weather conditions, it is important to test these systems in reduced visibility conditions. Water spray generated by passing cars on wet road surfaces impairs the driver’s ability to detect other vehicles, road signs and other critical information. However, testing these conditions can be challenging, as it is difficult to recreate the same level of spray and visibility in controlled laboratory conditions.

While much research has been conducted into the development of ADAS and AD technologies, there has been limited research into the effects of reduced visibility from bad weather on these systems. These technologies are growing in popularity and the importance of a high sensor reliability increases, even in bad weather conditions, so there is a need for further research into this area.

While there has been some research into the effects of reduced visibility from water spray on wet roads on active safety and automated driving systems, there is a lack of consensus on how best to test these conditions in a repeatable and controlled manner. Given the importance of this issue, there is a need for further research into effective testing methods for reduced visibility conditions caused by water spray on wet roads.

2.2 Purpose

The purpose of this project is to develop a repeatable and controlled method for testing the performance of sensors for ADAS and AD systems under reduced visibility from water spray on wet roads.

The project aims to further investigate the key challenges posed by reduced visibility and identify the most effective methods for recreating the same level of visibility degradation in controlled conditions. The results of this project will enable future research and methodology for sensor testing in adverse weather. This in turn will help the industry in their development of more robust driver support systems in adverse weather.

2.3 Research questions, scope, and limitations

While there are several adverse weather conditions to consider, this project is limited to the phenomenon of road spray. Compared to conditions such as rain, fog or snow, there has not been a lot of research regarding road spray even though it highly degrades visibility and sensor performance. According to members of the reference group, water spray is considered a harder phenomenon for optical sensors to handle than rain due to the small droplet size and high droplet distribution.

The project aims to gather data on characteristics for water spray and the influence of outer factors such as light and wind. By using this data, the project aims to create a method for weather emulation that can be used in the future to create similar test equipment.

From earlier tests it is clear that work must be done to help make data comparable between days and locations. A large amount of data collected in previous projects was rendered useless when it came to comparisons and repeatability. Therefore, some sort of calibration procedure or other method for comparing data must be developed.

At the end of the project AstaZero aims to have built a spray rig of their own for testing sensors within the automotive business. The spray rig will also be used in the future to validate different types of spray models. During the development and construction of the new spray rig it is the repeatability of the spray that will be in focus, the rig should also be user-friendly and as modular as possible.

Second to repeatability the emulated water spray also must be as real-world looking as possible. What this means in practice is to mimic existing data when it comes to drop sizes and, to some extent, distribution.

A reference group consisting of representatives from potential future users of the method will be used to guide the research and plans to visit other institutes for input and collaboration have been made. These companies are both OEM’s and sensor developers.

3 Literature study

3.1 SAE J2245

The SAE International, Surface Vehicle Recommended Practice J2245 (referred to as SAE J2245) from 1994 describes a way of testing the influence on visibility from water spray created by vehicles driving on wet roads. The method was created before much of the digital imaging methods and tools we have available today, but it still gives a good lead on how to perform tests. Also, it is one of very few recommended practices on the subject and that is why this project compares and evaluates the differences between our methods.

From SAE J2245:

“There are complex interactions of variables that affects the splash and spray, and by its nature, it is a very chaotic, turbulent phenomenon. This document attempts to address these variables as completely as they are understood at this time. Until they are better understood, it is necessary to limit this recommended test procedure to the following conditions:

1. It only applies to “A-B” comparisons done under the “same” conditions as outlined in the test procedure.
2. Tests done at different sites may not necessarily be comparable, depending on the exact conditions and specific locations at the time of the test.
3. Because uncontrollable variables such as wind speed and direction, water depth, humidity, and temperature can have a profound effect on measured results, small differences (on the order of 10 to 15%) in measured splash and spray may not be meaningful and the relevance of such small, measured differences should be viewed with caution.
4. Results from the testing should be reported as the difference between the 95% confidence bands and not as the difference between averages.
5. Each configuration tested shall have a separate value with 95% confidence bands reported for each of the eight wind conditions using the downwind rule, as outlined in the data reduction.”

From this recommended practice the project decided to focus on measuring contrast and how it is degraded by applied spray. It was also concluded that a method to try to get past the limitations listed in point 1 and 2 had to be created.

For stationary testing with a spray generating rig, it is possible to get rid of all the uncontrollable variables mentioned in point 3 by running it indoors.

For dynamic testing it is harder to control the external circumstances but with methods mentioned above to compensate for differences in light and special solutions to contain the water on the road at a certain depth it could be much improved.

3.2 Physical characteristics of splash and spray clouds produced by heavy vehicles (trucks and lorries) driven on wet asphalt

The report “Physical characteristics of splash and spray clouds produced by heavy vehicles (trucks and lorries) driven on wet asphalt" presented credible data for droplet sizes and drop distributions but also clear evidence of the impact on spray from different parameters such as water depth, vehicle speed and vehicle size.

The study concludes that the droplets in the spray created behind a truck with or without a lorry have diameters below 500 µm, approximately ranging between 100 and 400 µm. Reducing the water depth on the road results in a narrower size distribution with a higher part with small droplets and increasing the water depth consequently creates a wider size distribution with more large droplets. A lower vehicle speed (70 km/h vs 90 km/h) also gave more small droplets in a narrower distribution. It also enlightened the irregularities in water spray with some droplets as large as 4 mm in diameter.

Regarding the volumes of water that is ejected into the air by the vehicle the study measured averages around 0,2 to 0,7 kg/m³ with peaks as high as 1 kg/m³.

For contrast measurements it was concluded that the contrast can be reduced below 0,1 measured parallel along the driving direction of the vehicle. With a maintained vehicle speed, a smaller water depth can reduce the contrast as much but over a larger area and the spray stays in the air longer. Also, the spray generated by a truck with a lorry effect the contrast more than without a lorry and it lasts for longer.

3.3 Literature review from Chalmers

There was a short study conducted by Chalmers summarising literature and reports that relates to the subject of splash and spray. The review is linked in its full in *Appendices*.

4 Method

This chapter lists and describes the equipment and method used in the project.

4.1 Equipment

Panasonic Lumix DC-BGH1

A “box-style” camera with a 10,2 Megapixel Live MOS sensor (17,3x13,0 mm). The camera can record C4K (4096x2160) at 60 fps or FHD (1920x1080) with 240 fps.

Shutter speed:	1/16000 - 1/2
ISO:	80 - 204800

Camera control possible with Wi-Fi, Bluetooth, ethernet or USB 3.1. In this project it was driven with PoE to get both communication and power with one cable making batteries obsolete.

Figure 1 Panasonic Lumix DC-BGH1

Camera lenses

Panasonic Lumix G X Vario 35-100/2,8 II Power OIS and Panasonic Lumix G Vario 100-300/4-5,6 II Power OIS with digital high grade polarization filters from Dörr.

To protect the lens from water droplets a cardboard tube was mounted as an extension of the lens hood. The tube was cut to the length of 40cm which kept droplets from reaching the lens while still retaining a usable field of view.

Figure 2 Lumix G X Vario 35-100

Figure 3 Lumix G Vario 100-300

GoPro Hero9 Black
Version 9 of the classic, sturdy, camera from GoPro with a 23,6 Megapixel CMOS sensor. Records video at 5K (5120x2880) or 4K (3840x2160). Capable of recording at 24 fps up to 240 fps.

Shutter speed:	1/2000 – 1/125
ISO:	100 – 6400
Aperture:	ƒ2.8

Not the same amount of control as the BGH1 so it is mostly used as reference camera or outside of moving vehicles.

Figure 4 GoPro Hero 9 Black

GoPro Hero8 Black
A slightly older version of GoPro with a 12 Megapixel CMOS sensor that records at 4K (3840x2160). Capable of recording at 24 fps up to 240 fps.

Shutter speed:	1/2000 - 1
ISO:	100 – 6400
Aperture:	ƒ2.8

Not the same amount of control as the BGH1 so it is mostly used as reference camera or outside of moving vehicles.

Figure 5 GoPro Hero 8 Black

Spray rig v1

This equipment was developed and built by Veoneer in a previous project. AstaZero has been granted access to the equipment to help speed up the progress on the area of spray testing. The equipment was also used in the previous FFI project "Generate weather at AstaZero", (dnr 2018-01930).

The rig itself consists of a frame covered by an outer housing made of aluminium, 210x105x110cm [LxWxH]. A large fan is placed in one end and in the other end there is a grid of 36 square shaped channels to help make the airflow through the rig a bit more laminar. It can reach wind speeds of around 18 m/s (or 65 km/h)

Figure 6 Spray rig v1

In the front, above the air channels, water is ejected into the airstream using six atomizing sprinkler nozzles from Ultra Fog. The nozzles are supplied with high-pressure water (75 Bar) from two Kärcher K2 standard pressure washers.

This system creates a large volume of air filled with small water droplets moving toward the test object mimicking driving through the spray created behind a vehicle on wet roads.

The idea is to change fan speed to represent different driving speeds and waterflow to represent amount of rainfall or water on the road. Fan speed is regulated by a manual potentiometer and waterflow by switching on or off nozzles.

Figure 7 Spray nozzles on spray rig v1

Figure 8 Fan on spray rig v1

Spray rig v2
Using the spray rig from Veoneer (v1) during the previous project *"Generate weather at AstaZero"* generated a list of things to improve for our own version. This list included, among other things, shorter setup time, more flexibility, and increased mobility. The concept with a fan blowing the air towards the test object was paused initially to focus on improving the other parameters.

The spray rig v2 consists of a standard trailer with a steel frame covered with a thick tarpaulin. The cover and the flaps can be opened in both the front and the back for easy access. Building on a trailer increases the mobility of the equipment significantly and enables dynamic testing in the future with the trailer towed by a car in front of the test object.

The water system has a 250-liter water tank, with inner walls to reduce splashing when driving, that is connected to a 200 Bar industrial pressure washer from Alcon with an integrated pump. The water outlet from the pump is divided into several quick release connections via dedicated ball valves to maximize flexibility and setup time. One of the outlets is connected to a precision adjustment valve with a manometer. This outlet is used to dump water back to the water tank and in that way adjust the flow going out of the other outputs. This crude "control panel" is planned to be upgraded with electronic remote controls and digital manometers in future work.

The control panel has two outputs that can be connected with hoses to suitable spray nozzles. This project has mostly used the same nozzles from Ultra Fog as in Spray rig v1 but also larger cluster nozzles from PNR with 7 combined spray nozzles in one. The nozzles are mounted with ball connectors from RAM Mount for maximum adjustability and stability.

Figure 9 Spray rig v2

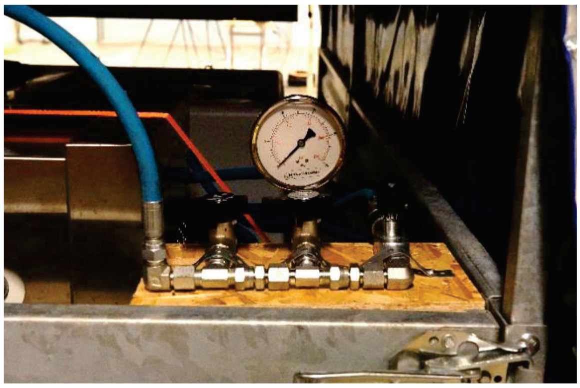

Figure 10 Control panel for spray rig v2

Spray nozzles
Two different models of spray nozzles were used during the project, the first one was a direct inheritance from the first version of the spray rig from Veoneer. The second model of spray nozzles was acquired to get the droplet to emulate natural spray as precisely as possible. This was done with the help from Paul Otxoterena Af Drake, and the data collected in the paper "Physical characteristics of splash and spray clouds produced by heavy vehicles (trucks and lorries) driven on wet asphalt".

Ultra Fog Open Nozzles
The first models of nozzles that was used in this project was Ultra Fog open nozzles with two different K-values, K=0.93 and K=0.35. Where K is the quantity of water that comes out of the nozzle according to the formula $Q = \sqrt{P} \times K$, where Q is flow and P is pressure.

Figure 11 Ultra Fog open nozzles

CAY1870T1 from PNR
The CAY nozzle is a made up of a cluster of 7 full cone nozzles that produce very fine droplets from high pressure over a coverage angle of 130 degrees. Water flow rates are rated as 5.20, 7.10 and 8.70 l/min for 1, 2 and 3 bar respectively.

Droplet sizes are rated by the supplier to be within 100-300 µm.

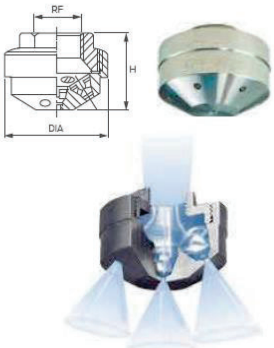

Figure 12 CAY1870T1

Antari - AF-4R Effect Fan
Special effect fan with a smooth airflow focused to the center up to 20 meters. Low noise level and adjustable wind volume from 20-100% with remote control capabilities. Airflow volume at 100% is 30 m³/min.

Figure 13 Antari AF-4R

Contrast targets

The contrast targets are created with black vinyl in a checkerboard pattern on 5mm thick, white, Forex board with measurements as stated in *Figure 14*. The pattern has 6x10 squares with a white “frame” around to help the automated analysis tool with the target detection and target following.

The Forex board is flexible but is supported by a frame made from 20x20mm aluminium profile that also helps with mounting of the target.

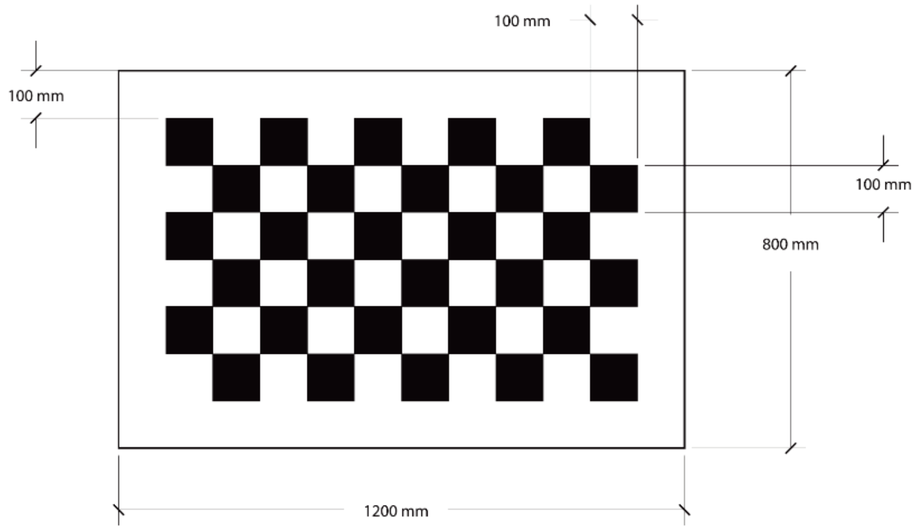

Figure 14 Checkerboard with measurements

When collecting data for real-world spray the target and frame is mounted on a bicycle holder on the back of a car so that the sensor carrier (car with camera in this case) can follow this target car.

Figure 15 Checkerboard on a bicycle stand

Figure 16 Checkerboard on a stand

Figure 17 Checkerboard mounted on a car

4.2 Mapped spray parameters

Contrast and visibility

Visibility can be measured by several different parameters, ranging from subjective judgements to objective data. This project has focused on using contrast as a way of quantifying visibility, since it is an objective and definitive unit. Comparing visible contrast with and without spray gives a contrast attenuation value, which corresponds to how much the visibility has been reduced.

Droplet size and distribution

Other parameters that are relevant when it comes to spray is the size and distribution of droplets. The selection of test equipment, in particular spray nozzles, was defined to replicate the droplet size and distribution found in real-world spray.

Light extinction

SAE J2245 and "Physical characteristics of splash and spray clouds produced by heavy vehicles (trucks and lorries) driven on wet asphalt" use this as a complement to contrast to help determine the intensity of the spray. Light extinction has not been used in this project but is taken into consideration for future projects.

4.3 Contrast calculation

Contrast can be described as the difference in colour between two adjacent areas (pixels). In the case of a black and white checkerboard, this means the difference in average intensity for black and white squares. For digital photography the intensity of a single pixel is typically measured as a value between 0 and 255, where a completely black pixel would mean 0 and the brightest white pixel would be 255.

This project uses the formula for Michelson Contrast as seen in *Equation 1* below where I_{max} is the average intensity of all the pixels in all the white squares and I_{min} is the same for all the black pixels.

$$C = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Equation 1 Michelson formula

In the standard for spray testing suggested by *SAE J2245*, a different method is used. This method compares all pairs of squares individually instead of an overall average.

Compared to the method suggested in SAE J2245 the Michelson contrast is slightly easier to calculate but should also give a contrast value more averaged over the whole target. So, to motivate the choice of method, they are compared with each other below.

a_0	b_0	a_1	b_1
b_2	a_2	b_3	a_3
a_4	b_4	a_5	b_5
b_6	a_6	b_7	a_7

Figure 18 Simplified checkerboard

Figure 19 shows an example of a contrast target with eight black and eight white squares. The values a_i and b_i describe the average intensity for that square on the target. For the actual tests described in SAE J2245 the targets are supposed to be two, 8 squares high by 12 squares wide, but this figure is for explanatory purposes.

Every interface between two squares is described by the intensity value for the white square minus the intensity for the black one, as visualized by the grey squares in Figure 19. The SAE method calculates the average of these interface values and calls it "Average Contrast Number" (named C_{SAE} below).

a_0	b_0-a_0	b_0	b_0-a_1	a_1	b_1-a_1	b_1
b_2-a_0		b_0-a_2		b_3-a_1		b_1-a_3
b_2	b_2-a_2	a_2	b_3-a_2	b_3	b_3-a_3	a_3
b_2-a_4		b_4-a_2		b_3-a_5		b_5-a_3
a_4	b_4-a_4	b_4	b_4-a_5	a_5	b_5-a_5	b_5
b_6-a_4		b_4-a_6		b_7-a_5		b_5-a_7
b_6	b_6-a_6	a_6	b_7-a_6	b_7	b_7-a_7	a_7

Figure 19 SAE calculation explanation

This Average Contrast Number is calculated for both cases without spray (C_{SAE_0}) and with spray (C_{SAE_S}) and then compared as a Figure of Merit (FoM) as seen in *Equation 2* below.

$$FoM = \frac{C_{SAE_0} - C_{SAE_S}}{C_{SAE_0}} * 100$$

Equation 2 SAE Figure of Merit

To describe the contrast for the same target with the Michelson formula instead it looks like Equation 3 *with a numerator very similar to the SAE formula.*

$$C_M = \frac{b_{average} - a_{average}}{b_{average} + a_{average}}$$

Equation 3 Numerator calculation Michelson

Compared to SAE, the Michelson formula used in this project evaluates all squares averaged instead of in pairs. As seen in Figure 19 squares are weighted differently depending on their location on the target because corners are only “connected” to two other squares while squares in the center of the target are connected to four, but in the Michelson method all squares are weighted the same.

Because Michelson delivers the average contrast over the whole area of the spray it is more suitable in this case since the project aims at mimicking the spray directly behind a moving vehicle on wet road.

The SAE method uses the targets on each side of the vehicle path to get both the level of contrast degradation and the distribution of the spray in the physical space on the sides of the vehicle. This method could be more interesting in following work when focusing more on the properties of real-world spray.

4.4 Data analysis

In the previous FFI project “Generate weather at AstaZero”, AstaZero developed a tool to extract contrast data from input video files. This was done by manually marking out what pixels that represented white squares and black squares. This was then print out to a CSV-file with contrast data for each video frame. This solution had drawbacks in usability since it could only handle one black and one white square and needed a lot of manual interaction to extract the data which also increased the margin of error.

With the goal to be able to collect spray data for stationary as well as moving targets this tool had to be developed further. Therefore, functionality was added for automated target detection, calculation of averages and possibility to run multiple files in batch mode. Results are then exported to a standardized CSV-file that makes it easier to analyse large amounts of data.

The analysis software, developed in the project, is written in Python and uses OpenCV for image processing. The provided footage is required to contain a black and white checkered surface for the analysis software to be able to define a specific area to analyse. From this, a pattern detection algorithm attempts to find a checkered pattern in each frame. It then compares the black and white regions of the checkerboard to get the average (Michelson) contrast across the entire area; from which the mean contrast values can be calculated.

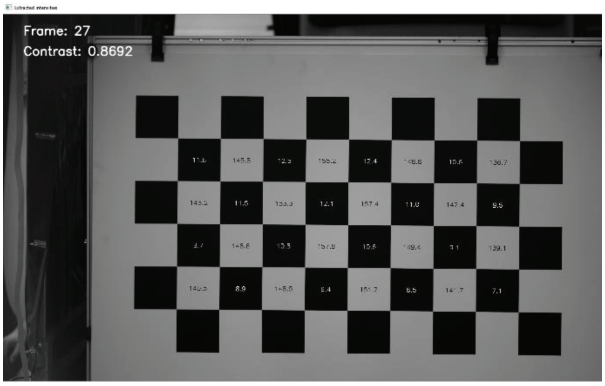

Figure 21 Contrast analysis tool without spray

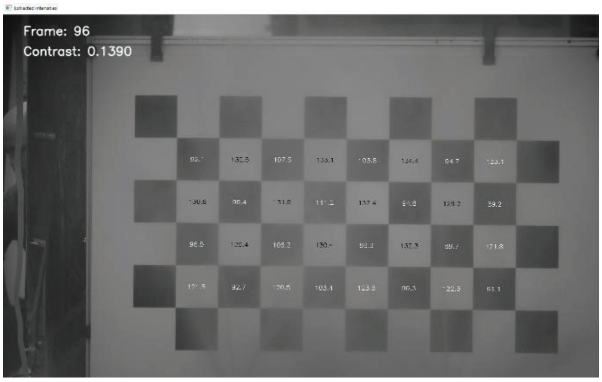

Figure 20 Contrast analysis tool with applied spray

4.5 Camera calibration

Since light conditions have a large impact on measured contrast, efforts had to be made to make the data more comparable between different occasions. To do this the cameras are calibrated to have a specific contrast value for the checkerboard when no spray is present. The contrast in the video can be changed by adjusting exposure (aperture, shutter speed and ISO) for the cameras.

The analysis tool mentioned in *Data analysis* has a dedicated calibration mode that displays a live stream from the selected camera with an overlay showing mean intensity for all squares of the target which makes it easier to see if the light on the board is uneven. The combined average contrast for the complete checkerboard target is also displayed in this overlay. By changing the camera settings, the contrast is tuned to match a desired baseline value for the contrast without spray present.

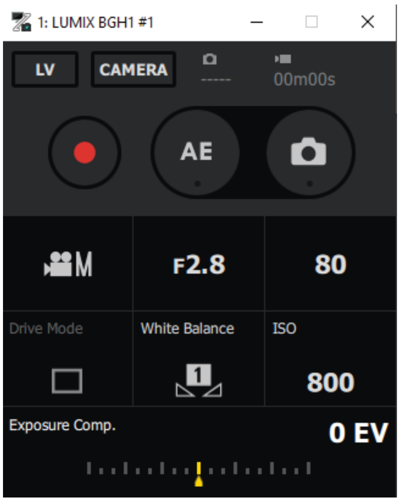

Figure 22 Camera settings in the Lumix Tether software

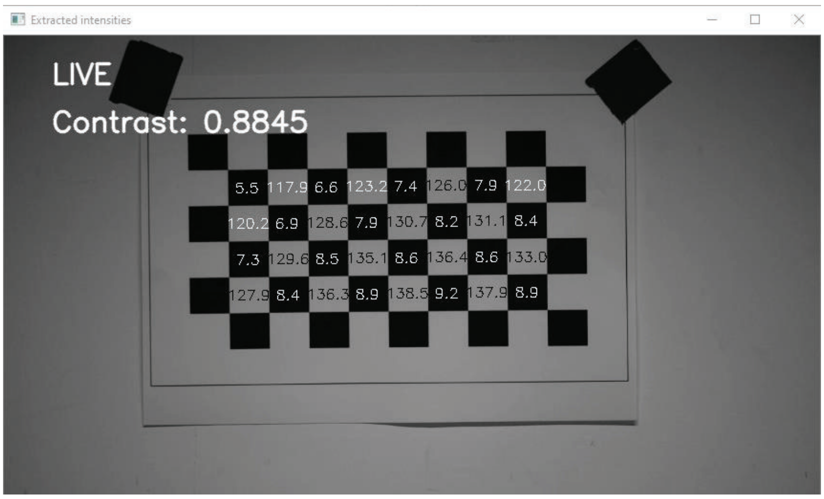

Figure 23 Contrast calibration tool

4.6 Data collection for natural spray

To be able to evaluate the spray emulated from the spray rig, a collection of data from natural spray was collected. This was done using a video camera (*Lumix BGH*) mounted on the inside of the windscreen of a car following another car with a checkerboard mounted on its back. With the analysis tool, described in *Data analysis*, the contrast data can be extracted from the checkerboard even if the target is moving.

The data was collected in speeds ranging from 50 to 130 km/h in different light and rain conditions to create a variation of contrast data to analyse. The distance between the cars was kept at 1 second using adaptive cruise control during video collection, to not introduce more variables to the tests.

The analysis method was done in the same way as for data collected from emulated spray. These tests were mostly done in the early stages of the project, but focus was later shifted more towards emulated spray for reasons further described in *Results and findings.*

Figure 24 Test driven in 130 kph on High Speed Area

Figure 25 Test driven in 70 kph on High Speed Area

Figure 26 Test driven in 110 kph on High Speed Area

4.7 Data collection for emulated spray

For the largest part of the project, tests with emulated spray have been done outside on different locations around the facilities of AstaZero with both versions of the spray rig. The goal has been to always pick a location with minimum wind interference based on the present wind direction and take ambient light into consideration. Even with these precautions however there was still visible influences from wind and light.

For the final test session, the project managed to find a location indoors with possibility to run tests with constant light conditions and without the influence of wind. This “water test facility” is located at Volvo Cars proving ground, Hällered, and is normally used for water intrusion tests for car doors and sunroofs for example. Here tests were done using Spray rig v2 with both versions of nozzles all described in the chapter *Equipment*.

Test Setup
The different test setups can be roughly categorized into four versions; rig v1 with targets on each side, rig v1 with target placed in front, rig v2 with one target outdoors and rig v2 with one target indoors. Spray rig design is described more in *Equipment* under *Spray rig v1* and *Spray rig v2*.

Spray rig v1 with targets on each side
This was the original setup, also used in the previous project "Generate weather at AstaZero" with one contrast target placed on the ground on each side of the rig. This setup was used with water from three or six nozzles and different fan speeds with the camera (inside a car as in *Data collection for natural spray*) placed on different distances from the targets ranging from 3 to 20 meters.

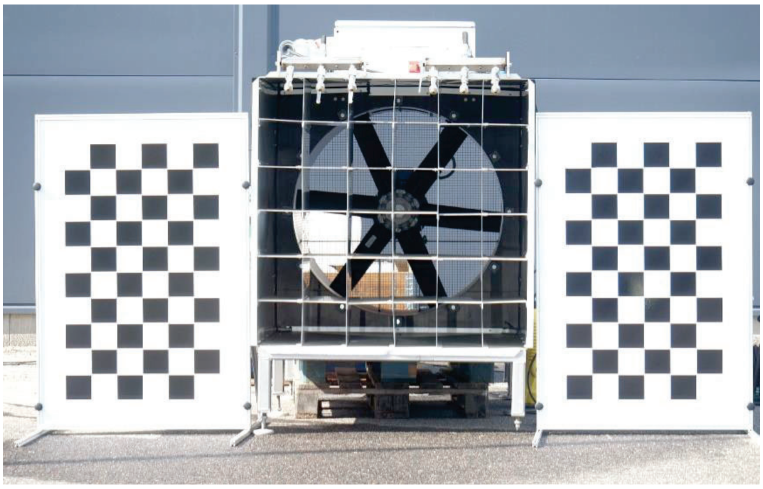

Figure 27 Spray rig v1 with targets on each side

Spray rig v1 with target in front
To better mimic the situation with the target mounted on the back of a car, a frame was built with a prism shape pointing back towards the fan for the wind to blow past the target. This setup was mostly used to get familiar with the spray rig and to see how to improve for the next version of spay rig.

Figure 28 Spray rig v1 with target in front

Spray rig v2 with one target outdoors
The contrast target was placed in the back of the trailer 94 cm from the ground and one or two cameras (Lumix BGH1) were then positioned 10 meters from the target at 120 cm from the ground. After experimenting with nozzle positions to best simulate a driving car they were placed underneath the checkerboard slightly angled upwards.

Every video file was started before the spray was applied so that every log has a reference contrast for that specific occasion. For some tests the spray was turned off before the video so that it was possible to see how the contrast slowly improved back to the initial value as the spray dissipated. For the most part the video was stopped before the spray was turned off since the contrast degradation with spray is of more interest than the re-stabilization back to the reference value.

This setup was run with different amounts of water by adjusting the flow back to the tank, so by dumping more, or less, the amount of water through the nozzles could be controlled. This was divided into seven different stages because of the way the flow nob is designed. For setting 1 and 2 almost no spray is formed so setting 3 was defined as 20%, setting 4 as 40% and setting 5 as 60% spray. These settings allow for high repeatability and a variation of spray levels, however the definition of what different water pressure levels and flow rates represents in terms of real-life spray will be further examined in future projects. These tests were run with two nozzles from Ultra Fog with K=0,93 mounted 48 cm apart for a wider spread.


Figure 29 Spray rig v2 outdoor testing

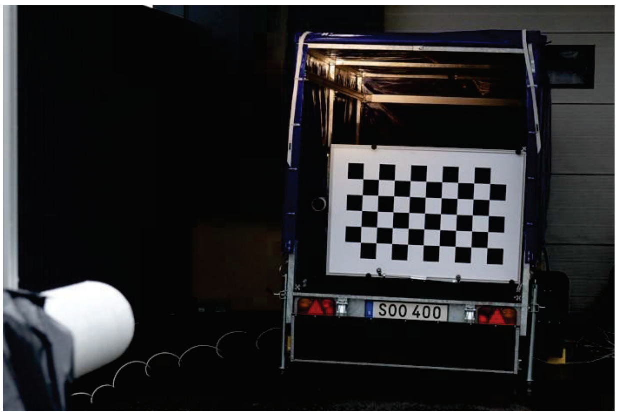

Figure 30 Spray rig v2 outdoor setup with camera

Spray rig v2 with one target, indoors
The tests done at Hällered used the same setup as the outdoor tests with a slightly shorter distance of 783cm between camera and target due to the length of the room. The contrast target was placed slightly lower, at 62cm, standing on the trailer floor. The camera was started one second before the spray, same as most of the other tests with the rig. Here a decision was made to film longer (30s) and with the spray on all the way to the end of the clip to see that the reduction of contrast stayed constant with minimum external impact.

Spray was emulated with both types of nozzles (Ultra Fog and PNR) and some controlled tests of wind influence using a fan were done. The nozzles from Ultra Fog were tested on settings 20%, 40% and 60% spray just as described in previous section.

For the nozzles from PNR three steps were used but this time with other ratings since the pressure now had to be controlled to protect the nozzles. The flow rate of the PNR nozzles is higher than for the ones from Ultra Fog and as a result the pump cannot supply both nozzles with more than 3 bar each. This resulted in three steps of 2, 3 and 5 bar when using one nozzle and three steps of 1, 2 and 3 bar when using two nozzles.

Figure 31 Spray rig v2 indoor test

5 Results and findings

This project has resulted in a large competence development in both image analysis and water spray behaviour, but also research methodology in general. As was concluded in the previous project "Generate weather at AstaZero" there are many factors that make it hard to collect contrast data from spray in a repeatable way.

Even if the initial plan for the project was to focus on the actual spray characteristics and how to create spray that resembled its real-world counterpart as much as possible it was soon shifted towards the complexity in test methodology and contrast measurements instead.

To evaluate the generated spray in a repeatable manner it was decided to keep the equipment stationary as to introduce a minimum of variations caused by changing surrounding factors such as light, road surface and view angles.

The usage of electric fans to replicate relative motion of the spray was tested to some extent. For a realistic effect this is something to investigate further but in the context of this project the addition of accelerating spray with a fan was concluded unnecessary since the spray characteristics was already defined by nozzle selection and the range of the spray cloud sufficient to cover the test subject.

Input from reference group

Our contacts with the reference group aimed to give the project some guidance on priorities and to get a better idea of what potential users of the results would want. These meetings and discussions showed that there was interest in spray with contaminated water such as salt or dirt but also for snow, rain, and fog. This information was useful in its whole, but the expectations had to be turned down a bit because of the high complexity of some of these wishes. As mentioned before, the project still had good reasons to prioritize spray before rain, fog, and snow.

Effects of the Corona pandemic

The pandemic has led to some limitations, but the contents of the project has been adapted over time to still make the best of it. Planned visits to CEREMA, CARISSMA and JARI were cancelled resulting in less input and ideas from these facilities, but this was partly complemented by contacts with them and studies of their publicly available information. Regular meetings with the reference group were also partly hindered by the pandemic.

Data normalization

For easier comparison between different datasets the data plotted in this chapter has been normalized. What this means is that the data has been amended so that all logs start at a contrast of 1.0 so the contrast with spray can then clearly be observed as a percentage of the initial contrast.

From data collected with a constant contrast in the beginning of the log, the average of the first ten frames has been subtracted from 1.0 and added it to all data in that log. This is then done individually for all logs used in the data below. Roughly speaking, the whole dataset has been moved "upwards" in the plot so that it starts at 1 instead of 0.87 for example. In some instances, this leads to a contrast value in the graph that is larger than 1 which should be impossible to get but for the purpose of a better visualisation this error is accepted and values over 1.0 are interpreted as 1.0.

Contrast effected by light conditions

One way to illustrate effects on contrast from light conditions outdoors is to drive in opposite directions while keeping all other (controllable) parameters constant. Results from this can be seen in Figure 32 and Figure 33 below. The graph in Figure 32 shows averaged data from three passes driving north to south and three driving south to north, all in 70 km/h. Figure 33 shows the same thing but for 90 km/h. It was raining and the clouds were evenly distributed so that the light was rather diffuse as can be seen in *Figure 34*.

Even thou this is conducted from a small number of samples it points out the significance of well controlled light conditions for repeatable tests.

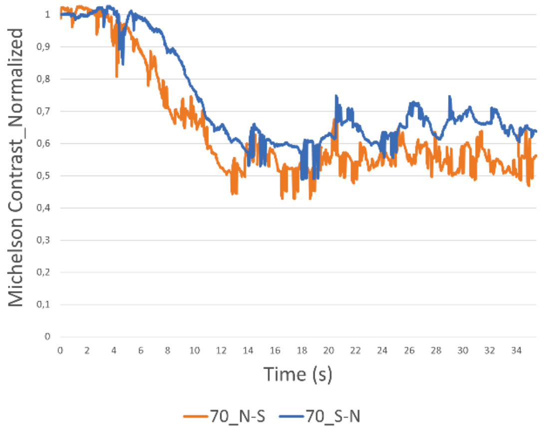

Figure 32 Outdoor driving 70kph

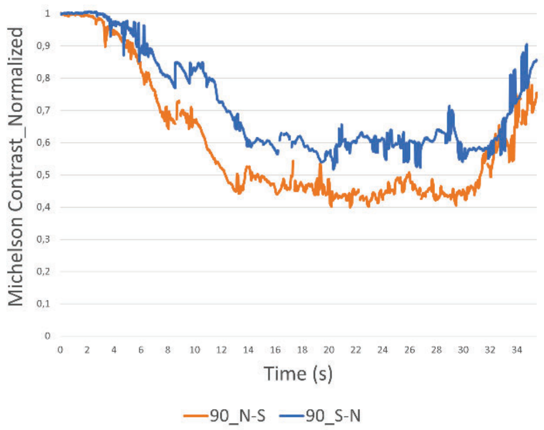

Figure 33 Outdoor driving 90kph

Figure 34 Weather conditions when driving outdoors

The same effects can be seen when emulating spray outdoors as seen in Figure 35 below. The graph shows data with two different spray settings averaged over ten logs each. This time the data is not normalized to better show the difference in light. The solid lines show data taken before lunch and the dashed lines show data from the afternoon the same day with all other settings identical. Between the test series the sun has moved so light conditions have changed from brighter to darker causing the average contrast to change. Important to note is that this data was collected outdoors so, apart from light conditions, there was also other factors effecting the spray.

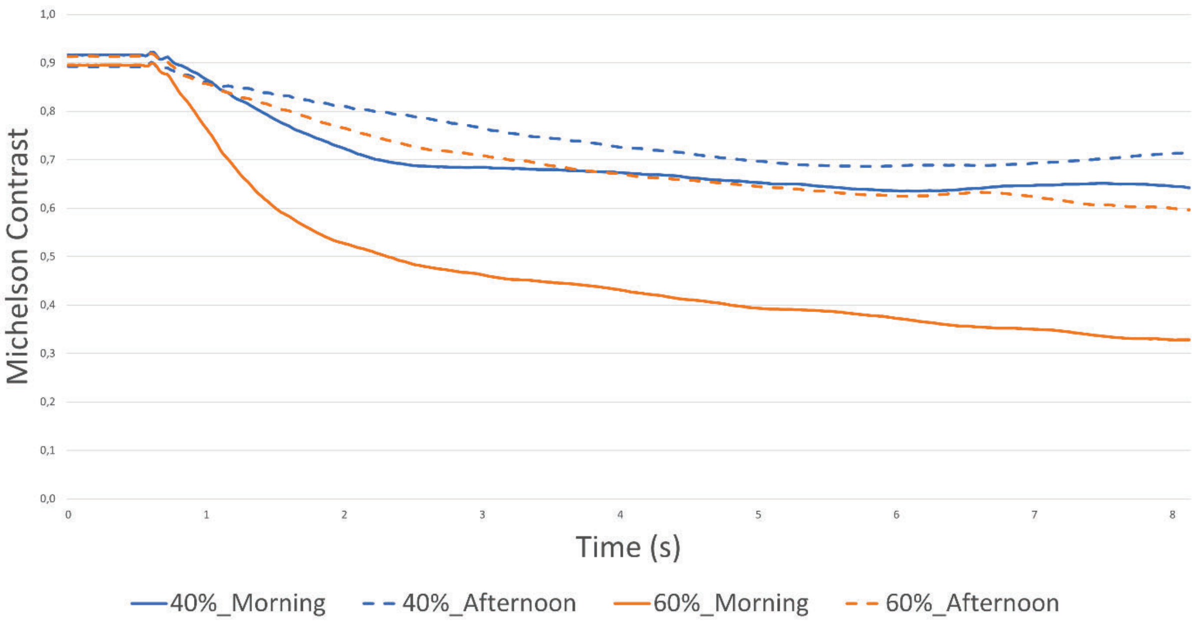

Figure 35 Outdoor emulated spray in different lighting (not normalized)

Effects from using camera calibration

As a measure to make data from different test series more comparable the calibration tool described in *Camera calibration* is used. In this way the reference contrast, without spray present, can be set to the same value despite different light conditions. However, this should be used with caution since a large difference in light is likely to also produce a large difference in contrast attenuation from the applied spray by more reflections in the water droplets.

Contrast effected by wind
Even if precautions were made to minimize the effect from wind when emulating spray outdoors there was still some cases were the effects where clearly visible. The Figure 36 below shows data from 16 runs outdoors with 60% spray from the rig. The contrast can be seen reduced by between 60% and 70% but two datasets clearly deviate from the rest. On these two occasions (marked in read) the wind caused the spray to drift to the side, no longer reducing the contrast as much. This implies that wind also is a crucial reason to aim towards indoors testing for repeatability.

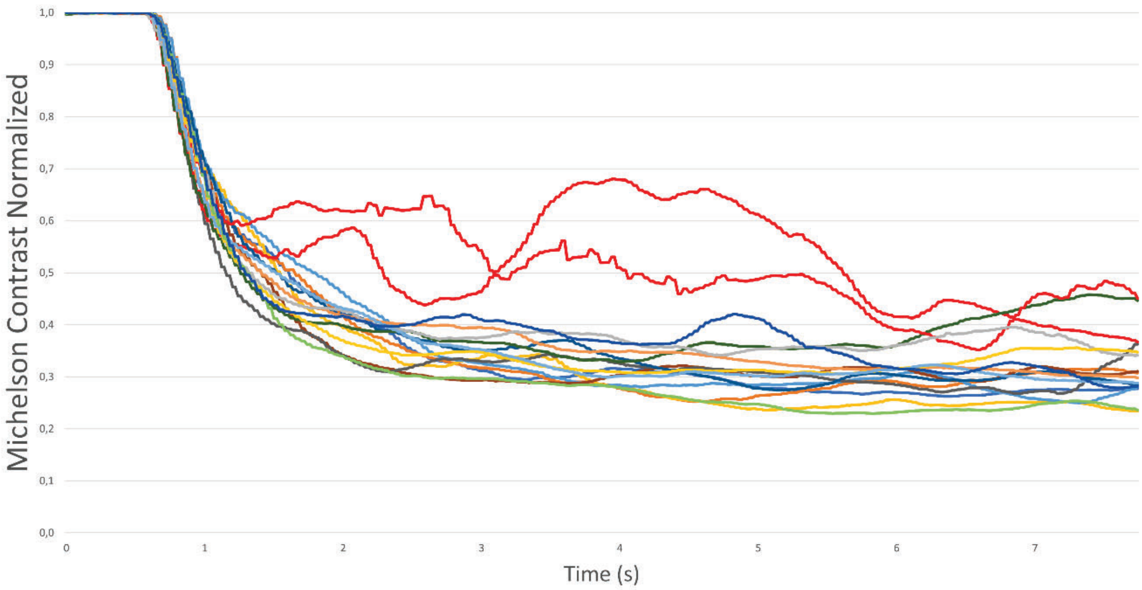

Figure 36 Contrast effected by wind

Outdoor versus indoor testing
A lot of effort in this project has been put into handle the uncertainties created by uncontrollable factors outdoors such as wind and light. A calibration tool has been developed to better handle different light conditions, and clear results on the effects of wind have been produced. All of this was considered when running tests outdoors over three days in November 2022 at AstaZero when around 240 tests were done with three different spray settings. Even if the data exhibits a large spread in contrast within each spray setting, the different settings can be mostly distinguished from each other since they do not overlap so much.

In the following six graphs (Figure 37 to Figure 42) the left column shows data from 20 logs on each spray setting, one day per graph. The right column shows an average of those 20 logs for each spray setting: green 20%, orange 40% and blue 60%.

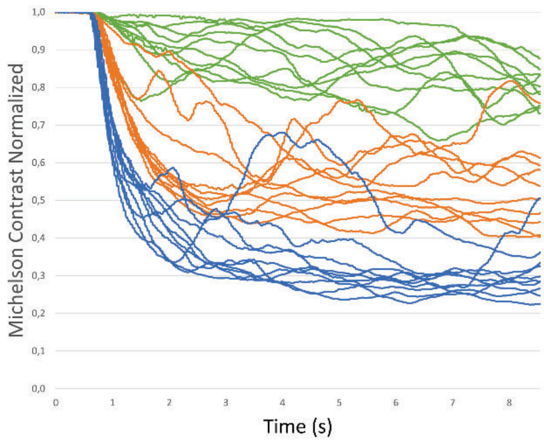

Figure 37 Outside day 1, all logs

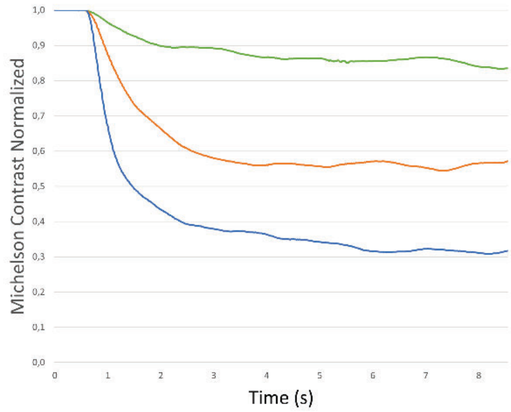

Figure 38 Outside day 1, average

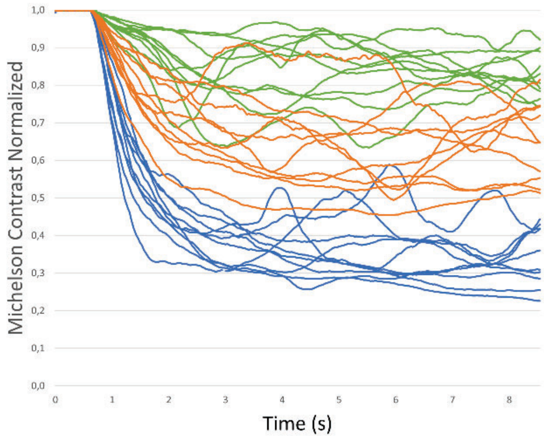

Figure 39 Outside day 2, all logs

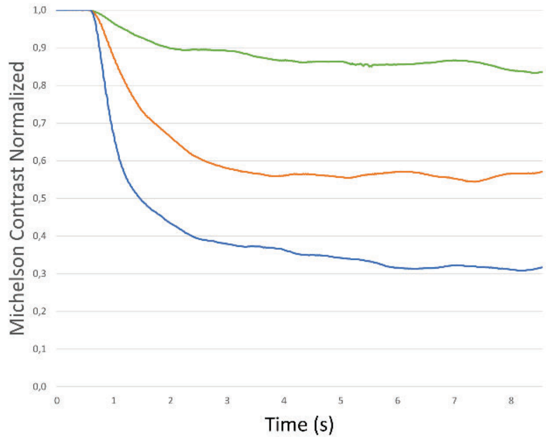

Figure 40 Outside day 2, average

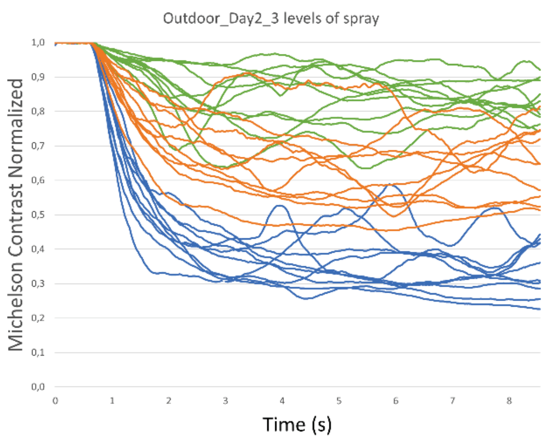

Figure 41 Outside day 3, all logs

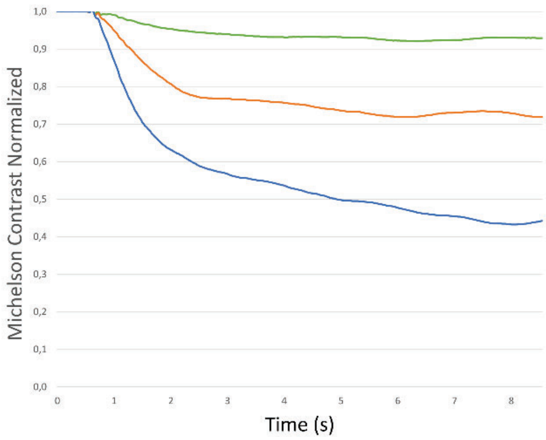

Figure 42 Outside day 3, average

For completeness, all 180 logs are also plotted in one graph below to the left in Figure 43 with their corresponding averages to the right in Figure 44.

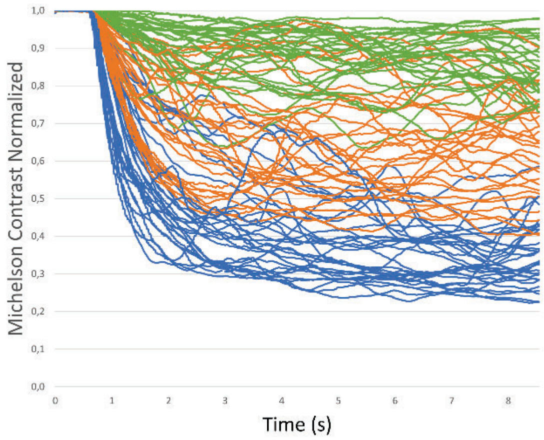

Figure 43 Outside day 1-3, all logs

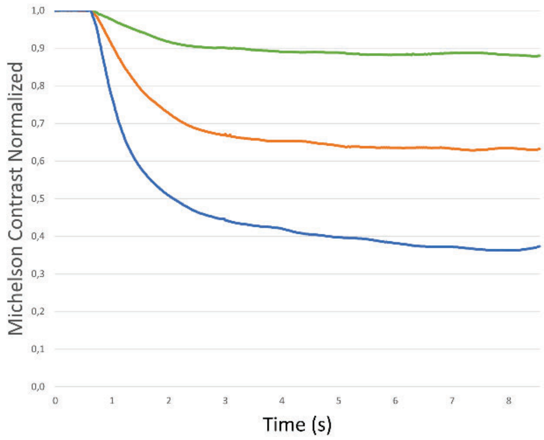

Figure 44 Outside day 1-3, average

As a final test session in the project, a location was arranged to evaluate the spray rig and method indoors, namely the water test facility at Volvo's test site in Hällered. This setting provided constant light all three days and no wind interference at all, meaning it could now be proven that the method with spray rig v2 creates a constant contrast attenuation if surrounding parameters as wind and light can be kept constant.

The following graphs in Figure 45 to Figure 50 plots the results from three consecutive days with every day containing data from ten runs each for the spray settings 20% (green), 40% (orange) and 60% (blue). In the right column the ten logs for each setting have been averaged. Compared to the corresponding data collected outdoors these results have a much smaller spread concluding that the spray created from the rig is repeatable with fair accuracy.

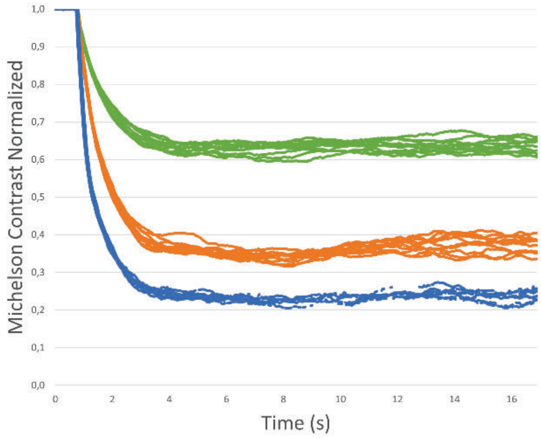

Figure 45 Indoors day 1, all logs

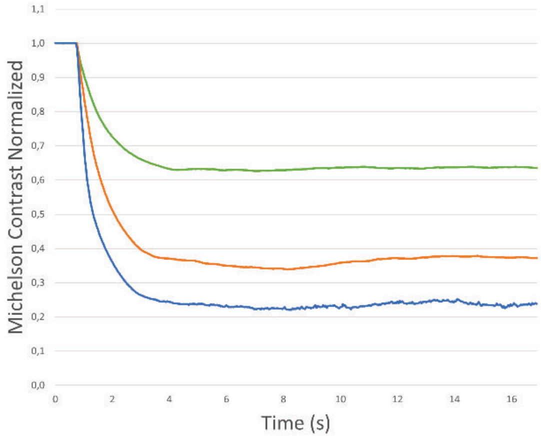

Figure 46 Indoors day 1, average

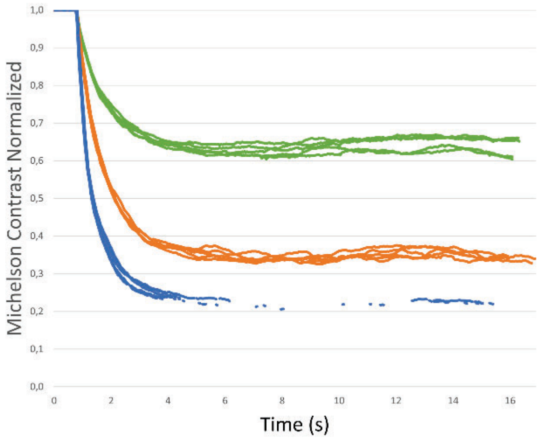

Figure 47 Indoors day 2, all logs

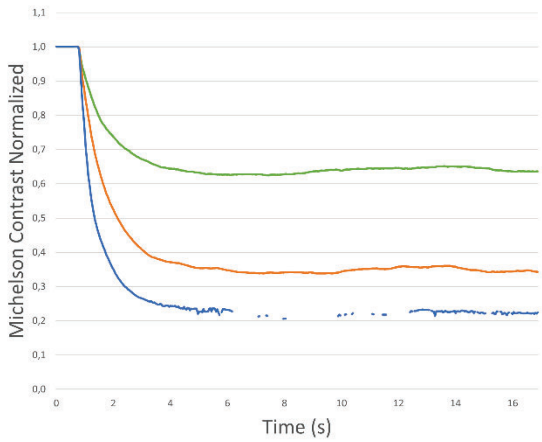

Figure 48 Indoors day 2, average

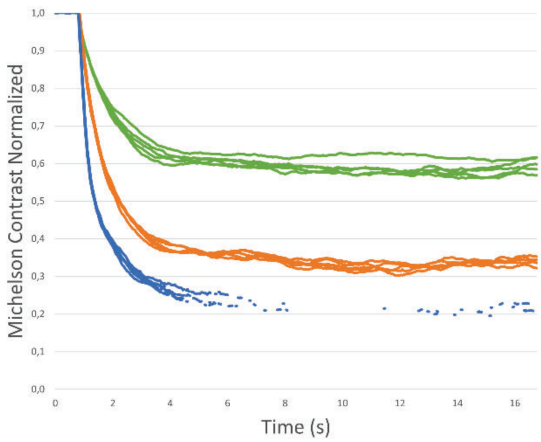

Figure 49 Indoors day 3, all logs

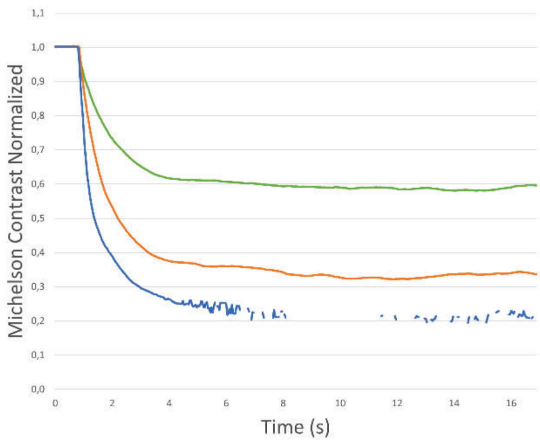

Figure 50 Indoors day 3, average

The contrast can be seen within a 5-15% interval even when plotting all 90 tests in the same graph as seen in Figure 51 below.

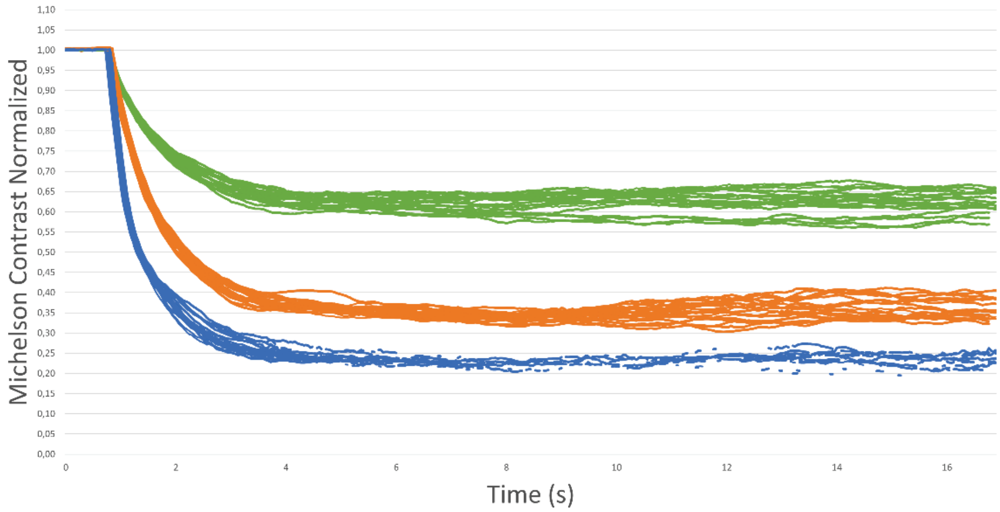

Figure 51 Indoors day 1-3, all logs

This comparison with the results and conclusions from it is very valuable for future work on the subject, both for emulating spray with a spray rig and for collecting data from real world spray. It is now clear that a very controlled and repeatable spray can be emulated indoors, but the project has also resulted in tools and knowledge on how to better handle the effects from the outside environment.

Accuracy and contrast attenuation

With the conditions optimized as in the indoors testing it was now more relevant to investigate the variability/repeatability of the spray rig. The data is first normalized as described in *Data normalization* and focused on the time frame where the spray is stable between T=5s and T=16s. The dataset consists of 20 logs taken with each spray setting as 20%, 40% and 60%. This means that there are 5520 data points evaluated for each spray setting in the specified time interval.

Listed in Table 5.1 are averages with standard deviations, max values, min values and the spread between them. As a comparison to further emphasize the level of noise in data collected outdoors the same set of data is listed from the three days of outdoor testing from previous chapter.

	Average_5-16s	Standard deviation	Max value	Min value	Spread
Indoors					
20% spray	0,625	0,025	0,678	0,561	0,117
40% spray	0,352	0,020	0,411	0,303	0,109
60% spray	0,233	0,012	0,274	0,195	0,079
Outdoors					
20% spray	0,888	0,067	0,991	0,634	0,357
40% spray	0,646	0,130	0,978	0,390	0,587
60% spray	0,399	0,116	0,798	0,227	0,571

Table 5.1 Table for standard deviations and spread.

As described in *Test Setup* the spray settings are not entirely derived from actual water- or pressure output but from the numbering on the adjustment nob. This could be the reason that the level of contrast attenuation does not scale with the noted amount of spray applied from the rig.

Different nozzles

The PNR nozzles have a higher flow rate and seem to produce a more concentrated spray cloud. In combination with a less tested setup this higher flow rate also caused the spray to obscure the lower part of the target even at a lower flow rate and this resulted in that the analysis tool dropped its target detection and returned no values for most of the frames at higher pressure settings. For this reason, the data below only presents the lower spray settings from the tests with the PNR nozzles.

Presented below in Figure 52 is a comparison between Ultra Fog and PNR for three and two different spray settings respectively. Since they use different definitions of spray settings, they are not directly comparable more than to show that they can produce similar contrast attenuations. For example, at 3 bar the PNR nozzle has a contrast attenuation that matches that from the Ultra Fog nozzles at 40% spray.

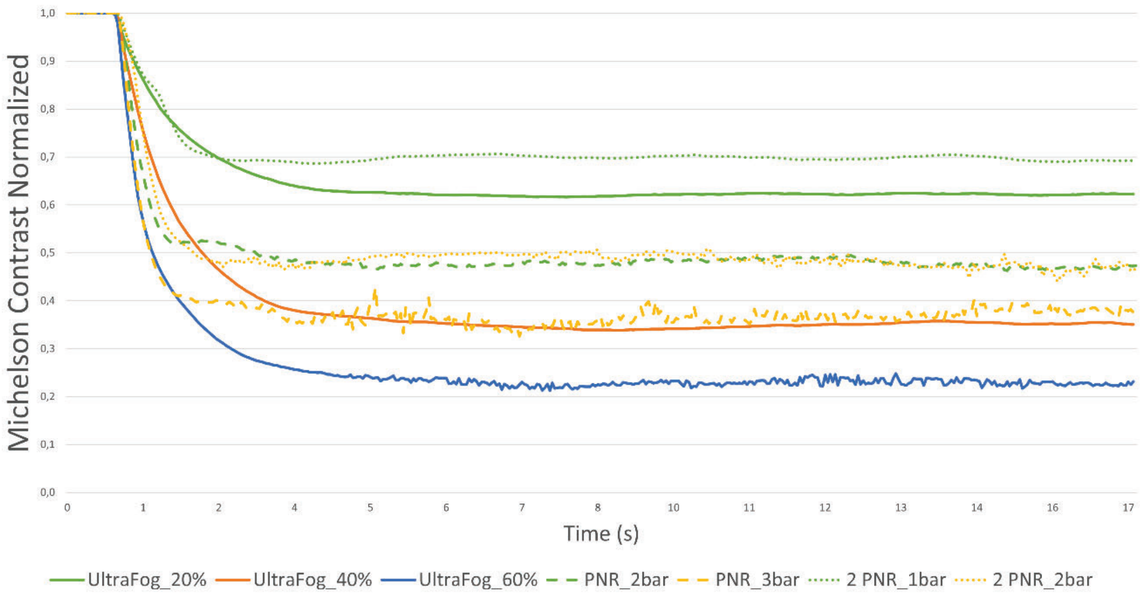

Figure 52 Nozzle comparison

Effects of a fan on emulated spray

A small amount of test data was collected when using the fan and these results are mostly for completeness and to start investigating the subject. More tests need to be done with different positions, angles, and settings for the fan to further investigate the effects of a controlled and repeatable airflow. Adding multiple fans can also be of future interest.

The way the fan was positioned for these tests resulted in that the spray was dragged down so that the target was less obstructed by spray. In general, the contrast attenuation was reduced much like when the wind impacted the outdoor tests but this time the spray was moved down instead of to the side and in a more constant way.

Figure 53 shows data averaged from 15 logs each with spray using one PNR nozzle at 2 and 3 bar, with and without the fan. Both spray settings show a contrast around 30% units higher with the fan on.

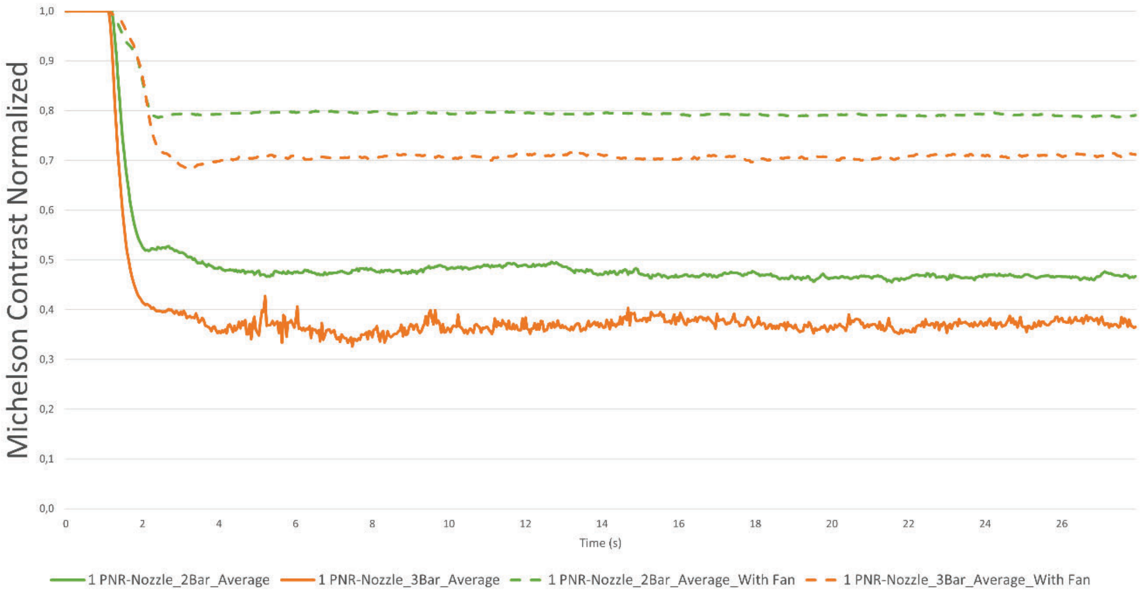

Figure 53 Contrast effect from added fan

6 Dissemination

6.1 Knowledge- and result spread

How have/will the results from this project been/be used and spread?	Mark with X	Comments
Increased knowledge in the area	X	The project has led to a better understanding of the complexity involved in weather emulation. Regarding the phenomena of road spray, we have raised the internal knowledge and created equipment that can be used by industry and research projects to further enhance common understanding.
Carried over to other advanced technical development projects	X	SEVVOS will further investigate some of the questions from this project, like droplet sizes of real-world spray.
Carried over to product development projects	X	The method and equipment from this project will be developed further to work as a product/service and research platform for costumers and academia at AstaZero.
Introduced to the market		
Used in investigations/regulations/authorization matters or political decisions.		

This project is followed by the project SEVVOS (Simulation and Evaluation of Water spray for Validation of Optical Sensors) funded by FFI. The project also acts as an associated partner to the large European collaboration project AI-SEE, funded by the Euripides2 and Penta organization, a cluster under the Eureka network. SEVVOS aims to further evaluate the spray created by this project and validate it with data from water spray created in real scenarios under controlled conditions.

7 Conclusions and future research

Many different factors effect visibility in adverse weather and water spray itself make up a very complex phenomenon that is hard to measure with good repeatability. As a targeted effort to create a more controllable test environment a new spray rig was developed in this project with good results. Unfortunately, only the last test session was performed in a sufficiently controlled environment, but that data proved very valuable and fortified the repeatability of the spray rig.

Light has a known and obvious impact on contrast and this project has showed results that support this, in both real-world and emulated spray conditions. For this same reason, contrast measurements in water spray are very hard to make comparable between test series from different days or locations. There is more to be done to overcome this issue even more, but some progress has been made here.

When testing outdoors, wind is also a problem for repeatable spray data because of the small and light droplets that make up the spray. This project has produced some results to visualize this. Similar results have also been repeatably produced in a more controlled indoor environment with a large fan representing wind.

In controlled conditions indoors the spray rig has shown repeatable contrast attenuation data within ±5 for different spray amounts. Corresponding data from outdoor conditions on the other hand, show data with a spread of ±18% to 29% caused by the influence of light and wind conditions.

The new spray rig can also be fitted with different nozzles for different drop sizes to better customize the spray according to real-world data when that is more developed. Initial tests on the rig shows that repeatable contrast attenuation can be achieved even with different nozzles.

The camera calibration tool developed in the project enables a good overview and high control over the camera settings and their effect on the contrast. This makes it much simpler to setup tests and visualize the effect on contrast from present surroundings. Furthermore, the analysis tool itself is very much an enabler for collection and analysis of large amounts of contrast data with a decent level of customization.

Future users are interested in the progress of the testing with water spray but even more interested in higher level of complexity such as contaminated water, dirt or even snow. The increasing interest and efforts towards AD continue to motivate research on the subject and for higher levels of AD, sensor systems need a higher availability even in adverse weather. To reach this higher availability there must be methods for repeatable and reliable testing of sensor performance and AstaZero hopes to be a part of that development to support the industry.

8 Participating parts and contacts

AstaZero AB:

Peter Eriksson, Research engineer and Project manager, *peter.n.eriksson@astazero.com*
Erik Ronelöv. Research engineer, *erik.ronelov@astazero.com*
Oscar Tullberg, Research engineer, *oscar.tullberg@astazero.com*

Chalmers University of Technology:

Valery Chernoray, Senior researcher, *valery.chernoray@chalmers.se*
Sai Anirudh Ravichandran, MSc Student, *asai@student.chalmers.se*

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[1] E. Peli, "Contrast in complex images," *Journal of the Optical Society of America,* 1 October 1990.

[2] P. Otxoterena Af Drake, O. Willstrand, A. Andersson and H. Biswanger, “Physical characteristics of spray clouds produced by heavy vehicles (trucks and lorries) driven on wetasphalt,” *Journal of Wind Engineering and Industrial Aerodynamics,* vol. 217, October 2021.

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[1] E. Peli, "Contrast in complex images," *Journal of the Optical Society of America,* 1 October 1990.

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[4] D. Wier, J. Strange and R. Heffley, "Reduction of adverse aerodynamic effects of large trucks," 1978.

11 Appendices

11.1 Chalmers literature review

Weir et al. (1978) provides one of the most extensive and multi-sided studies on the topic. Of particular interest are mechanisms of creation of splash and spray, their modelling, and full-scale test-track experiments. The report describes the mechanisms for water ejection by a tire via the bow and side splash waves, tread pickup, and capillary adhesion. All four are functions of tire speed, road water depth, and tire design.

According to the report, the droplets in the tread pickup stream are distributed in size from small (less than 1 mm) to reasonably large (3 to 5 mm), but the stream is not characterized by large droplets as are the bow and side wave streams. Most of the drops thrown by the treads travel in low trajectories, but some are ejected high enough to degrade visibility.

A greater contribution is created by the impaction of tread-thrown droplets on-following tires, or on parts of the truck body such as the gas tanks, fender wells, mud flaps, or frames. These impacting droplets break up into clouds of fine droplets (much less than 1 mm) which are carried away from the truck at sufficient height and in sufficient concentrations to cause a considerable reduction in visibility.

For water depths greater than about 3 mm the tread grooves are filled, and excess water in the tire path is displaced into the bow and side waves. The droplets thrown by smooth or worn tires in general appear to be smaller than those thrown by treaded tires. Under conditions of deep water and high speed, severe bow and side wave splash streams can result. It has been noted that at a given speed the size of the droplets ejected by a tire increases as the water depth increases. The contribution of the side and bow waves to the spray volume may be quite low because the side waves lie along low trajectories.

Furthermore, according to Weir et al. (1978), the speed of the tire through the water is a major factor in splash and spray generation. Maycock (1966) showed that the overall spray water density measured 9.2 m behind a test truck increased in proportion to the 2.8 power of the vehicle speed, with the best fit for speeds between 20 m/s and 33 m/s.

Very little spray was measured at speeds below 13 m/s. Since the amount of water encountered by the adjacent vehicle is equal to the spray density times the vehicle velocity, the visibility effect could increase in proportion to as much as the 3.8 power of the velocity. Maycock also noted that the length of the spray cloud trailing the vehicle was proportional to the velocity squared.

It has been observed that wave splash is thrown farther laterally and vertically as vehicle speed increases and that droplet size is strongly affected by increasing speed. Maycock indicated that below 13 m/s water is ejected principally in tread throw and waves as large droplets which do not break up into spray and fall back to the ground where they are extinguished (no rebound). However, as speed increases, more water is ejected as fine spray, until at speed of 33 m/s most of the water thrown is in a fine spray, and very little falls to the ground as large drops.

Further discussion of the effect of operational and tire factors on droplet size is given in Lissaman et al. (1978) where a theoretical treatment of the tread pickup phenomena including the consideration of a number of possible mechanisms has been made. Some interesting results have been obtained which contain the correct physical character of the observed phenomena using ordinary continuum, fluid mechanics concepts and some simplifying assumptions.

Each of the various tread throw models tried started with a different set of assumptions for the throw mechanism. Each assumed that the tire tread starts flat on the ground with zero velocity. A tread point starts accelerating upward at a uniform rate, and the water in the tread grooves is assumed to start at rest. Details of these modelling approaches are given in Lissaman et al. (1978).

The set-up for road wetting in full-scale tests implemented in Weir et al. (1978) was based on a road with 1% slope and an irrigation pipe along the edge. The resulting water depth was around 1.5 mm. The visibility measurements were relying on checkerboard filming, laser transmission, lamp-photometer transmission, and observer evaluations. Correlations between these measurement methods are discussed. One of the interesting results of the study is the effect of wind and truck position on visibility.

Similar approach for wetting the road was implemented in Dumas and Lemay (2004). The setup was also relying on 1% sloped road and a perforated pipe. However, from all the methods of visibility evaluation they have only used laser transmission and a photometer sensor array. They have recommended three photometric sensors on each side of the road.

In paper by Walz et al. (2021) the spray was generated by 8 nozzles on the vehicle: four on the back and two on each side. The nozzles were activated in different combinations and at different flow rates. Further details on the machine are provided in Doric and Ritter (2019) and Ref [7].

In Riahi et al. (2022) the wetting was created by a nozzle on the main vehicle directed to the wheel of a van attached to it. An Aquasence sensor was used to measure the water film thickness on the road. Water depths up to 0.7 mm at 30 km/h and 0.5 mm at 50 km/h were reported in the article.

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11.2 Chalmers tests and investigations

The experiments carried out by Valery Chernoray and Sai Anirudh Ravichandran at Chalmers are described and compiled in a separate report included as a separate attached file named “*SUS related research conducted at Chalmers*”.