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Problems related to the operation of autonomous vehicles in adverse weather conditions

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The article introduces and discusses the sensors used in autonomous cars. The reliability of these devices is crucial for the proper operation of autonomous driving systems. The research works related to the issue of the performance of autonomous sensors in adverse weather conditions is discussed and critically analysed. The negative effects caused by bad weather conditions are characterised. The paper presents the result of author's own research concern on the effects of rain, snow and fog on lidar measurements. The results obtained are presented, detailing the most important threats from each weather phenomenon. Attempts currently being made to address these issues are presented as well. The paper concludes with a summary of the research results, the current state of knowledge and suggestions for future developments.

Key words: *lidar, autonomous vehicle, adverse weather, rain, detection*

1. Introduction

Technologies related to autonomous cars are currently being widely developed. Selected autonomous driving systems are increasingly appearing in new cars. The aim of using these technologies, is primarily to improve road safety and assist the driver. The overall name for this system is used ADAS (Advanced Driving Assist Systems). System ADAS consist of elements:

– partly autonomous driving:
– lane keep assist
– lane change assistant
– active cruise control
– emergency braking
– traffic sign reading (and automatic vehicle speed correction)
– driver fatigue assessment
– automatic parking
– cross traffic warning, etc.

There are six levels of autonomy according to the widely accepted classification developed by the SAE (Society of Automotive Engineers). The highest, fifth level, assumes that autonomous driving takes place without driver involvement, regardless of weather conditions [31]. Some of the cars can be classified as, being on the borderline of levels 3 and 4. This means that in favourable weather and road conditions, the car takes complete control of the steering, leaving the driver as an observer. Before bringing in vehicles on level 5, it is necessary to solve a number of technical problems, taking into account both the structure of the vehicle itself and its mobility[26].

2. Sensors used in autonomous cars

2.1. Sensor characteristics

When an autonomous car moves, it uses data from sensors installed in the vehicle. The simplest division of sensors can be made them as internal and external. Internal sensors provide information on the state of the vehicle. These include among others: speed sensor, accelerometer or gyroscope. These sensors are not affected by adverse weather conditions.

External sensors are responsible for analysing the environment. Nearby objects are analysed by sonar, those at medium distances by lidar and cameras, and by radar those objects that are far away. In addition, data obtained from the car's communication with the environment (V to X) are used. The external sensors may be strongly affected by adverse weather conditions.

A prerequisite for safe driving of an autonomous car is the acquisition of reliable data regardless of the traffic and weather situation. Based on the information from the sensors, the car driving system: creates a map of the environment, identifies and classifies objects, and finally creates a complete parametric model to determine the trajectory of movement [3, 27, 36]. These tasks include detection and tracking of moving objects, hereinafter referred to as DATMO and simultaneous localization and positioning on the map (mapping) referred as SLAM. The basic characteristics of the sensors used in autonomous cars are shown in Table 1.

Table 1. Basic characteristics of sensors used in autonomous cars

	Tasks	Range	Weather vulnerability
Radar	DATMO	medium and long	minor
Sonar	DATMO	short	minor
Lidar	SLAM, DATMO	short and medium	significant
Cameras	SLAM, DATMO	short	critical
Internal sensors	SLAM	n/a	minor

Radar is an acronym for Radio Detecting and Ranging. It is one of the most commonly used sensors among road-approved vehicles. It is relatively inexpensive, easy to implement in a vehicle, and weather-resistant. It performs well in measuring distances over both short and long distances. It enables quick determination of the speed of an object. The biggest disadvantage of radar is its low accuracy in determining the shape of objects, which greatly limits its usefulness in object identification and classification tasks.

Sonar is a specific type of radar used for object detection at very short distances, e.g. during a parking manoeuvre or driving in heavy traffic. Experiments are being conducted on its use in lane change warning or pedestrian detection systems [22]. The biggest disadvantage of sonar is its short range – usually below 5 meters. In addition, it can be susceptible to interference from other objects generating sounds such as the noise of the wheels or of a passing train [34].

Lidar is an acronym for Light Detection and Ranging. It is a remote sensing technology that creates a three-dimensional image of the environment by illuminating objects with a laser beam and analysing the energy of the reflected beam. In the automotive industry, pulsed lidar is most commonly used. The device consists of a transmitter, a mirror and a receiver. The laser beam, upon encountering an object in space, is reflected from its surface and returns to the light-sensitive diode. The time from emission to reception and the reflection intensity indicator allow the position of a given point in space to be determined. Each point is defined by four parameters: x,y,z coordinates, and the reflection intensity index [10]. Lidar has a wide range of applications in autonomous driving systems, as it is used both as a tool to identify and track objects and to detect environmental features (e.g. kerbs) [6, 13, 29]. It is considered to be one of the most important sensors used in autonomous cars and is also used in currently new road-approved vehicles (e.g. Mercedes-Benz EQS 2022). Lidar prices are decreasing year on year and the technology is being developed intensively. The disadvantage of lidar is that the information obtained does not allow the exact nature of the object to be determined, e.g. lidar does not provide colour information. The problem worsens as the distance from the object increases. Lidar is susceptible to interference from adverse weather conditions.

Camera as well as camera systems (stereovision) are commonly used in autonomous vehicles. Cameras have a very wide range of applications, being effective in detecting road signs and signals. It is used to locate the vehicle in its surroundings, because it allows you to detect the edges of individual objects and their colours. Cameras are a good source of data for object identification systems, as the video image is detailed and easy to analyse. The biggest disadvantages include: susceptibility to processing errors, low resolution at longer distances and, above all, high susceptibility to adverse weather and light conditions.

2.2. Impact of adverse weather conditions on the performance of sensors used in autonomous cars

It is believed that it is currently impossible to build an autonomous vehicle that can navigate in all conditions (SAE level 5), because weather conditions affect the data received from sensors of such a vehicle too much [2, 24, 25, 33, 38]. A single drop of water on a camera lens can scatter light blurring the camera's field of view. Most algorithms used in vision systems based on cameras, assume that light intensity is proportional to the brightness of the scene. However, dynamically changing weather conditions introduce sharp fluctuations in light intensity that reduce picture quality. Raindrops in the air reduce the intensity of the image and blur the edges of analysed objects [40]. An experiment conducted by Ferreira and Martins [12] showed that when performing the task of detecting a vehicle in the rain, the quality of the image obtained from the camera deteriorates due to poor colour gradient saturation which, at a later stage of image processing, results in problems in creating the envelope of the detected vehicle – the algorithm has a problem when restricting the images field in which the vehicle is visible [12]. Based on experimental studies in rain conditions, a decrease in object detection quality of 20 to 65% was reported. Another experiment showed a decrease in detection performance of up to 65% during rain-fall and up to 45% during thunderstorms (results obtained with clear skies were taken as 100%) [41]. Fog, although less frequent than rain, is very disruptive to camera operation. First of all, it causes the effective range of vision of the camera to shrink considerably, so that detection of the rear lights of the vehicle ahead or the edge of the road becomes very difficult. The same problems can be applied to snowfall, relatively they are much more frequent. The snowfall conditions are a serious problem, because even if the autonomous car uses additional localization methods (e.g. GPS), snow accumulation can lead to serious localization errors [38].

Radar shows little susceptibility to bad weather conditions. Part of the radio wave can be absorbed by water droplets in the air (attenuation effect), the wave can also be depolarized or scattered by rain [12]. The most disruptive effect on radar operation is the occurrence of backscattering. This effect occurs because the size of the water droplet is comparable to the radio (millimetre) wavelength. The attenuation effect reduces the received power of the signals and the backscattering effect increases interference to the receiver [38]. Rain also causes a decrease in the effective radar range. For 50 mm/h intensity of rain, the range decreases by 11%, and a more significant reduction in range is caused by 150 mm/h rain [39]. At the same time, it should be remembered that rainfall of 150 mm/h is already a true tropical typhoon. In rainy conditions, the smaller the object is, the faster the distance from which it can be detected decreases. This is particularly important for pedestrian detection [35]. Studies show that for obstacles at ranges of up to 25 m, even dense fog has a negligible effect on radar performance. However, in the case of heavy snowfall, the effective radar range decreases up to 25% [19].

Rain poses a threat to lidar on many levels [37]. It can lead to a number of adverse effects such as: deterioration of reflectivity, decrease in effective range, and distortion of the shape of the identified object [41]. The more intense the rain, the more these effects increase – rain intensity of 15 mm/h does not cause significant interference, but already intensive rain of 30 mm/h reduces the effective range of lidar operation by 50% [16].

In the authors' own research, it was found that during heavy rainfall, when measuring at a distance of 10 meters, the quality of detection drops by several percent. The shape and size of the droplets are also important as larger droplets distort the laser beam more [39]. On the other hand, a decreasing number of generated points on the picture, not only results in a decreasing range but also reduces the amount of data available for analysis [4]. In addition, splashes from other vehicles can result in the detection of falsely existing points and consequently the generation of phantom (unreal) objects [29]. This effect leads to an enlargement of the real object by non-existent points which affects the detection process. This is because the falsely curvature of the shape of analysed object, can result in a poor match of the object class. Points of phantom objects (unreal) generally have a low reflection intensity index, however, as a result of precipitation, the intensity of points resulting from reflection from real objects also decreases. According to a study by Hesper Riviere et al. [18], for the emitted by lidar wavelengths of 905 nanometres (95% of the devices currently use this wavelengths), fog is more challenging to analyse than rain. This is due to the scattering of light by the fog particles. At the same time, the denser the fog, the more problems the sensor has in providing reliable information. Tests in the chamber show that target detection at a distance of 10.5 m in 10 m visibility is impossible for most lidars [19]. Where visibility is understood as a parameter subjectively assessed. Similar conclusions were obtained by conducting the Authors' own studies on the effects of fog on lidar performance. Similar effects to fog are also caused by dust – especially PM10 particles [4].

3. Studies on the effects of atmospheric conditions on lidar

As part of the in-house research, a series of experiments were conducted to determine the susceptibility of the lidar to adverse weather conditions. For this purpose, special test rigs were built, consisting of the Livox Horizon lidar and reflective targets – road signs of different diameters. The basic parameters of the equipment used are shown in Table 2.

Table 2. Basic parameters of Lidar Livox Horizon

Wavelength	905 nm
Maximum range	260 m @ 80% reflectivity
Point of View	81.7° vertically× 25.1° horizontally
Beam divergence	0.28° vertically × 0.03° horizontally
Number of points generated	240,000 points/s (first or strongest reflected signal) 480,000 points/s (both signals)

As part of the research carried out, an attempt was made to establish the effect of rainfall on lidar performance. The study was an extension of earlier tests conducted by authors [7]. The work was divided into two stages. Firstly, the interference that rain causes when identifying objects was measured, and then the phenomenon of unreal points – resulting from the reflection of the laser beam from water droplets in the air – was investigated. To perform the tests, a special test rig – a rain gauge – was constructed. A major problem was to ensure, by all time, high water pressure in the system, which was achieved by using an 850 W pump and a hydrophore tank. Uniform and controllable water distribution was achieved by using ¼" diameter pipes. A section of the point cloud image generated by the lidar during the high intensity rain impact study (> 25 mm/h) was shown in Fig. 1.

The blue points visible in the figure are the result of the laser beam reflecting off water droplets floating in the air. These points are blue in colour because the reflection intensity factor of water drops is low. The traffic sign shield visible in the centre, made of reflective material, is bright red. In spite of this, even on the background of the sign, blue dots appear which directly indicates that the number of dots generated for the sign face has been reduced caused by the beam reflection from the water droplets. Studies have shown a decrease in overall object detection quality and blurring contours as a result of rain-induced interference.

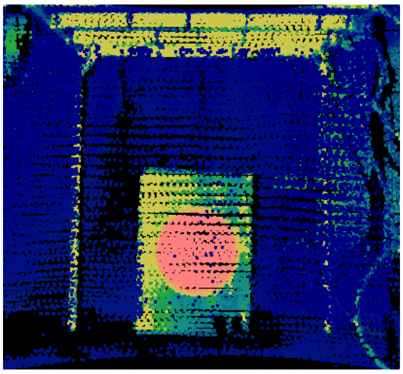

Fig. 1. A section of a point cloud generated by lidar during a study of the impact of high-intensity rain

As part of the second part of the study, the effects on the point cloud generated by the lidar were investigated which has been created by a splash of water is observed behind a vehicle travelling on wet pavement. An existing test rig was modified to capture by lidar the water cloud formed behind one of the rear wheels of the vehicle. A driving speed of approximately 36 km/h was simulated. In the tests, the movement of the air masses surrounding the vehicle (using a blower) were assumed too. Figure 2 shows a section of the point cloud generated by the lidar.

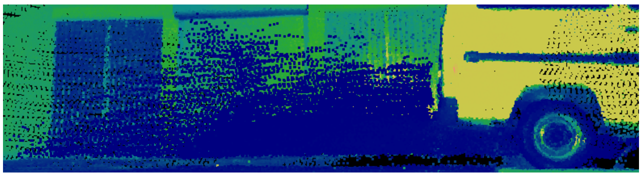

Fig. 2. A section of the point cloud generated by the lidar during the investigation of the water splash by the wheel

The cloud of blue points visible behind the vehicle is the result of the laser beam reflecting off the water droplets. This cloud significantly obscures objects behind it.

The study of the effect of fog on lidar performance, was carried out on a test stand located inside a building. Some limitation for the tests was the small size of the room; however, even under such specific conditions, it was possible to observe the effect of fog on sensor performance. Targets with high reflection index were positioned at a distance of 6 m from the sensor, and reference posts allowed the level of visibility to be determined. The view of the targets which was beam-illuminated of the lidar is shown in Fig. 3.

As part of the tests carried out, visibility was progressively reduced, to the point of complete absence, by fog. As the opacity was gradually increased (for this purpose, steam from heating the water-glycol mixture was sprayed), a decrease in the visibility level of observed objects. The reflectivity index has been measured. The maximum achievable reflectivity index was 255, and the lowest was 10. The differences in the measured index value, for the different levels of visibility (smoke), are shown in Fig. 4.

Fig. 3. Test stand for measuring the effects of fog on lidar performance

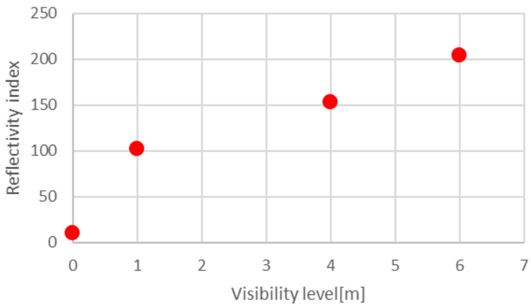

Fig. 4. Dependence of reflectivity on visibility level

Reflection index readings were taken at irregular intervals as it proved very difficult to obtain a specific level of visibility under the conditions of the actual experiment. Maintaining an evenly distributed artificial fog on a test rig is a challenge in itself.

The study showed that the decrease in reflectivity as a function of distance is nonlinear. However, it can be assumed that the greater the opacity, the steeper the drop in the reflectivity value. During the almost completely smoke-filled room (visibility less than 1 m), the lidar could still see the target, although the reflectivity index of them has dropped to a level of 10.

When investigating the effect of snowfall on lidar performance, it was decided to use naturally occurring atmospheric conditions, the falling snow had an intensity of about 5 mm/h with visibility below 800 meters. Such conditions, are considered high intensity precipitation [9]. A series of experiments were conducted with targets placed at different distances from the lidar (5, 10, 15 m). As the distance increased, an increase in snow-induced interference was observed. The effect caused by snow is very similar to that generated by rain – the laser beam reflects off snow-flakes swirling in the air, causing unreal points obscuring the target. The characteristic blue points caused by falling snow are shown in Fig. 5. The picture shows a large disturbance caused by snowflakes.

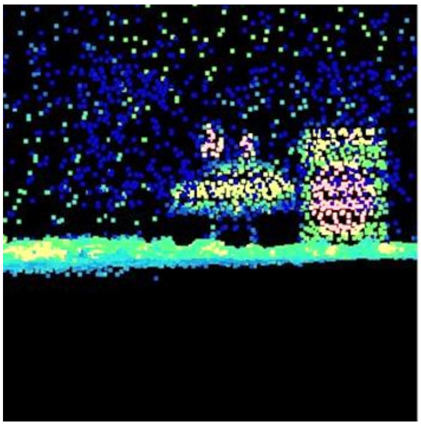

Fig. 5. A section of a point cloud generated by lidar during a snowfall impact study

4. Analysis of the measurement results

Developing a methodology to accurately assess the impact of changing atmospheric conditions on lidar is difficult because the difficulty is in repeating exactly the same conditions for each experiment. This is because it is necessary to take into account not only the repeatability of the distance, but also the position of targets, relative to the sensor, the angle of incidence of the laser beam, the height of the targets, interference from, wind and other disturbances. Despite these difficulties, efforts have been made to develop an in-house detection algorithm that can be used to assess the magnitude of interference. This algorithm has already been used successfully in previous work [7]. It works on the basis of a two-dimensional point cloud image, and uses information from lidar about the reflectivity index of a given object points. Objects with a high reflectivity index are displayed as red, while those at the other end of the scale (objects that reflect the laser beam poorly) are shown as blue. Once the survey area has been delineated, the program analyses the image for the presence of the specified pixel colour – this colour must first be read from an image sample or otherwise determined. The bright red colour of the sign shield read from the image has RGB components of 255. 97. 89. The program allows a colour selection tolerance to be set, e.g. by setting a tolerance of 10, the program will label the pixels not only with the RGB colour 255.97.89, but also e.g. 245.105.95 or 250.87.79. After the initial identification of the pixels meeting the colour criterion, the program applies a mask filter. This filter increases the area to be analysed from one pixel (1 × 1) to a three-by-three pixels area (3 × 3). A field is marked as it fulfil the colour criterion if at least half of the pixels in it fulfil this criterion. The mask filter was introduced to improve detection quality, which has been confirmed by tests. The operation of the algorithm can be described by the following formula. A given pixel is marked if it meets the condition:

$$\mathrm{W(i)} = \begin{cases} 1 \text{ when } \mathrm{R}\mp < \mathrm{T}, \mathrm{G} \mp < \mathrm{T}, \mathrm{B}\mp < \mathrm{T} \\ 0 \text{ when } \mathrm{R}\mp > \mathrm{T}, \mathrm{G} \mp > \mathrm{T}, \mathrm{B}\mp > \mathrm{T} \end{cases} \quad (1)$$

where T is the colour selection tolerance. Area O (3 × 3 pixels) is then highlighted in red if:

$$\sum_{i=1}^{9} \mathrm{W(i)} \geq 5;\ \mathrm{i} = 1, \dots 9 \quad (2)$$

When testing the effect of rain, for the reference measurement 1640 pixels have been matched to the object surface. Comparing the number of identified pixels to the reference number, tests carried out for rain intensities ranging from about 5 mm/h to more than 30 mm/h have shown the interference rate was between 11% and 25%. It should be noted that the rain not only reduced the total number of identified pixels, but also distorted the image of the targets. Potentially, this effect could also hinder object identification. However, it is difficult to measure.

Investigations of the splash of water from under the wheels showed that, for an air speed around the car of about 36 km/h, the water cloud assumes a size of ~ 2.23 m × 1.10 m, and the number of points formed by the reflection of the laser beam from the water droplets was 68446. Which accounts for almost 30% of all generated points by lidar. Thus, the water cloud formed behind the vehicle when driving on wet pavement (or during rainfall) represents a significant disturbance in the picture, somewhat resembling very high-intensity rain.

The falling snow caused a very noticeable reduction in the number of identified pixels on the lidar picture. As the distance increased, the visibility of the targets decreased. There is an overlap between two phenomena: a general decrease in the number of points generated for objects further away from the sensor and an accumulation of disruption caused by snow-flakes. Changing the measurement distance from 10 to 15 m with snow intensity of about 5 mm/h resulted in a 22% decrease in visibility level. The effect caused by snow is essentially similar to that caused by rain.

When examining the effect of fog on the lidar operation, the number of pixels visible to the sign face did not change, Thus, it is impossible to determine the impact of disturbances. The effect that fog causes on lidar performance is different from that caused by rain or snow. While raindrops or snowflakes reflect the laser beam and cause unreal points, fine fog droplets do not reflect the beam but cause a decrease in its energy. This effect was very evident in the tests carried out.

Table 3 summarizes the impact of the different weather conditions on lidar performance. As shown in Table 3, heavy rain and snow have the most negative effects on the lidar operation.

Table 3. Impact of the different weather conditions on lidar performance

Phenomenon	Effect
Light rain	Decrease in reflectivity index
Heavy rain	Decrease in reflectivity index, Formation of phantom points, deformation of the shape of objects
Light snow	Decrease in reflectivity index, deformation of the shape of objects
Heavy snow	Decrease in reflectivity index, Formation of phantom points, deformation of the shape of objects
Rare fog	Decrease in reflectivity index
Dense fog	Almost total lack of visibility of targets

5. Counteracting the effects of adverse weather conditions on lidar operation

Based on research into the impact of weather conditions on lidar operation, it was found that the effect can be both an overall decrease in the reflectivity index and the formation of unreal low-intensity points on the lidar picture. Methods to counteract the effect of adverse weather conditions on lidar performance can be divided into:

– equipment optimization which is general improvement of the technical performance of the equipment
– use of advanced filtering algorithms, aimed primarily at removing low intensity points.

An example of optimizing lidar technical parameters could be: selecting the optimal wavelength, adjusting possible power levels and optimizing optical and electronic components [21]. For example, a way to solve the problem of lidar operation in fog, could be to use lidars with a wavelength of 1550 nm. According to this, the longer wavelength scatters less in the fog with less loss of beam energy, resulting in an increased reflectivity index [20].

A much more developed group of methods are filtration algorithms. In order to apply an additional algorithm to facilitate image analysis, it is necessary to first correctly identify the atmospheric phenomenon in question, which is a difficulty in itself [4]. An example of a filtering algorithm is an algorithm that restores the reflectivity index [1]. This uses different types of filters (e.g. particle filters) optimizing lidar performance for wet surfaces [40]. As an example of another method, a system comparing the position of a given point on successive scans can be used. Authors Hahner et al [17], on the other hand, propose their own filtering algorithm to improve object detection quality during snowfall. The authors used point clouds on which they had independently simulated snow for their study.

Also, camera operation during adverse weather conditions can be improved. Examples of optimization for greater reliability include the use of polarization filters in cameras and other techniques based on polarimetry [11, 32]. According to Blin and Ainouz, the use of polarimetry increases the quality of object detection in difficult conditions by up to 20% [5]. Another method is the use of infrared cameras or cameras whose operation is combined with the action of a laser (gated camera) [4, 38]. An example of an algorithm that improves the quality of the camera image can be the method of determinants. An experiment shows that this method actually works and increases object detection accuracy by more than 2% [15]. Other methods involve removing rain from the image. Examples of algorithms working in this way are: DDN [14], DeRaindrop [28], PreNet [30], UNIT [23]. Algorithms of this type are designed to remove the effects of rain and restore the image to a version undisturbed by drops and streams, thereby increasing image quality and the amount of visible detail.

As part of the research work, some researchers are proposing combining data obtained from different sensors as a solution to problems arising from bad weather conditions. This work deliberately does not approximate such research. In the authors' opinion, combining data from different sensors is not a solution, just a way around the problem. Though, such methods, have been presented in an earlier paper on autonomous cars [7, 8].

6. Conclusions

Studies reported within the literature show that the extent to which adverse weather affects objects detection quality varies. This is due to both the nature of the atmospheric phenomenon in question and the detection algorithm used, and finally the parameters of the device itself. Although an official methodology for testing such types of sensors has not yet been developed, this paper compiles the results of Authors' own tests, carried out using the same sensor (Livox Horizon Lidar), in an attempt to replicate actual conditions as accurately as possible. Both the results obtained from our own research and information from other researchers show that the impact of adverse weather conditions on the performance of autonomous car sensors is significant and needs to be addressed. Work on minimizing this impact, comes down primarily to hardware optimization and the use of filtering algorithms. Based on the – Solving the problems associated with the operation of ambient sensors in harsh atmospheric conditions, is necessary for the introduction of vehicles to level 4 autonomy.

– The correct identification of an atmospheric phenomenon is crucial not only for the sensors of an autonomous car, but also for its control system, as it makes it possible to take into account, for example, the decreasing grip coefficient of the tires when planning the traffic path.
– Low-intensity rain poses little disruption to the lidar, while medium and heavy rain reduces the number of detected pixels by up to 24.6%.
– The reflection of the laser beam from water droplets in the air creates unreal points with a low reflection intensity index. This effect also occurs during snowfall.
– The water cloud formed behind the wheels of a vehicle travelling on wet pavement, at urban speeds, assumes a size of more than 4 m^2.
– Water in the form of rain or snow on surfaces negatively affects the reflectivity of the laser beam, which can lead to blurred shapes. Largely accumulated snow can strongly alter the shape of an object, making it impossible to identify.
– During heavy snowfall, a road sign with a diameter of 50 cm at a distance of 15 m from the sensor is already poorly visible. This applies to both the camera and the lidar (when viewed straight ahead in two-dimensional space). This clearly impedes the movement of the autonomous vehicle.
– Snow and rain cause formation of unreal (phantom) points, while fog causes a reduction in the reflectivity index from objects. This decrease is nonlinear. In fog, when the observer or camera is no longer able to see the targets, the laser beam continues to reflect off them. Although the reflectivity index of such points is low, the lidar still sees the targets, which gives a considerable advantage over the camera, which is by then completely ineffective.
– Various attempts are being made to counteract the effects of atmospheric conditions on the sensors of an autonomous car. These methods are divided into hardware optimization and the use of filter algorithms.
– Selecting the right filter algorithm for each weather phenomenon can have the effect of negating part of the negative effect caused by bad weather.

Ongoing research shows the importance of the problem of how weather conditions affect the performance of autonomous vehicle sensors. Without solving this problem with fast filtering algorithms, it is not possible to reach SAE Level 4 of autonomous vehicle traffic. In the authors opinion of the authors, further activities should focus primarily on a thorough understanding of individual atmospheric phenomena and the preparation of appropriate correction algorithms.

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Nomenclature

DATMO	Detection and Tracking of Moving Objects
SLAM	Simultaneous Localization and Mapping
ADAS	Advanced Driving Assist Systems

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