WEATHERSAFE

SAFETY ENHANCEMENT UNDER ADVERSE WEATHER CONDITIONS THROUGH IMPROVED ADAS/AD ROBUSTNESS

Deliverable D2.2

Sensors limits under Adverse Weather Conditions

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EXECUTIVE SUMMARY

Autonomous & Assisted driving is essentially based on perception sensors (Radar, LiDAR, camera, thermal camera, ultrasonic sensors) and associated algorithms. It is therefore important to understand which sensors are present in autonomous driving, how they work and how their performance can be reduced, including adverse weather conditions. A review of the literature is therefore proposed, including a selection and definition of the main sensor families used for Advance Driver Assistance Systems (ADAS) and Automated Driving Systems (ADS). After describing how sensors work in normal conditions, this review looks at the impact of weather conditions in the broad sense (including side effects) on them. This impact is analyzed both theoretically and experimentally, drawing on several scientific sources. This allows to conclude on the following aspects: which are the best sensors according to macro criteria, what is the best combination of sensors to guarantee all-weather system safety, what are the most critical test scenarios to set up for each sensor (including weather), what are the guidelines for carrying out the tests.

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ABBREVIATIONS

ABS	Anti-lock Braking System
ACC	Adaptative Cruise Control
ADAS	Advanced Driver Assistance Systems
ADS	Autonomous Driving System
AEB	Automated Emergency Braking
ALKS	Automated Lane-Keeping System
AMCW	Amplitude-Modulated Continuous Wave
CCD	Charge-Coupled Device
CMOS	Complementary Metal Oxide Semi-conductor
CW	Continuous-Wave
ESP	Electronic Stability Program
EuroNCAP	European New Car Assessment Programme
FMCW	Frequency Modulated Continuous-Wave
FPA	Focal Plane Array
FoV	Field of View
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air Conditioning
IMU	Inertial Motion Unit
ITU	International Telecommunication Union
LiDAR	Light Detection And Ranging
LRI	Laser Return Intensity
LSS	Lane Support System
LWIR	Long-Wave InfraRed
MEMS	Micro ElectroMechanical System
MIMO	Multiple-Input Multiple-Output
MOR	Meteorological Optical Range
MWIR	Mid-Wave InfraRed
NETD	Noise Equivalent Temperature Difference
NIR	Near InfraRed
ODD	Operational Design Domain
Radar	RAdio Detection And Ranging
SAE	Society of Automotive Engineers
ToF	Time of Flight

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2 Introduction

Automated driving is on the rise. Certification up to Society of Automotive Engineers (SAE) level 3 [1] is now possible for vehicles featuring partially automated driving, for the Automated Lane-Keeping System (ALKS) task [2] [3]. The manufacturer must demonstrate that its vehicles ensure adequate safety conditions within their operational design domain (ODD), having conducted tests in diverse scenarios [2]. At the same time, European New Car Assessment Programme (EuroNCAP) offers scenarios for evaluating increasingly advanced driving aids. Examples include collision avoidance systems Automated Emergency Braking (AEB) car to car [4] and AEB car to pedestrian [5] or Lane Support System (LSS) systems [5]. For the time being, the corresponding EuroNCAP tests are not conducted under adverse weather conditions [5] [4], unlike the ALKS homologation procedure, which allows all types of weather conditions, provided they are well specified in the ODD [2].
This deliverable in combination with input from the prior deliverable, deliverable 1 and the next deliverable, deliverable 3, aims to study how accidents in adverse weather conditions occurs, and what safety benefits could be drawn from incorporating robust ADAS systems in the vehicles tomorrow. This deliverable aims to shed light on the sensor's performance in different weather conditions.

Autonomous & Assisted driving is essentially based on perception sensors (RAdio Detection And Ranging (Radar), Light Detection And Ranging (LiDAR), camera, thermal camera, ultrasonic sensors) and associated algorithms. It is therefore important to understand which sensors are present in autonomous driving, how they work and how their performance can be reduced. When the performance of the sensors decreases, the competency of the system decreases to the point where the driver assistance system may have a reduced competency. Sensor performance can be reduced by several effects: deteriorated sensor or adverse environmental conditions [6], including adverse weather conditions. To achieve this, it is particularly important to identify the conditions and scenarios that pose problems for each type of sensor. This makes it possible to determine the specific tests to be carried out to push each sensor to its limits. First, it's essential to identify which types of sensors exist for automated driving tasks, and to understand how they work in general. This will then allow to better understand the impact of the environment on each of these sensors.

A review of the literature is therefore proposed, including a selection and definition of the main sensor families used for driver automation. After describing how sensors work in normal conditions, this review will look at the impact of weather conditions in the broad sense (including side effects) on them. This impact will be analysed both theoretically and experimentally, drawing on several scientific sources. This will allow to conclude on the following aspects: which are the best sensors according to macro criteria, what is the best combination of sensors to guarantee all-weather system safety, what are the most critical test scenarios to set up for each sensor (including weather), what are the guidelines for carrying out the tests.

There already exist some literature review and surveys about sensors and Advanced Driver Assistance Systems (ADAS) under adverse weather conditions [7] [8] [9] [10] [11] [12] but they are not up to date, limited to one kind of sensor, or too much research centred (not about automotive compliant sensors). In this sense, our literature review surpasses previous ones and is more specific to the certification context.

The report breaks down as follows. Firstly, the sensors most used in the automotive context are identified in Section 3.1. To remain close to homologation tests, only sensors that are marketed

on vehicles are considered in this report. Next, a reminder and selection of adverse weather conditions are given in Section 3.2. These are not described in detail, as they are already covered in the deliverable D2.1. Section 4 then describes in detail the general operation of each sensor family. The sub-families are also addressed, to highlight any differences between them, particularly if these may lead to different behaviour in difficult weather conditions. Section 5 then shows which meteorological conditions are critical or not for each sensor family. This review of the impact of different weather conditions on sensors will be carried out from a theoretical point of view (physiological law and simulation), but also from a practical point of view, by analysing feedback from the literature. Finally, Section 6 presents the results obtained. The conclusions derived will enable the determination of the most challenging weather conditions for sensor perception, as well as defining the most effective sensor suite for autonomous driving in all weather conditions. Section 7 give an overall conclusion.

3 Sensors and weather selection

3.1 SENSOR SELECTION

Sensors developed for assisted and autonomous mobility are numerous, in terms of sensor type, technology and model, sometimes even within the same manufacturer. The aim of this report is to focus on sensor technologies:

- actually, used in automotive production at the time of publication. This includes realistic integration into commercial vehicles, sufficient resistance, and costs compatible with large-scale deployment.
- that enable the ADAS system to achieve the highest standard of state-of-the-art safety assessed in Euro NCAP. [5] [4] [6].
- widely used in the world of research, with a very promising future in the coming years.

That selection excludes sensors that may have been integrated into early autonomous vehicles but are no longer in use today, as well as sensors under development that are not yet effectively integrated. Sensors used in upstream research are mentioned in this report but will not be discussed further.

The market is both too vast and too opaque to carry out a study of the sensor models integrated into vehicles on the road. The present report is therefore focusing on the types of sensors found in assisted and autonomous vehicles and not the sensor models. In the sensors used for ADAS and Autonomous Driving System (ADS), the algorithmic part is very important. There are processing algorithms that operate very close to the raw signal, on the scale of the sensor or even the chip. There are also algorithms that process the signal on a larger scale, generally based on the signal given by the sensor itself. This deliverable attempt to free itself from this algorithmic part in the sense that it is a question of understanding how degraded weather impacts the very functioning of the sensor, independently of the improvement in this functioning made possible by an algorithm. At present, it is also virtually impossible to evaluate all sensors and algorithms, either because the algorithms are integrated into the sensor and cannot be dissociated, or because the algorithms used in the studies are not necessarily applied to all existing sensors models. So, this report tries to use as many examples as possible of specific sensor models to draw the most neutral overall conclusions possible about sensor families.

As already explained, the first proposed method of sensor selection is to check which sensors are in use on the automotive market today. To do this, public data from major automakers and automotive suppliers was researched. For the public, sensors for ADAS/ADS are LiDAR or camera sensors, which have been the subject of much debate in the news, not least because of the debates surrounding Google and Tesla. These sensors, that will be considered, are not, however, the first to be deployed on the vehicles of major automakers. Proprioceptive sensors have been deployed on vehicles for much longer [13]. In this report, proprioceptive sensors include all the sensors that enable the vehicle to know its status: Global Navigation Satellite System (GNSS) [14], Inertial Motion Unit (IMU), speed sensors, specific braking-related sensors, etc. Proprioceptive sensors were in fact the first sensors to enable the development of driving aids. Examples include Anti-lock Braking System (ABS) and Electronic Stability Program (ESP), which enable the driver to correct his trajectory in the event of loss of grip. These sensors are essential for ADAS/ADS, as they provide feedback to the vehicle's control algorithms. With the development of ADAS, other sensors for perceiving the environment have appeared. Visible cameras were among the first to be installed on vehicles. Initially, they were used to assist the driver in his or her driving tasks (e.g. rear-view cameras). Nowadays, they are used to detect objects or read road signs, making them an integral part of today's ADAS/ADS [14] [15] [16] [17] [18] [19] [20] [21] [22] [23]. In fact, they are probably the most widely used for this task. Some of today's cameras are even stereoscopic, to enhance depth perception [24]. At the same time as cameras, ultrasonic sensors made their appearance on vehicles [22]. They are now widespread. Their main use is for parking assistance, as their detection range is very limited (around 5m). However, it is thanks to these sensors that vehicle control has been achieved for the first time on commercial vehicles, with park assist technology [25] [18]. At the same time as cameras, radar sensors have appeared on vehicles. They help detect obstacles in front of the vehicle for Adaptative Cruise Control (ACC), ALKS and AEB functions [25] [18] [20] [21] [23]. Radar and LiDAR are currently in clear competition, as will be described in more detail at the end of this section. As a result, radar is currently in full development with the appearance of 4D radar [18] [16] (described in Section 4.1.2.3). Finally, the last category of sensor, which is much talked about because it is more recent, but which is not yet widely used on commercial vehicles, is LiDAR. As will be described in more detail later, LiDAR has been used extensively in the research field, as it offers many advantages. However, its deployment on commercial vehicles is much trickier, although models are beginning to be developed [25] [26] [16] [22] [23] [27] [28] [29] [14] [17]. In the same way as for radars, radar/LiDAR competition has led to the emergence of solid-state LiDAR models [18]. Other sensors are used to a lesser extent on vehicles. For example, thermal imaging cameras are installed on some top-of-the-range vehicles but have never made much headway [18] [30]. Thermal cameras will nevertheless be dealt with in this report, as they behave very differently from other sensors. Similarly, visible cameras are sometimes deliberately stripped of their infrared filter to make them Near InfraRed (NIR) cameras [30]. As technology is very close to visible cameras, the latter will not be explicitly covered in this report. Similarly, certain scenarios, such as the arrival of a police vehicle (sirens), are managed by microphones [22]. These will not be included in the analysis, however, as they are very special cases. In addition, EuroNCAP [6] currently considers that the sensors that may be involved with the driver assistance system may be radar, LiDAR, or camera. This confirms our selection of main sensors.

Following this initial analysis of the sensor market, it is interesting to propose a complementary analysis of research projects. This could help identify future technologies. Several projects are currently underway in Europe:

- ROADVIEW [31]: 4D Radar, LiDAR, Camera, GNSS, IMU, thermal cameras
- AI-SEE [32]: Radar, LiDAR, Gated Camera [33], Camera, Polarized camera, GNSS, IMU
- AWARD [34]: Radar, LiDAR, Camera, GNSS, IMU, Thermal camera

This analysis of research projects shows that there are specific camera variants, such as gated cameras, which are active cameras and thus is a hybrid between camera and LiDAR; or polarized cameras, which can better manage certain water-related aspects (rain, wet ground, etc.). There are also other very recent types of cameras, such as plenoptic, neuromorphic, or event-based cameras. In the same way, some cameras exploit the SWIR wavelength band (between the visible and thermal wavelengths). All these sensors are too recent to be integrated into commercial vehicles, so there's very little feedback, and it's hard to say whether they'll ever be used on a large scale. For this reason, they are not included in this report.

Finally, our selection of sensors will therefore focus on the following families:

- Radar, including Frequency Modulated Continuous-Wave (FMCW) and 4D variant. (Section 4.1)
- Camera: including visible, mono and stereo. (Section 0)
- LiDAR, including rotating and solid-state variant. (Section 0)
- Thermal cameras (Section 4.4)
- Ultrasonic sensors (Section 4.5)
- Proprioceptive sensors, including GNSS, IMU. (Section 4.6)

Figure 1summarizes the role of each sensor family.

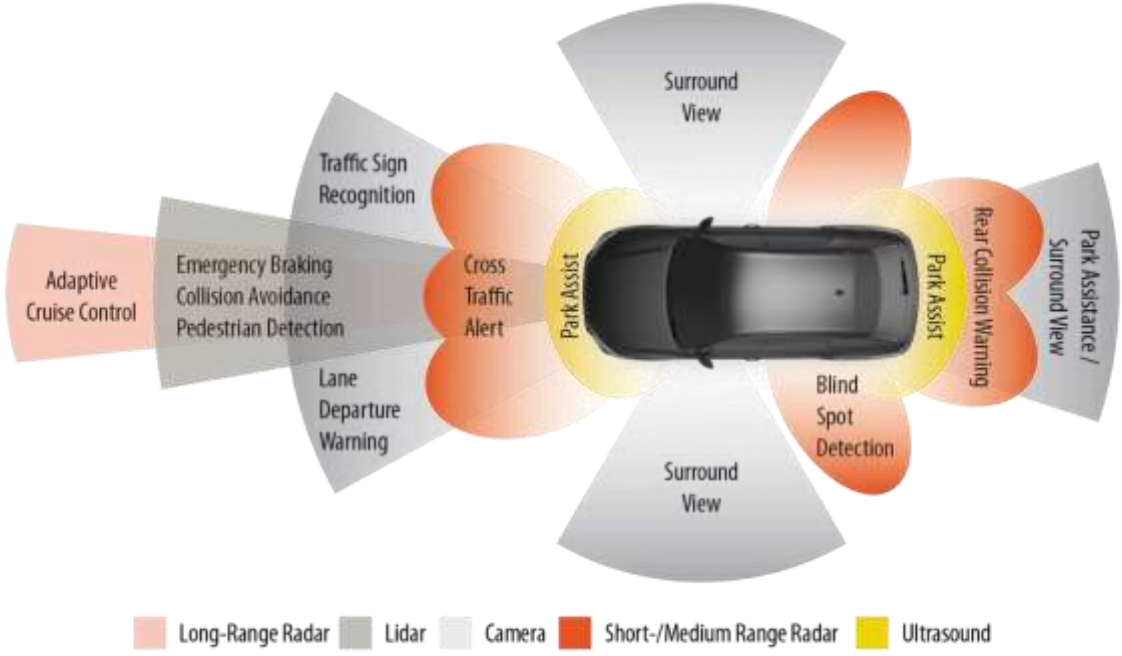


Figure 1: Illustration of ADAS/ADS sensors in vehicles. (Source [35])

3.2 WEATHER SELECTION

Report D2.1 of the WEATHERSAFE project focuses on analysing and defining adverse weather conditions that negatively impact sensor perception in autonomous and assisted vehicles. The various direct and indirect influencing factors identified are therefore summarized in this report.

Moreover, meteorological aspects are broken down considering the various aspects of disturbance: atmospheric, surface state wet/dry/covered (road, object, sensor), indirect disturbance (windscreen, spray effect, dirt, etc.). These side effects sometimes have more impact and/or occurrence probability than the atmospheric disturbance itself. For example, the spray effect can append with wet roads only. In general, for European countries, wet roads appear more regularly than heavy rainfall, dense fog and blizzards) [36]. Moreover, we won't stop at atmospheric conditions alone (fog, rain, snow). We'll also consider their aspects such as lighting conditions (glare) and temperature. On the other hand, other influencing factors identified in the literature but not linked to weather, such as vibrations or remote attack [37], have been disregarded.

In conclusion, weather effects that will be described in this report are:

Rain: Scattering or absorption caused by droplets. Raindrops are drops of water ranging in size from 0.5 to a few millimetres.

Spray/Splash effect: Splash is the mechanical action of a vehicle's tire forcing water out of its path. Splash is generally defined as water drops greater than 1.0 mm in diameter which follow a ballistic path away from the tire. Spray is formed when water droplets, generally less than 0.5 mm in diameter and suspended in the air, are formed after water has impacted a smooth surface and been atomized [38]. Spray droplets are therefore located between fog and rain. As the drops are the result of water lifted off the ground by the tires, the water is contaminated.

Fog: Scattering or absorption caused by droplets. Fog droplets range in size from 0.5 to 100 microns. The effects induced on light-based sensors (camera, LiDAR) are therefore much greater than those of rain due to the scattering phenomenon.

Snow: Scattering or absorption caused by particles. The dimensions are similar to those of rain, but snow particles are composed of water in solid form (ice) rather than liquid.

Lighting effects such as glare, tunnel exit, sun in front, shadows effects, night, etc. these effects also change the background illumination which is particularly important for passive sensors such as cameras.

Temperature: very hot or very cold. In particular, the sensors must be able to continue to operate in all kinds of conditions, both electrically and mechanically. In addition, the temperature of the scene can influence the measurements made by thermal imaging cameras.

Objects surface state: The effects of weather can induce secondary effects on objects and the vehicle's environment. In particular, objects can be dry, wet, or even snow-covered.

Sensor surface state: In the same way, the effects of weather can induce secondary effects on the sensor itself like dust, water film, water droplets, covered by snow.

4 Sensor definition and their sub-families

4.1 RADAR

4.1.1 GENERAL PRINCIPLE AND HISTORY

Radar means Radio Detection and Ranging. It is used to for detection, tracking and imaging. It allows to estimate the velocity and range of objects in the road scene. A radar is an active sensor since it emits electromagnetic energy from an antenna or antenna array illuminating

the surrounding targets. This radiated energy is reflected by the targets and a part of this reflected energy returns to the radar. The radar system uses one or more reception channels to detect the reflected energy and determine the range, speed and relative angles of the targets. The International Telecommunication Union (ITU) dedicates 4 frequency bands that include the 24 and 77 GHz bands for automotive radar applications.

Frequency	Bandwidth	Type of band
24–24.25 GHz ISM Band	250 MHz	Industrial, Scientific and Medical band, Automotive short range (Blind Spot Detection)
21–26 GHz	5 GHz	Ultra-wide band
76–77 GHz	1 GHz	Automotive Long Radar Range
77–81 GHz	4 GHz	Automotive Short Radar Range

Table 1: Automotive radar frequency bands [39].

The first frequency band is shared with other applications and can lead to interferences. The second one is limited by the authorities for the emitted power. The automotive sector uses then the third and the fourth band (between 76GHz and 81 GHz) with 2 different bandwidths (ΔB). Due to physical laws, the range resolution ΔR is proportional to 1/ ΔB. The band 77-81 GHz is then used for tasks requiring more precision.
The first radars arrived on vehicles in the 1999 years, with the introduction of the ACC function [40]. More recently, by increasing the number of transmitters and receivers in the sensors, but also by improving signal processing, developments have led to 4D radar technology [41] [42] [43].

4.1.2 SUBFAMILIES

4.1.2.1 Continuous wave versus frequency modulated continuous-wave
Following [44], automotive radars are pulsed radars or continuous-wave (CW) radars. A pulsed radar consists of the emission of short-duration pulses. The range of the target is obtained thanks to the time delay between the emitted pulse and the received pulse, e.g. Time of Light (ToF). A CW radar does not emit a pulsed radiation but a time continuous radiation during period of time. The target range is calculated by a comparison between the received signal and the emitted signal. For automotive applications, CW radars are the dominant radars used in the automotive sector. Moreover, the most relevant signal analysis lies on a frequency modulation of the emitted signal FMCW. The frequency is modulated linearly with the time.

We give in Table 1 the recommendations of ITU [45] for the use of automotive radars ranging in the band 76 – 81 GHz. Functions like collision avoidance require a detection of objects near the vehicle (about 15 metres), such as vulnerable users. These functions need a precision less than 10 centimetres corresponding to a bandwidth of 4 GHz. Note that in this case the maximal range is 100 meters. For the Adaptive cruise control (ACC), requiring radars of type A (see Table 2), the maximal range is higher (250 meters) with a precision around 75 cm, corresponding to the bandwidth 1 GHz.

	Radar A (Front applications e.g. ACC)	Radar B (high-resolution, front)	Radar C (high-resolution radar, corner)	Radar D (high-resolution)	Radar E (high-resolution, very short range e.g. parking-aid)
Sub-band used (GHz)	76-77	77-81	77-81	77-81	77-81
Typical operating range (m)	Up to 250	Up to 100	Up to 100	Up to 100	Up to 50
Range resolution (cm)	75	7.5	7.5	7.5	7.5
Typical emission type	FMCW, Fast-FMCW	FMCW, Fast-FMCW	FMCW, Fast-FMCW	FMCW	FMCW, Fast-FMCW
Max necessary bandwidth (GHz)	1	4	4	4	4
Chirp bandwidth (GHz)	1	2-4	2-4	2-4	2
Typical sweep time (µs)	10 000-40 000 for FMCW 10-40 for fast-FMCW	10 000-40 000 for FMCW 10-40 for fast-FMCW	10 000-40 000 for FMCW 10-40 for fast-FMCW	2 000-20 000 for FMCW	10 000-40 000 for FMCW 10-40 for fast-FMCW
Maximum e.i.r.p. (dBm)	55	33	33	45	33
Maximum transmit power to antenna (dBm)	10	10	10	10	10

Table 2: Automotive radar characteristics in the frequency band 76-81 GHz according to [45]

4.1.2.2 MIMO radar

Multiple-Input Multiple-Output (MIMO) radar is an extension of a traditional radar system to utilize multiple-inputs and multiple-outputs (antennas). Then, MIMO radar employs digital receivers and waveform generators distributed across the aperture, each generator uses a different waveform to be recognized by the receiver. Using several transmitters and receivers increases the aperture of the radar. A set of N transmitters and K receivers is mathematically equivalent to a virtual antenna of K-N elements, and therefore to an antenna with an aperture much larger than that of the sum of the antenna surfaces.

4.1.2.3 4D radars

In order to enhance the elevation resolution, high-resolution radars are now on the market with better angular resolution in azimuth and elevation. These new types of radar can deliver a 3D point cloud and we call then these radars 4D radars since the velocity is always measured. For this purpose, the idea of using several antennas and several receivers is used

again, as with radar MIMO. However, the spatial distribution of the antennas is now horizontal and vertical, so that objects can be perceived in 3D. Added to this is a great deal of processing to determine the position of the various objects. The latest radars on the market can have up to 48 transmitters and 48 receivers, over 2,000 equivalent channels [43]. Radar often received criticisms for the insufficient ability in pedestrian detection and object shape & size information classification due to low spatial resolution [8]. However, with 4D radars, this remark will be less and less true.

4.1.3 KEY FEATURES

Now we need to define the main characteristics of radars. To do this, we'll focus on the most recent and most highly developed radars on the market: 4D Radars. Technical data from main radar providers [42] are reported in Table 3 [41] [42] [43] [46] [47]. From these elements, we can retain the information of the column 'Current automotive 4D radar' of the Table 3. These results will be summarized in Section 6.1, then contrasted with the degraded weather in Section 6.2.

Table 3: Main features of automotive grade 4D radars.

	[45]	[41]	[42]	[43]	**Current automotive 4D radar**
Max range [m]	300	300	300	300	300
FoV (H/V) [°]	120/30	120/X	120/30	100/30	120/30
Distance resolution				9cm @ 36m 60cm @ 300m	~10
Angular resolution (H/V) [°]	1/1	0.1/0.1		1.25 / 1.5	1/1
Velocity measurement	Yes			Yes, 0.1m/s	Yes
Point density	Medium	Medium	Medium	Medium	Medium
Frequency (Hz)				30	30
Volumetric perception	Yes				Yes
Experience in automotive industry					1999 [40]
Interference / Active sensor					Yes
Design / Vehicle integration					Easy
Power (W)	5	23	15		15
Mechanical robustness		High (no mobile parts)			High
Temperature range [°C]		-40 - +85			-40 to +85
Unit cost					Medium

4.2 CAMERAS

4.2.1 GENERAL PRINCIPLE AND HISTORY

A digital camera is an instrument used to capture and store images and videos via an electronic image sensor. It is in 1969 that the first digital camera was developed in Bell Laboratories and was able to grab an image discretized in picture elements or pixels. These cameras were based on the use of a Charge-Coupled Device (CCD) matrix sensor and were rapidly introduced for astronomical imaging and soon in the consumer market. A charge coupled device is a highly sensitive photon detector. In a CCD matrix, each cell is a photodiode which converts the light which strikes it in electrons and then an analog-to-digital converter is used to encode the resulting electric voltage. Usually, for a grey level camera, the encoding of each pixel value is performed using 8 bits, i.e. 256 values. For colour images, each photodiode is covered with a filter that lets red, green or blue light rays pass through. The repetitive colour filter patterns used on the cell matrix is called a Bayer grid. The missing colour components are computed later by interpolation. Sony, second largest manufacturer of photo sensors has recently stopped the production of CCD sensors. Indeed, in the 1980s, Complementary Metal Oxide Semi-conductor (CMOS) sensors were used to integrate in each cell a photodiode and a dedicated logic circuit. CMOS matrices are thus more complex to manufacture but can be produced according to conventional techniques of microelectronics. The logic circuit on the CMOS cell allows various analogy processing but the sensitive area is reduced in percentage in comparison to a CCD cell, leading to lower signal noise ratios for the first generations.
Thus, concretely, CCD sensors are an older, more mature and less expensive technology. CCD and CMOS sensors are susceptible to different problems — CCD sensors are more susceptible to vertical smear from bright light sources, while CMOS sensors are susceptible to skewing, wobbling and partial exposure. However, neither technology is a clear winner over the other in overall image quality.
The camera sensors are mainly designed to obtain images close to what can be seen by humans, the main application being photography. Camera shares the same limits than the eye and is even more limited. For instance, a standard camera is not able to directly estimate motion as our eye. The eye is able to adapt to the lightening conditions in such a way that it is able to distinguish between 2^10 intensity levels in outdoor sunlight but 2^20 intensity levels in shadows, where standard cameras are restricted to 256 intensity levels, with a global gain automatic control. For example, a camera may not accurately represent subtle brightness changes in high-contrast scenes, particularly in shadowed and highlighted areas. A standard camera is thus subject to glare and its performances are much reduced during night. The field of view of a camera is reduced in comparison of the eye field of view. Similarly, to eye, a pair of cameras is requested to achieve depth information at a relatively high computational cost. Moreover, a camera image is subject to occultation by scene objects, specular reflections and bad visibility conditions due to weather such as rain, fog, snow and dust. Specular reflections of light sources are one source of difficulty in understanding an image. There are specular reflections on material which are mirror-like, i.e. not with a pure diffuse reflection. Examples of such materials are metals, glass and water. Due to rain, wet surfaces become specular. The second visual effect of rain is rain streaks in the image. The third effect of rain, at large range, is a contrast decrease and the addition of an atmospheric veil. This last visual effect is similar to the effect of fog which applies to any range in fog. Snow falls and dust, like rain falls and fog, leads to a similar contrast decrease related to the distance. Snow is also a source of occultation of the scene. Drops due to rain and snow must be wiped by an adequate system.

If camera sensors are primarily designed for photography usage, it seems that the development of image processing and maybe also advertising around automatic vehicles encouraged the development of new kind of cameras which started to be available on the consumer market. These new kinds of cameras are able to overcome one of the standard camera limits previously described. Cameras have been used in a wide range of automotive applications, starting with reversing cameras to assist the driver. They are now used for a wide range of tasks, such as traffic sign detection, lane tracking, obstacle detection.

4.2.2 SUBFAMILIES

4.2.2.1 High Dynamic range cameras

To avoid glare and saturation in high contrast scenes, High Dynamic Range (HDR) cameras are needed. In these HDR cameras, the number of intensity levels is higher than 256 (8 bits), for instance coded on 10, 12, or 16 bits. Another approach is to grab several images at different exposure times but it is valid only for static scenes. Due to its log intensity response, the eye is able to achieve an even higher dynamic range. Some companies propose a CMOS camera with a close to log intensity response [48] [49]. During night, standard camera images are saturated in the black due to the lack of signal to noise ratio. Image intensification can be used to improve the image contrast [50] but this applies only during night and cannot be used in daylight. An alternative is to work in the infra-red spectral range rather than in the visible spectral range (Section 4.4).

4.2.2.2 Field of view variation (objective choice)

The camera field of view is related to the objective choice. There is a large variety of objective with fields of view ranging from a few degrees (zoom) to 180/200 degrees (fisheye). Larger is the field of view, lower is the resolution, for a fixed number of pixels, when assumed of same pixel sizes. In our eye, the density of sensors is not uniform and the resolution is decreasing with the angle to the main eye axis, allowing a large field of view of 170/175 degrees with a good resolution near the main eye axis. It seems that this interesting property of our eye has so far not been a source of inspiration for the image sensor companies.

4.2.2.3 Stereo cameras

Stereo reconstruction algorithms have become quite mature and many stereo camera systems are now available on the market. Pure stereo is used for instance by IDS [51] and StereoLabs [52]. For better performance on surfaces with a uniform colour, in Intel Realsense system [53], stereo reconstruction is performed in infra-red with a structured light (structured light in infra-red was also used in the Microsoft Kinect1, when Microsoft Kinect2 uses the ToF, see Section 0 about LiDAR). All these systems are able to obtain the depth information only at short range distances, no more than 10 meters, due to a short distance between the stereo cameras.

4.2.2.4 Polarized cameras

Light polarization properties are invisible to eye. These properties specify how the light wave oscillates in space. There are four kinds of pure polarization state: linear vertical polarization, linear horizontal polarization, circular polarization and unpolarized light. Camera able to measure the four components of the polarization state are available [54]. A filter, based on ferroelectric liquid crystals, is used to select every component successively, leading to inaccuracies in case of fast motion. One or two years ago, a

new kind of camera was proposed which is able to obtain the linearly polarized and unpolarized components but not the circular component. This kind of camera sensor is built by simply adding small different linear polarization filters in front of each pixel of the CMOS matrix, like for colour camera [55]. The characterization is incomplete, but all components are obtained at the same time. This kind of camera can be used to restore visibility in presence of fog as shown first in [56]. The question arises about the possible extension to snow and dust. When the light is reflected on a smooth surface, such as a mirror, the reflected light is polarized. This kind of camera may thus be used to mitigate specular reflections, improve contrast and also to detect wet or icy surfaces. But this needs to be confirmed by extensive experiments.

4.2.2.5 Gated cameras

Time gated imaging or ballistic photon principle can be used to see through fog, rain, snow, dust and thus to go beyond visibility restoration by image processing. The idea is to illuminate the scene with a short flash and to collect only the photons that managed to make a round trip to a given distance. Several images are taken, with adequate tuning, to observe different depth slices of the scene. A few systems are currently marketed [57] [33] but in the SWIR infra-red.

4.2.3 KEY FEATURES

In conclusion, if the limits of standard visual cameras are known and if several improved cameras are marketed to tackle one or two of these limits, there is currently no camera able to go beyond the whole previously listed standard cameras limits. Different camera variants were presented, but they all behave in the same way when it comes to the weather. Gated cameras are not included in this study, as they operate more like solid-state lidar (active sensor), and are currently less widespread on the commercial market. They will all be grouped together in the following analysis. As identified in the previous Section, the main camera characteristics to be considered are identified in Table 4.

	[58]	[59]	[60]	**Current automotive camera**
Max range [m]		150	250 (vehicle) 100 (ped.)	150
FoV (H/V) [°]	120 / X	100 / 48	120 / 55	120/50
Distance resolution (cm)	No	No	No	~20* [61]
Angular resolution (H/V) [°]			0.03 / 0.03	0.03 / 0.03
Velocity measurement	No	No	No	No
Frequency		45	30	35
Point density				High
Volumetric perception	2D	2D	2D	2.5D* [62] [61]

Experience in automotive industry				1991 [63]
Interference / Active sensor	No	No	No	No
Design / Vehicle integration	Behind windshield	Behind windshield	Behind windshield	Medium
Mechanical robustness	High (no mobile part)	High (no mobile part)	High (no mobile part)	High
Power (W)				12 [64]
Temperature range [°C]			-40° - +85	-40° - +85
Unit cost				Medium

*Table 4: Main features of automotive grade cameras. *using multiple (stereo) cameras, it is possible to estimate the distance of objects.*

4.3 LiDAR

4.3.1 General principle and history

A LiDAR is a device for measuring the distance to an object [65]. The basic principle of LiDAR is to use a laser beam to obtain the distance between the sensor and a given point. This beam is then deflected in many directions to obtain spatial information in several dimensions [66]. LiDARs are used in a wide range of fields, but here we will only describe LiDARs used in assisted and autonomous vehicles.

Most of the case for assisted and autonomous vehicles, it is a pulsed emission and the beam is slightly divergent [67], then the backscattered signal is a combination of the signal obtained from all the impacted objects. The complete signal is then obtained as a result of absorption, light scattering in the atmosphere and ambient noise, making up what is generally known as the full waveform. Usually, the signal is then processed and the system returns digitized echoes.

Then the ToF principle is applied: knowing the ray's propagation speed and the time it takes to cover twice the distance (outward and return), it is possible to determine the object's distance, as shown on Figure 2. This all process is applied for every laser beam, resulting in a full 3D-pointcloud.

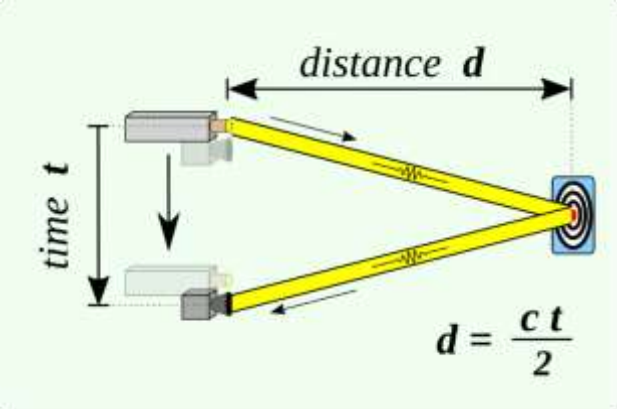


Figure 2: Operating principle of a TOF system (e.g. LiDAR) [68]

As described above, the basic measurement of LiDARs is the distance to a target object using the travel time of a light beam. Some LiDARs are also capable of estimating the speed of target objects based on the evolution over time of their distance from the LiDAR. Finally, some LiDARs can assess the reflectance of target surfaces by analysing the amplitude of the received signal in relation to that of the transmitted signal. This is sometimes called Laser Return Intensity (LRI) in the literature [66]. Since the LRI is characteristic to a specific material type, it is potentially useful for identification of surface properties of a target material.
In 1997, the first LiDARs appeared on vehicles to offer ACC functionality [69]. The first LiDARs were not multidirectional like today's LiDARs. A second phase of development saw the emergence of rotary LiDAR, with 360° vision capability. Section 4.3.2 will present the different LiDAR variants. Rotary technology has been used extensively in the field of mobile robotics research. However, this type of LiDAR presents definite problems for use in the automotive sector: (a) its integration on vehicles is extremely complicated, as it has to protrude beyond the vehicle's bodywork; (b) this technology presents moving parts and therefore an insufficient resistance to travel thousands of kilometres.

4.3.2 SUBFAMILIES

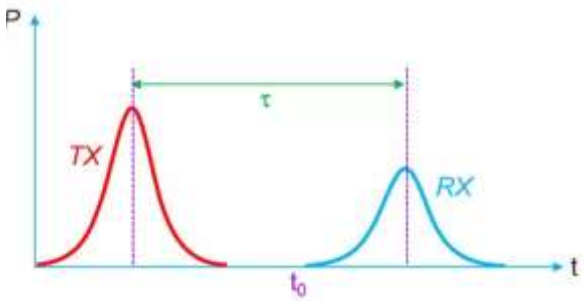
LiDARs subfamilies can be essentially characterized by three features: the measurement principle, the scan architecture and the optical part. These three characteristics are not independent of each other, since certain measurement methods involve constraints on the optical part, for example.

4.3.2.1 Distance measurement principle

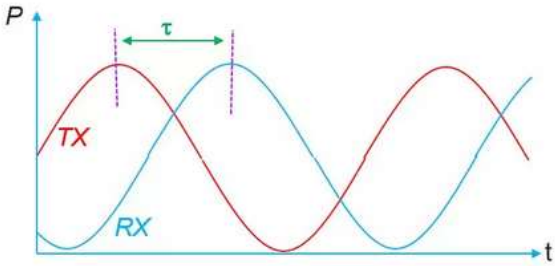
The different distance measurements are all derived from an analysis of the received signal in relation to the transmitted signal. Several techniques are available. In practice, there are three main methods for analysing the received signal and measuring the distance to the target object, as shown on Figure 3:

- Direct ToF: the laser source emits pulses, and the duration for each pulse to reflect and come back to the sensor is gauged. Direct ToF systems facilitate resilient and energy-efficient distance measurements. Nevertheless, the receiver commonly employs a single photon avalanche detector and timing circuit. There are practical constraints on the array size achievable with this setup, thereby limiting the resolution of solid-state systems to typically fewer than 100 depth points [70] [71].
- Indirect ToF, also called Amplitude-Modulated Continuous Wave LiDAR (AMCW). The principle is to transmit a signal whose shape is generated by modulating its amplitude. The signal pattern is a pseudo-random sequence of digitally encoded ones and zeros. Then, the phase contrast between the emitted light and the light returned to the sensor is assessed and transformed into time. The receiver can be integrated into a specialized image sensor, allowing for high resolutions without any mechanical components. Nevertheless, indirect ToF is susceptible to crosstalk and multipath interference, rendering it less resilient compared to direct ToF systems. Typically, it finds application in short-range, high-resolution setups.
- FMCW: the principle behind FMCW LiDARs is that the transmitted signal Tx is transmitted at a continuously varying frequency with a sawtooth waveform [72]. This is known as 'chirp' and the slope of the variation in frequency, i.e. the chirp rate, is given by κ. The reflected signal Rx is optically combined with a reference signal from the source. Through spectral analysis, the resulting signal reveals a "beat" frequency corresponding to distance. It is then possible to obtain the time delay. One advantage is that this type of laser is less sensitive to interference at a given wavelength, such as from other LiDARs or the sun. Then, FMCW measurement method offers robustness and performance benefits such as extended range, minimal emitter power requirement, high resilience to ambient light, and the capability to directly measure radial velocity. However, these devices are complex from an optical point of view. Clearly, the latter is the technology currently favoured.

a.



b.



c.

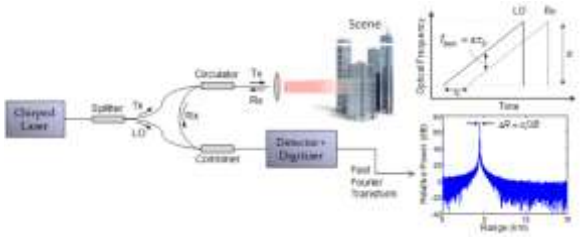


Figure 3: LiDAR sub-families for distance measurement principle. A. Direct TOF [70], b. AMCW [71] c. FMCW [70] [50].

4.3.2.2 Wavelength used

The second variation in LiDAR technology is the wavelength used for the transmitter. This wavelength range (900nm - 2000nm) offers two major advantages: it's invisible to the naked eye, and electronic transmitters and receivers in this wavelength range are less expensive. Automotive LiDARs therefore use the following wavelengths: 805nm, 905 nm or 1550 nm. The further away from the visible range (800nm), the opaquer the eye is to light. As a result, more light can be emitted at 1550nm than at 905nm [73], resulting in better detection.
It should be noted, however, that light detectors at 850 and 905 nm can be built using relatively inexpensive and widespread silicon technologies whereas light detectors at 1550 nm require the use of more expensive materials such as indium gallium arsenide [71]. Most of the current automotive grade LiDARs are 1550nm [74].

4.3.2.3 Scanning architecture

The ToF principle of LiDAR, using a laser emitter and a receiver, only allows distance measurement in a single direction. To obtain a 3D point cloud, it is therefore necessary to use a mechanism that allows this beam to be scanned. First, it's possible to separate LiDAR into two main categories: those that use a laser beam (beam scanning), and those that send light in all directions (flash) [66]. In the second case, we're getting very close to gated cameras, and the boundary is very blurred between gated cameras and flash LiDARs. Then, in the case of LiDARs using a scanning beam, the latter can be sent in different directions by various types of scanning systems to generate specific beam scan patterns, such as rotors, polygonal mirrors, galvanometric scanners or oscillatory scanners [66], as shown in Table 5. These different solutions are generally grouped into mechanic and solid state. In the automotive context, solid state solutions are the preferred choice to guarantee the sensor's durability over time. The operating principles of the various scanning solutions are not described in detail here. There is a great deal of variety, because unlike cameras and radars, the most appropriate scanning technology has not yet been decided. Most sensors on the market are of solid state [75] or hybrid solid state type [74] [76] [77] [78].

Mechanical	Electromechanical scanning	"classic" 360° spinning
Hybrid Solid-State	Opto-mechanical scanning	1D (line scanner): Rotating mirror

		rotors, polygonal mirrors, galvanometric scanners or oscillatory scanners
		2D (area scanner): Rotating polygon mirror Rotating Risley prisms (gyroscopic mirror)
	Micro ElectroMechanical System (MEMS) Mirror scanning	
Solid state	Solid-state scanning	Optical phased array beam scanning Photonic Crystal Waveguide Beam scanning Flash

Table 5: Classification of LiDAR's scanning architectures [79].

4.3.3 KEY FEATURES

Now we need to define the main characteristics of LiDARs. To do this, we'll focus on the most recent and most highly developed LiDARs on the market which are automotive compliant.

	Rotating LiDAR [45]	**Solid state LiDAR** [45]	[76]	[77]	[74]	[78]	[75]	**Current automotive LiDAR**
Max range [m]	200	200	190	210	300	200	250	250
FoV (H/V) [°]	360 / 40	120 / 25	120 / 26	120 / 25	125/25	120/25	120/30	120/25
Distance resolution (cm)								1
Angular resolution (H/V) [°]	0.1 / 0.3	0.2 / 0.2	0.05 / 0.05	0.1 / 0.2	0.05 / 0.075	0.09 /0.09		0.1/0.2
Velocity measurement	No	No				Indirect	Yes	Yes/Indirect
Point density	High	High						High
Frequency (Hz)			10	10 – 20	10 – 20			20
Volumetric perception			Yes					Yes
Experience in automotive industry								1999
Interference / Active sensor	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Design / Vehicle integration						Behind windshield, in		Medium

						headlamp or rooftop		
Power (W)	15			14				15
Mechanical robustness	No	Yes	Med	Med	High	Medium	High	Medium
Temperature range [°C]					-40 to +85		-40 to 85	-40 to 85
Unit cost	High	High						High

Table 6: Main features of automotive grade LiDARs.

4.4 THERMAL CAMERAS

4.4.1 GENERAL PRINCIPLE AND HISTORY

A thermal camera, also known as an infrared camera or thermographic camera, is a device that captures images of the heat radiation emitted by objects and converts it into a visible image. Unlike traditional cameras that capture visible light, thermal cameras detect infrared radiation, which is emitted by all objects with a temperature above absolute zero (-273.15°C). Thermal cameras use sensors called microbolometers to detect infrared radiation with wavelengths between 7.5 and 14 μm (Figure 4). These sensors are made of materials that change their electrical resistance when exposed to heat. When infrared radiation strikes the microbolometer, its temperature changes, which alters its electrical resistance.

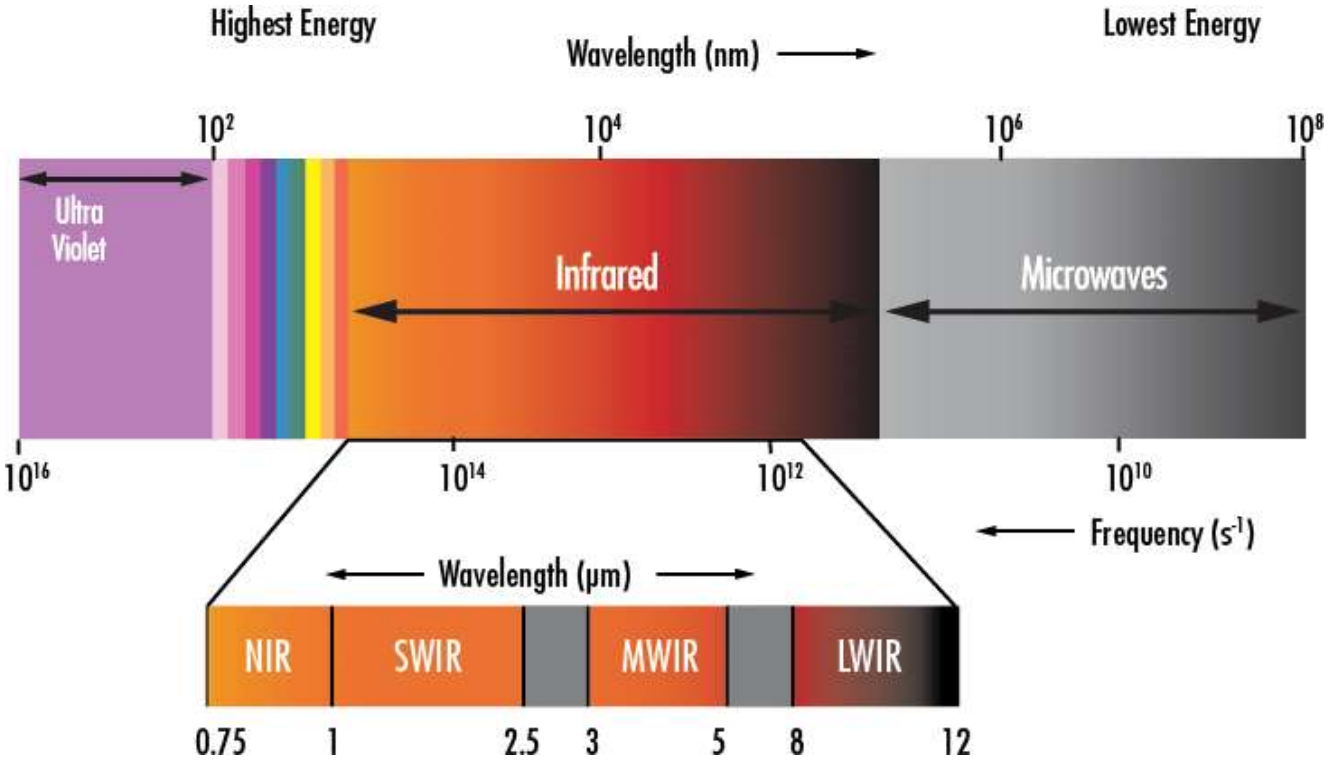


Figure 4: Wavelengths in the thermal infrared range compared with the visible range [80]

The thermal camera shape structure is like a digital camera. The main components of an IR camera are the optics, the detector, the cooling or temperature stabilization of the detector, the electronics for signal and image processing, and the user interface with output ports, control ports, and the image display. Two basic camera concepts for thermal imaging are scanning and staring systems. In this paper, we will focus on staring systems as it is the most used type in the automotive field.

Staring system cameras are composed by a Focal Plane Array (FPA). The latter contains detectors that are arranged in a matrix of columns and rows. Several types of detectors exist. This point will be detailed in Section 4.4.2. Today infrared FPA is the clearly dominant technology, as it has no moving parts, is faster, and has better spatial resolution than scanning devices.

The changes in electrical resistance of the microbolometer are converted into an electrical signal. This signal represents the intensity of the infrared radiation emitted by different objects in the camera's field of view. The electrical signals from the microbolometers are processed by sophisticated electronics within the camera. Algorithms are applied to translate the intensity of the infrared radiation into temperature values for each pixel in the image. The processed temperature values are then mapped to a colour scale or grayscale, where different temperatures are represented by different colours or shades of grey. This information is displayed on a screen, producing a thermal image where warmer objects appear brighter or in warmer colours, and cooler objects appear darker or in cooler colours.

It is possible to integrate thermal imaging technology into ADAS. ADAS encompasses a range of technologies designed to assist drivers in the driving process and improve overall safety. Thermal imaging can enhance ADAS capabilities in several ways:

- Enhanced vision in low-light and adverse conditions: Thermal imaging allows assisted and autonomous vehicles to "see" beyond the limitations of traditional visual sensors. By capturing thermal radiation emitted by people and objects, thermal cameras can provide clear vision in low-light conditions, complete darkness, and weather such as fog, rain, or snow. This enables assisted and autonomous vehicles to operate safely and reliably in a diverse mix of environments, reducing the risk of accidents and improving passenger and pedestrian safety.
- Object detection and classification: Thermal imaging excels in detecting and classifying some objects based on their heat signatures (pedestrians, thermal vehicles...). This is particularly useful for assisted and autonomous vehicles to identify pedestrians, animals, or other vehicles, even in obstructed or visually challenging scenarios. By complementing traditional sensors, thermal imaging enhances object recognition accuracy, reducing false positives and ensuring robust detection capabilities.
- Early detection of hazards: Thermal imaging enables assisted and autonomous vehicles to proactively identify potential hazards on the road. By detecting heat signatures, vehicles equipped with thermal cameras can identify overheating engines, and smouldering objects, or even detect tire blowouts in real-time. This early warning system allows the vehicle to respond promptly, mitigate risks, and prevent accidents before they escalate.
- Enhanced situational awareness: Thermal imaging provides an extra layer of awareness for assisted and autonomous vehicles. By detecting and visualising thermal signatures, vehicles can perceive the environment more comprehensively, including identifying hidden obstacles, tracking heat patterns, and identifying changes in road conditions. This heightened awareness empowers assisted and autonomous vehicles to make informed decisions and adapt to dynamic scenarios effectively.

Before talking about the specificities of each kind of existing sensor it is great to know the specific parameters used to characterize a thermal imaging system from a more global point of view. The purpose of this part is to give a brief overview of the most popular thermal imaging characterization parameters:

- Temperature range / value to be measured: the highest and lowest temperature required to be measured defines the temperature range required by the thermal camera. The range is the set of temperatures that the camera is capable of measuring.
- Spectral range: the spectral range is the range of wavelengths that the thermal camera sensor can detect. To minimize errors and increase the accuracy of the measurement we have to choose the thermal camera with the shortest wavelength that can measure the temperature range of our application. For example, if we want to measure 600°C and we do not need to measure values less than 450°C, a 1 micron camera (NIR camera) is enough. Although we can use a Long-Wave InfraRed (LWIR) (7 to 14 microns), the temperature measurement will be more accurate with the shorter wavelength.
- Sensitivity: the thermal sensitivity (Noise Equivalent Temperature Difference, NETD) is equivalent to the smallest differential in temperature that is able to measure the thermal camera without being attributed to its own noise. Thermal sensitivity is equivalent to the thermal resolution of the camera (it is the minimum measurement value between two consecutive temperatures). The more sensitive the detector (lower NETD), the finer the temperature details the thermal camera is able to display. Conventional cameras have a NETD between 80mK and 100mK, while the cameras with the highest sensitivity can have 40mK at competitive prices or at 20mK or even 10mK for those with the highest performance (usually cooled and with high cost). If the objectives to be measured have large temperature differences, a camera with a low NETD is probably not necessary.

4.4.2 SUBFAMILIES

As we mentioned above, FPA are arrays of detectors. Thermal detectors can be separated into two groups: photon detectors/cooled cameras and thermal detectors/uncooled cameras. The thermal sensitivity is down to 40 mK for uncooled cameras and 20 mK for cooled devices.
In comparison with the cooled cameras, uncooled ones have a better lifetime and are more compact. Cooled cameras need service and replacement of the cryocooler due to its moving parts and helium gas seals. That is the reason why the overall price for a cooled detector system is therefore higher than a thermal detector system, both its initial costs and its maintenance.

4.4.2.1 Photon detectors / cooled cameras

In photon detectors the radiation is absorbed within the material by interaction with electrons either bound to lattice atoms or to impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution.

Photon detectors require cryogenic cooling. Those two systems are a core feature of cooled thermal cameras. It is the kind of system that lowers the sensor's temperature to cryogenic levels. To eventually lower the thermally actuated noise to a level below that of the sign from

the scene being captured, the sensor needs to be cooled to a temperature below 77K to reduce thermal noise (for LWIR cameras). The cooling process is called Stirling process. Stirling coolers are used for several reasons as the small cooler size and weight, the electrical (e.g., electrical power consumption) and mechanical (e.g., mechanical vibrations) properties, reliability, and the life time (27000 h of operation guaranteed for FLIR cryocoolers).

For applications that demand precise and consistent data, cooled thermal imaging technology is widely regarded as the most sensitive thermal imaging technique. It can even detect very minute temperature changes between objects. They can generate images in the wavelength spectrum of the Mid-Wave InfraRed (MWIR) typically with wavelengths of 3-5µm (3000nm to 5000nm) and LWIR range.
This kind of sensor needs service and replacement for the cryocooler due to its moving parts and helium gas seals.

4.4.2.2 Thermal detectors / uncooled cameras
In this section we will focus on the most widespread technology of thermal detector that is the microbolometer detector (ferroelectric detectors are not described).
Microbolometer is a type of bolometer. Bolometers exploit the temperature dependency of electric resistance. The sensitive element consists of a resistor, which changes when it absorbs heat. The change in resistance leads to a changed signal voltage. The material should have a high temperature factor of the electrical resistance in order to achieve high sensitivity and high specific detectivity.
Bolometers that operate at room temperature use the temperature coefficient of metallic resistors (e. g. black layer and thin layer bolometer) as well as of semiconductor resistors (e. g. thermistor bolometers). Vanadium oxide is the most used material for the resistor. Bolometers do not need cooling systems.
Modern microbolometer arrays are driven by the rapid progress of semiconductor technologies and MEMS technologies. These arrays can capture images at 60Hz speed with 1024 × 768 pixels that each pixel is fabricated in 12µm size.

4.4.3 KEY FEATURES

Now we need to define the main characteristics of thermal cameras. To do this, we'll focus on the most recent and most highly developed thermal cameras on the market which are automotive compliant.

	[81]	[82]	[83]	**Current automotive thermal camera**
Max range [m]	>=300 m (car) >=150 m (ped)	200 meters (adult pedestrian)	660m	200
FoV (H/V) [°]	37 / 28	75 / X	28 / X	70 / 30
Distance resolution (cm)	No	No	No	No
Angular resolution (H/V) [°]	0.10 / 0.10	0.11/ X		0.1 / 0.1

Velocity measurement	No	No	No	No
Frequency (Hz)	25	30 - 60	25	30
Point density				Medium
Volumetric perception	2D	2D	2D	2D
Experience in automotive industry				2000 [84] [85]
Interference / Active sensor	No	No	No	No
Design / Vehicle integration		In the vehicle or out of the vehicle (IP67-rated kit included)	out of the vehicle (Hood mount included)	Medium
Mechanical robustness				High [86] [87]
Power (W)	3.5 - 9	1 - 12	4	10
Temperature range [°C]	-40 to 85	-40 to 75	-40 to 60	-40 to 85
Unit cost	High	High	4019 €	Very High

Table 7: Main features of automotive grade thermal cameras.

4.5 ULTRASONIC SENSORS

4.5.1 GENERAL PRINCIPLE AND HISTORY

Ultrasonic sensors measure the distance to surrounding objects using sound energy. The principle is as follows: a transmitter sends out an ultrasound signal, and when the sound wave hits an object, it is reflected and the receiver can measure it. The sensor uses a modulation system to recognize its own sound wave. Ultrasonic sensors were installed on the first vehicles in the early 1990s, initially for the park assist function [88]. They are mainly installed in the front and rear bumpers of the vehicles.

4.5.2 SUBFAMILIES

Unlike LiDARs and radars, ultrasonic Sensors do not have a sub-family, as the technology is simpler. They only vary in the frequencies they use: between 43kHz and 60kHz [89], generally at 52kHz [90] [91].

4.5.3 KEY FEATURES

Ultrasonic sensors have the following characteristics for different providers.

	[90]	[89]	[91]	**Current automotive ultrasonic sensor**
Max range [m]	5.5	5.5	4.1	5.5
FoV (H/V) [°]	120/60		75 / X	120/60
Distance resolution (cm)	1		1	1
Angular resolution (H/V) [°]		0.3		0.3
Velocity measurement				No
Point density				Low
Frequency (Hz)				
Volumetric perception				2.5D*
Experience in automotive industry				1982 [92]
Interference / Active sensor				Yes
Design / Vehicle integration	Behind bumpers	Behind bumpers	Behind bumpers	Easy
Power (W)			6	6
Mechanical robustness	High (no mobile part)			High
Temperature range [°C]	-40 to 85			-40 to 85
Unit cost				Very Low [93]

Table 8: Main features of automotive grade ultrasonic sensors.

Ultrasonic sensors have their own advantages and disadvantages. They can detect objects of any colour (which means better detection of dark objects). They are inexpensive [93] and give good distance accuracy and the ability to detect small objects. On the other hand, their detection range is very small and the angular resolution is very low. Then for ADAS, their application is mainly for low speed manoeuvres, automatic parking and blind spot detection. They can therefore only be used in conjunction with other long-range sensors, such as cameras, radar or LiDAR.

4.6 PROPRIOCEPTIVE SENSORS

4.6.1 GENERAL PRINCIPLE AND HISTORY

The sensors we refer to here as proprioceptive are all those that enable the vehicle to know its status and location. These include GNSS, speed sensors, Inertial Motion Units (IMU)... These are the sensors that first equipped vehicles. The 1980s saw the introduction of electronics in vehicles, with the ABS functionality [13]. Since then, many vehicles have been fitted with proprioceptive equipment. In-vehicle GNSS was introduced in the 1990s [13]. Since then, functionalities such as ESP, first marketed in 1995, use a wide range of proprioceptive sensors: wheel rotation speeds in the drivetrain, steering wheel angle, yaw rate (vehicle rotation in

relation to the vertical axis) and transverse acceleration. In the research world, this sensor set is known as an IMU. Proprioceptive sensors are not perception sensors for detection purposes like LiDARs, radars and cameras. However, in automated driving, they are indispensable for providing the vehicle with detailed feedback on its actions.

4.6.2 SUBFAMILIES

4.6.2.1 GNSS

Navigation or positioning systems are among the most basic technology found in robots and assisted and autonomous vehicles. Groves [94] provides a list of diverse measurement types and corresponding positioning methods. The global navigation satellite system (GNSS) is an international system of multiple constellations of satellites, including systems such as Global Positioning System (GPS) (United States), GLONASS (Russia), BeiDou (China), Galileo (European Union), and other constellations and positioning systems. GNSS operates in the L-Band (1 to 2 GHz) which can pass through clouds and rain, with a minimum impact on the transmitted signal in terms of path attenuation [8].

4.6.2.2 IMU

IMU combines motion sensors (accelerometers), rotation sensors (gyroscopes), yaw rate sensor, wheel speed sensor, and also magnetic field sensors (magnetometers) to determine vehicle acceleration and speed in all directions [8] [95].

4.6.3 KEY FEATURES

Proprioceptive sensors are identified here because they are essential for ADAS/ADS, and should therefore be mentioned. However, they are treated differently from other sensors, as they do not detect the vehicle's environment. The aim of this report is to compare vision sensors, i.e. LiDAR, radar and camera.

5 Impact of weather on sensors

5.1 RADAR

Unlike LiDAR and cameras, which are discussed in the other sections, the literature shows that radar is not or only slightly sensitive to degraded weather [8] [96] [73] [12] [97]. As a result, very little work has been done on radar versus degraded weather conditions. As an example, [45] refers to 25 datasets containing radar data over the last ten years and only 2 of these 25 show degraded weather conditions to our knowledge [11] [98]. As with other sensors, physical models and experiments do exist [45] [99] [39]. From a physical model point of view, the radar is only affected by heavy rain or heavy snow [100] [45]. [100] estimates from simulations that the detection range of radar can be reduced by 45% under severe rainfall conditions (150 mm/h), for a target such as a pedestrian, which is already tricky for radar under normal circumstances. This very high intensity of rain is, however, very rare in a concrete case, it corresponds to a huge storm peak, in which the vehicle will probably have to make an emergency stop (human drivers being obliged to stop in such conditions). Limiting ourselves to extreme but realistic rain intensities for driving, the effect of rain does not exceed 20% for pedestrian detection range, and 8% for car detection range [100]. By examining the

electromagnetic power attenuation in different rain rates [39] [99], we can observe that the attenuation for radar at 77 GHz is at the level of 10 dB/km in a 25 mm/hr heavy rain, while 905 nm LiDAR's attenuation is about 35 dB/km under similar visibility condition (0.5km of visibility) [101] [102]. Similarly, other studies show that radar is less affected than cameras [97]. Radar once again proves resistant to spray phenomenon [36]. Regarding the impact of rain vs. snow, the literature is divided [12] with some explaining that the water content of snow has an impact on the severity on the radar [103], while others explain that the effect is identical between rain and snow. Some models of radar's signal attenuation in snowfall [103] show that a higher snow rate yields larger attenuation as expected, and that wet snow shows higher attenuation because of the higher water absorption and larger snowflakes. Considering a snowfall with 10 mm/h, we yield that the specific attenuation for a radar in a 10 mm/hr snow is about 6 dB/km, which is seemly acceptable given the rain data [8]. Concerning the experiments, [8] explains that the radar is not impacted by light rain and fog, that it is negligibly impacted by heavy rain and that it is only slightly impacted by snow. [104] [105] compares radar, LiDAR, and camera performances in simulated and real-world adverse climatic environments and concludes that radar is significantly less impacted than LiDAR and cameras under the rain conditions. However, it should be noted that snow on the bumper can affect radar detection. Finally, from the point of view of light effects, radar is naturally insensitive, since the electromagnetic wavelengths it uses are not at all in the visible light range [106].

In conclusion the impacts of weather on radar are:

Rain: only a noticeable effect of tropical rainstorm conditions. Medium and light rain have only a small effect.
Spray/Splash effect: idem as for light rain, radar is almost not impacted.
Fog: idem as for light rain, radar is almost not impacted.
Snow: There are few results in the literature, but the tendency is to say that the impact is the same as rain. Wet snow is worst for radar than dry snow.
Lighting effects: The radar is insensitive to lighting conditions.
Temperature: The radar is insensitive to thermal conditions. Moreover, the manufacturer's data collected show that it is possible to have radars that can be used over a large range of temperature –40 to +85°C. The radar is insensitive to thermal conditions.
Objects surface state: The literature does not reveal any problems related to the surface condition of the objects for radar.
Sensor surface state: The effects of wet or dirty road surfaces do not pose a problem for the radar, but you need to be vigilant in the event of snow accumulation on the bumpers, where the radars are located.

5.2 CAMERA

Cameras are significantly affected by various weather conditions.
Regarding rain under the atmosphere, there are models in the literature that justify its impact on cameras [107]. The variance at pixel level over time under rainy conditions can be determined by formulas [107]. It is a good indicator of the visibility of rain and can be used as a quantitative measure of it. The variance is expressed as a function of camera and rain parameters. That shows that the visibility of rain increases as with the size of the raindrop and the density of rain. The visibility also decreases linearly with background brightness.
A camera in rain, no matter how high-resolution, can also be easily incapacitated by a single water drop on the emitter or lens [108] [8] [100]. The blockage and distortion in the image would instantly make ADAS/ADS lose the sense of the input data and fail to process correctly.

[109] conducted a quantitative experiment for measuring the effect of rainfall intensity on an ADAS camera. As a result of the empirical experiment, based on the view range reference analysis, as the rainfall increases, the ability of the ADAS camera to identify and recognize lane information decreases rapidly. When the rainfall exceeded a precipitation of 20 mm/h, the ADAS sensor did not operate, regardless of the vehicle speed. Apart from their influence on the image, raindrops, hail stones, and snowflakes can affect the camera directly. Rainy conditions affect the system with electrical and optical malfunctions. If the system is not waterproof, it can be damaged by a short circuit from raindrops.

The spray effect also has an impact on cameras. [36] tested spray disturbances on cameras and 2D object detection. The test setup consisted of a spray vehicle cutting in front of a test vehicle equipped with a sensor setup. Spray affects camera-based systems in two ways: First, scattering of light caused by the water particles in the air. Second, water build-up on the windscreen, which can be reduced by windshield wipers. Results indicated that 2D-detection problems include false positives around the rear lights, wrong object dimensions, and missing detections. The 2D detection results indicated that the algorithm has no trouble recognizing the spray vehicle in bright daylight. However, at night and when the test vehicle was inside the spray corridor, the detection performance decreases significantly. Water droplets on the windshield influence the camera sensor more than the water particles in the air. Additionally, the results indicated that spray cloud has less impact the further its distance from the perceiving sensor. A second test setup, where vehicles were kept static, showed that without an activated cleaning system, the camera's view is totally blocked, and the detection algorithm is unable to recognize the spray vehicle ahead. It also indicated that the object detector is severely affected by the scattered lights from the bright brake lights, even if the windshield itself is clean.

The literature also contains models and feedback on fog. In computer vision and graphics, the widely used model for describing the formation of haze or fog in images is the Koschmieder model [110] [111] [112] [113] [114] [115]. This model first attenuates the light coming from objects as this part of the light is scattered and absorbed. Secondly, this model adds stray light from ambient light, due to the scattering of the ambient light. Air light results from light scattered by the medium towards the viewpoint and causes an increase in brightness as the depth of the scene increases. This model assumes a homogeneous atmosphere. Based on several feedbacks, fog negatively influences perception and creates potentially dangerous situations because it can reduce the contrast of the image and increase the difficulty of pattern edge recognition [9] [100]. [116] proposed a Camera-in-the-Loop method to evaluate the performance of the object detecting algorithm under different weather conditions. The environment model data are acquired by a set of cameras and processed by an object classification algorithm, the result is then fed to the decision maker which re-engages in the simulation environment and completes a closed loop. The result showed up to 40% rise of miss rate in the fog.

As all other dynamic weathers (rain, snow, and hail) snow introduces sharp intensity fluctuations and obscure the edges of the pattern of certain objects in images and videos, which degrade the quality of these [117].

The visible light cameras are highly dependent on the environmental lighting conditions and subsequently, show reduced performance at low lighting. [118] found that a too high illumination can degrade the visibility of camera down to almost zero and that glares reflected by all kinds of glossy surfaces could make the camera exposure selection a difficult task.

[119] worked on image distortion of digital camera induced by environmental temperature and camera self-heating. Their experiments indicate that there is a significant distortion.

Concerning objects surface state, reflective surfaces reflections of light impact the camera. If the reflection happens to be ideal, it might confuse the camera into believing it and transmitting a false signal due to the lack of stereoscopic consciousness. Surface scattering of

reflectance on liquids (sun glint) can be a problem as vision or object-detection could be faulty when receiving a light signal back at a certain size. Furthermore, snow can accumulate on the surface of the earth and block road marks or lane lines [120] making the acquisition of data sources compromised for cameras, and the process of perception interrupted at the very beginning.
Concerning the sensor surface state, [121] studied the effect of a single adherent raindrop. They found that the effect of a raindrop is similar to that of a fish-eye lens and that the scene is contracted through the drop [121]. It was also noted in the same study that motion viewed through an adherent raindrop is significantly slower than in other parts of an image, on the order of 20 - 30 times. However, this phenomenon of water droplets in front of the sensor has only a minor impact in automotive applications, as the cameras are installed behind the windscreen, where the windscreen wipers counteract this phenomenon. Upon accumulation of atmospheric icing, especially wet snow on the lenses of the cameras, the visual sensors become partly or completely blind and fail to detect the surroundings of the vehicle. Apart from their influence on the image snowflakes can affect the camera directly. In snowy conditions, cool temperature affects a camera system because of optical and mechanical disruptions. An unshielded camera can easily be damaged by ice [122]. If the on-board camera is a powered rotation camera, such as an auto tracker, the ice formed by residual moisture from rain or sleet can cause the camera to be locked in place and prevent rotation.

In conclusion the impacts of weather on camera are:

Rain: The main effect of rain is visibility degradation. Rain introduces sharp intensity fluctuations and obscure the edges of the pattern of certain objects.

Spray/Splash effect: Spray affects camera-based systems in two ways: scattering of light caused by the water particles in the air and water build-up on the windscreen.

Fog: The main effect of fog is visibility degradation. It negatively influences perception because it can reduce the contrast of the image and increase the difficulty of pattern edge recognition.

Snow: Snow affects the camera similarly to rain concerning the visibility degradation.

Lighting effects: Visible light cameras are highly dependent on the environmental lighting conditions and subsequently, show reduced performance at low lighting. Under direct strong light, a normal visible camera is almost blinded. The sun glare light phenomenon also causes whiteout of objects from camera's point of view.

Temperature: Results indicated that it exists an image distortion due to temperature conditions.

Objects surface state: Reflective surfaces reflections of light are an issue for cameras. If the reflections happen to be ideal, it might confuse the camera into believing it and transmitting a false signal. Road surface snow occlusion also badly influences camera perception.

Sensor surface state: Lens occlusion caused by adherent raindrops creates s a fish-eye lens effect. Furthermore, If there is snow on the sensor, it becomes completely blind.

5.3 LiDAR

LiDARs can be impacted by various weather conditions of varying degrees of importance [123] [124]. Some theoretical models are even proposed for fog and rain [124] [125]. Firstly, focusing on rain, from a theoretical point of view, rain can have an impact on LiDAR, as shown by the various models in the literature [124] [125] [126] [127] [128] [129]. For LiDAR, the impact of rain clearly depends on rain intensity [130]. Theoretically, light rain doesn't affect LiDARs that much on small aperture LiDAR sensors [128]. In this case, the percentage diminution caused

by rain at the criteria of how much signal stays above 90% of the original power [8]. Other works proved that the signal reflection intensity drops significantly at a rain rate of 40 mm/hr and 95 mm/hr by using the method of dividing the signal transmission path into layers in simulation [131]. All the tests carried out on natural or artificial rain, ranging from intensities of 0 to over 50 mm/h, show that the LiDARs are significantly impacted by rain [130] [132] [73] [133]. But some tests show that on natural rain (between 0 and 7 mm/h) there are variation of the detected range (up to 20 cm), returned intensity decrease with the increase of rain and the number of detected points decrease with the increase of rain [130]. In the same way, other tests shown that with strong rain (55 mm/h), number of detected points reduced, especially for medium range points (about 30 meters) even if a car at 19 meters is still detected [132]. These tests also shown that there is the presence of 2 echoes (one from rain, one from objects), which could be used to help limit the effects of rain using algorithms [132]. In addition, one study points out that non-uniform rain (e.g. from a tunnel exit) has a greater impact and could be considered as an object by LiDAR [133]. However, the impact of rain on LiDAR is minor (even at 55 mm/h) compared to that of fog, due to the size of the drops [73].

The spray effect also significantly affects LiDARs, as shown by simulation [10] and real measurement [134] [36]. It may correspond to the attenuation of a moderate rainfall (with an intensity of around 3 mm/h) [134]. But some specific learning can be done to improve the object detection task and reconjoining result by 17% [134]. Further tests show that the LiDAR detects a cloud 22 m long behind the vehicle at a speed of 100 km/h [36]. This has a major impact on the detection of the vehicle, which should be made.

In rainy conditions, the water film on the LiDAR, if it isn't mechanically removed, can also lead to a 96% loss of points normally detected [36]. It is therefore essential to provide an active water-removal system or an aerodynamic vehicle profile that allows water to drain away naturally when the vehicle is in motion.

LiDAR is also greatly affected by fog, as shown by theoretical models [125] [124] [135] and a lot of studies with fog visibilities between 10 m and 80 m [123] [73] [136] [133] [132] [8] [137] [138]. In fog below 30 m, detection becomes very difficult [73] [136] [133] [132]. When the fog is too dense, the target is not detected as the laser signals are highly scattered inside the fog clouds and never reach the detectors or even the target itself [133] [73] [67] [132]. Moreover, the laser beam can also be reflected by the fog clouds and create random noise points in front of the sensor [67] [133]. Another study specifies that these points appear around 5 m, with the first echo, for visibilities of less than 40 m [132]. Fog also tends to reduce the intensity of points that remain detected in foggy conditions [133] [132]. Thus, points with high reflectivity (e.g. highly reflective white markers in the road and the diamond-grade and white reflectors) are better detected in foggy conditions [133]. Moreover, multi-echoes LiDARs have better performance, as the first echo is generally from fog but the second one is still coming from the object [132]. In addition, tests comparing 905nm and 1550nm LiDARs in rainy and foggy conditions show that the power gain at 1550nm is extremely beneficial for improving resistance to disturbance [73]. In conclusion about fog, there is a strong impact of fog, which is directly dependent from the distance of the object, the fog density and the point reflectivity [8] [137]. On this last point, one study goes a step further [137], proposing to estimate the distance at which an object would disappear, based on its reflectivity and the density of the fog. This study was carried out for visibilities ranging from 10 to 200m.

Snow also has a high impact on LiDAR [136] [139] [124] [140]. As for fog and rain, snow models exist for LiDARs [124] [140]. In turbulent snow tests, the powder snow blocks the detection and the viewing distance is shortened [136]. The powder snow itself can also be perceived by the

LiDAR, which then adds noise points in addition to the reduced detection distance [136]. Another study precise that in this case, detected snowflakes are detected only under the range of 14 m [139]. In addition, snow on the ground changes the ground's reflection rate. This means that LiDAR, which has only one wavelength with which to understand the environment, can no longer read the ground markings [123].

The glare effect can also be problematic for LiDAR. Indeed, using artificial sunlight, it has been shown that it can significantly interfere with LiDAR detection, by saturating the LiDAR's receivers [133].

One other factor is the temperature range of the LiDAR. Considering a LiDAR with a minimal operating temperature of -10°C, when the temperature change is at a large scale, such as from an extremely cold (−20°C) to an extremely hot (+60°C) environment, the time delay of LiDAR measurement would increase about 6.8 ns, which widens the LiDAR ranging by over a 1 meter and lower the precision at near field [141].

In conclusion the impacts of weather on LiDARs are:

Rain: Rain has a major impact on LiDAR. This impact results in imprecision in distance estimation, a decrease in the intensity of detected points, the appearance of noise points, and the disappearance of some normally visible points. The impact is present for low rainfall (<8mm/h) and becomes increasingly significant as rainfall intensity increases.

Spray/Splash effect: The spray effect also significantly affects LiDARs, creating a big noisy cloud of points behind moving vehicles. It may correspond to the attenuation of a moderate rainfall.

Fog: There is a strong impact of fog on LiDARs, which is directly dependent from the distance of the object, the fog density and the point reflectivity. The fog may be the worst weather condition for LiDARs.

Snow: Snow have similar impact as rain. However, snow cover adds an additional difficulty by uniformizing ground reflectivity, which masks the ground markings for LiDAR.

Lighting effects: Some results show that the LiDAR is sensitive to strong glare (such as at sunrise or sunset).

Temperature: Temperature can also have a significant impact on the LiDAR, by modifying the distance estimate. However, this happens at extreme temperatures, below -10°C.

Objects surface state: As already explained, LiDAR is affected by the presence of snow on the ground. No results were identified for the wet/dry comparison.

Sensor surface state: Results show that a film of water on the LiDAR can have a dramatic impact on detections. It goes without saying that if there is snow on the sensor, it becomes completely blind.

5.4 THERMAL CAMERA

Like visible cameras, thermal cameras are also affected by the weather. But there are a few differences.

Rainy weather introduces sharp intensity fluctuations due to increased atmospheric scattering and general obscuration, which degrade the quality of images and videos taken from a standard camera [117]. Thermal cameras perform similarly to standard cameras in the presence of rain. When thermal cameras are set behind windshield, raindrops that stay on the

glass can create a raindrop pattern on the image, which decreases the image intensity and blurs the edges of other patterns behind it [142].
[143] gives an overview of the impacts of rain on thermal cameras through virtual simulation. They created a simple scene containing a cottage and several sphere and cubic objects around an assisted or autonomous car. Visible and thermal cameras are mounted behind the windshield of the assisted or autonomous car to get realistic data in the rain. The results showed a slight reduction of the thermal camera images contrast. The areas that have strong contrast in colour and covered by raindrops are distorted with reflection of some patterns behind raindrops whereas those areas with less contrast were blurred.
Concerning fog, several studies focused on testing commercial thermal sensing systems in indoor facilities, these latter allowing to control fog conditions. [144] tested an object detection system and studied the relative contrast of images. The contrast was great in almost every foggy condition, except for very dense fog (Meteorological Optical Range (MOR) of 10m). [145] tested a specific thermal camera. The experiments showed that, at a distance between 10 and 25 m away, the thermal camera can detect objects under very thick fog conditions (up to a meteorological optical range of 13 m in the best case). The results also showed that cameras with angles of view 18° and 30° are more suitable for object detection than those with AOVs of 60° and 90 °. These results show that thermal imaging cameras perform well in foggy conditions, unlike visible light cameras.
For lighting conditions, the visible light cameras are highly dependent on the environmental lighting conditions and subsequently, show reduced performance at low lighting (night) levels. This is not the case for thermal cameras, however, as they are dependent entirely on object heat and emissivity. On this basis, the results of different lighting conditions do not show any change in performance. LWIR detection which is widely used in ADAS/ADS sensors is not sensitive to any dazzle [146].
[147] indicated that the results obtained from the active thermography techniques will be more apparent if the inspection is conducted on a day with high ambient temperature and humidity. Indeed, absolute contrast between target and environment increases with the increase of the ambient temperature and the absolute contrast between the target and the environment decreases with the decrease of the ambient temperature. This shows that thermal cameras are highly dependent on temperature conditions.

In conclusion the impacts of weather on thermal camera are:
Rain: Results show that thermal cameras perform similarly to standard cameras in the presence of rain.
Spray/Splash effect: Theoretically same impact as rain, but no feedback from real measurements.
Fog: It works well in almost every foggy condition, except for very dense fog (MOR of 10m).
Snow: Theoretically same impact as rain, but no quantitative measurements found.
Lighting effects: Light does not affect thermal cameras. Results showed that thermal detection which is widely used in ADAS/ADS sensors is not sensitive to any dazzle.
Temperature: Thermal cameras are highly dependent on temperature conditions.
Objects surface state: No feedback from real measurements.
Sensor surface state: Studies show that raindrops on the lens can cause distortion and blur.

5.5 ULTRASONIC SENSOR

Ultrasonic sensors use sound energy for detection. They can therefore detect liquids such as water and are therefore potentially impacted by the degraded weather conditions of rain and fog [8]. On the other hand, it was not possible to find any feedback in poor weather conditions (fog, rain, snow).
As ultrasonic sensors use sound energy, lighting conditions (day/night) have no impact on these sensors. In particular, they are glare-resistant. Likewise, changes in surface condition (wet, dirty, etc.) do not affect these sensors.
Variation in atmospheric conditions (like temperature, pressure and humidity) cause significant changes in the speed of sound. The accuracy of measurement by a sonar sensor is, therefore, critically dependent on these factors [148]. Air flux or turbulence also affects the accuracy of measurements by disturbing sound waves and reducing the echo
from the target [148].
Dirt, snow and ice on the bumper can also hinder the sensors ability to work.

In conclusion the impacts of weather on ultrasonic sensors are:

Rain: Theoretically medium impact, but no feedback from real measurements.
Spray/Splash effect: Theoretically medium impact, but no feedback from real measurements.
Fog: Theoretical medium impact, but no feedback from real measurements.
Snow: Theoretical medium impact, but no feedback from real measurements.
Lighting effects: No impact.
Temperature: As the temperature change the sound wave velocity, it may have an impact.
Objects surface state: Theoretically no significant impact, but no feedback from real measurements.
Sensor surface state: Dirt or snow accumulation onto the bumper may prevent the sensor from operating.

5.6 PROPRIOCEPTIVE SENSORS

Signals from satellite-based navigation systems, such as GPS, Galileo and others, experience some attenuation and reflection with passing through water in the atmosphere and other water bodies [8]. As GPS communication is directed skywards, there are no other influencing factors.

Concerning IMUs, external factors have no direct impact on the sensors. On the other hand, in the event of a change in road conditions (slipperiness), the control algorithms must correct their behaviour in order to remain adapted.

In conclusion the impacts of weather on proprioceptive sensors are:

Rain: Some little attenuation of GPS signal may occur.
Spray/Splash effect: No impact.
Fog: Some little attenuation of GPS signal may occur.
Snow: Some little attenuation of GPS signal may occur.
Lighting effects: No impact.
Temperature: No impact.
Objects surface state: Slipperiness need some correction from control algorithms.
Sensor surface state: Not concerned as internal sensors.

6 Sensor comparison and analysis under different weather conditions

6.1 SENSOR MAIN CHARACTERISTICS

In Section 4, the sensors have been described and their main characteristics analysed based on a study of the automotive compliant sensor market. Table 3, Table 4, Table 6, Table 7 and Table 8 give the main characteristics of radar, LiDAR, ultrasonic, camera and thermal camera sensors respectively. Table 9 summarizes these results. Based on these detailed results, it is proposed to assign a score based on macro criteria (see Table 9). Indeed, to reach a conclusion that will enable the sensors to be compared, including meteorological aspects, it is necessary to summarize the results at this stage. The scoring method is as follows: a score between 1 and 3 is awarded by summarizing the results of the section concerned. A score of 1 means that the sensor is very poor compared to all sensors, a score of 3 means that the sensor is very good compared to all sensors.

It is not possible to assign scores based on weighted averages, as the data available are partial and not all quantitative. Moreover, the weighting of sub-criteria could only be arbitrary. It is therefore proposed to assign an overall score for each macro criterion, based on a discussion of the advantages and limitations of each sensor in relation to the average of all sensors:

Sensor global range: a score of 3 was awarded if the sensor can reach a range of 200m at the same time as a horizontal FoV of at least 120° (i.e. Radar and Lidar). This seems to be the minimum required for an automotive application, and at the same time corresponds to the best currently available. The ultrasonic sensor was given a score of 1, because its range means it can only be used for low-speed applications.

Sensor global resolution: a score of 3 was awarded only if the angular resolution was less than 0.1°. This makes it possible to distinguish an object with dimensions of 40 cm at a distance of 200 m, which can be considered significant for automotive applications. The choice was made to penalize the thermal camera compared with the visible camera, because angular resolution is less good for the thermal camera and stereovision techniques are currently only used with visible cameras, so depth information is not available for thermal cameras. The radar sensor was given a resolution score of 1, as it only has an angular resolution of 1° (even for 4D radar), which represents 3.5m at 200m, and is therefore too imprecise for automotive applications, compared to other sensors.

Vehicle compatibility: the choice was made to give a mark of 3 if the sensor is compatible with integration in the bodywork (i.e. bumpers). A mark of 2 is awarded when the sensor must be installed behind the windshield and is passive. Lidar gets a rating of 1, as some models have several shortcomings: not all the models identified are compatible without modifying the vehicle's design, some of them contain moving parts, making them potentially less robust mechanically, and lastly, as they are active sensors.

Global cost: the ultrasonic sensor is rated 3 because it is by far the least expensive, although it requires a larger quantity of sensor to cover the entire vehicle. The camera and radar were then rated 2. The thermal camera is very expensive, hence the rating of 1. Finally, the Lidar was given a rating of 1. This choice was made because lidar currently appears to be more expensive than radar. However, if the quantities sold increase, this may smooth out in the future.

	Radar	Camera	LiDAR	Thermal camera	Ultrasonic
Max range [m]	300	150	250	200	5.5
FoV (H/V) [°]	120 / 30	120 / 50	120/25	70 / 30	120/60
Sensor global range	**3**	**2**	**3**	**2**	**1**
Distance resolution (cm)	~10	~20*	~1	No	~1
Angular resolution (H/V) [°]	1 / 1	0.03 / 0.03	0.1 / 0.2	0.1 / 0.1	0.3 / X
Velocity measurement	Yes	No	Yes/Indirect	No	No
Frequency (Hz)	30	35	20	30	
Point density	Medium	High	Medium	Medium	Low
Volumetric perception	3D	2.5D*	3D	2D	2.5D*
Sensor global resolution	**1**	**3**	**3**	**2**	**2**
Experience in automotive industry	1999	1991	1999	2000	1982
Interference / Active sensor	Yes	No	Yes	No	Yes
Design / Vehicle integration	Easy	Medium	Medium	Medium	Easy
Mechanical robustness	High	High	Medium	High	High
Power [W]	15	12	15	10	6
Temperature range [°C]	-40 to 85	-40 to 85	-40 to 85	-40 to 85	-40 to 85
Vehicle compatibility	**3**	**2**	**1**	**2**	**3**
Unit cost	Medium	Medium	High	Very High	Very Low
Number of sensors for 360°	4	4	4	6	8
Global Cost	**2**	**2**	**1**	**1**	**3**

Table 9: Automotive grade sensors main characteristics. 1 poor, 2 moderate, 3 good.

6.2 MAIN SENSOR CAPABILITIES IN ADVERSE WEATHER CONDITIONS

	Radar	Camera	LiDAR	Thermal camera	Ultrasonic
Fog	3	1	1	2	3
Rain - Light and moderate	3	2	2	2	3
Rain - Heavy	2	1	1	1	2
Snow	3	1	1	1	2
Spray/Splash effect	3	1	1	2	3
Lighting effects	3	1	2	3	3
Temperature	3	3	3	1	2
Object surface state	3	2	2	1	3
Sensor surface state	2	1	1	1	1
Sensor weather capacity	**3**	**1**	**1**	**2**	**2**

Table 10: Impact of weather on sensors. 1 severe impact, 2 moderate impact, 3 negligible impact.

Based on the elements identified in Section 5, it is now possible to identify the impact of the various weather factors on the sensors. Table 10 shows the results obtained. The choice was made to keep to a scale of 1 to 3, to be consistent with Table 9 on non-weather sensor characteristics. A score of 1 means that weather has a strong impact on the sensor (sensor is not good in that weather condition), while a score of 3 means that weather has negligible impact on the sensor (sensor is very good in that weather condition). An average score was then established for all criteria, to arrive at general conclusions in the following section.
As explained in 5.1, the radar is very little affected by degraded weather, apart from heavy rain. In the case of heavy rain, the radar is three times less affected than the camera. On the other hand, snow accumulation on the bumper can prevent the radar from operating.
As explained in Section 5.2, cameras are very much affected by all weather conditions, whether precipitation, side effects or lighting. As a result, they score very poorly in Table 10.
For LiDARs, as discussed in Section 0, rain, fog and snow have a very significant impact. For lighting conditions, only strong glare can disrupt it. Surface conditions, such as the presence of snow, can also disrupt certain detections. Finally, the LiDAR must remain perfectly clean to operate.
According to Section 5.4, thermal cameras are also affected by certain weather conditions, but unlike visible cameras, these are insensitive to lighting conditions, and fairly resistant to foggy conditions.
As explained in Section 5.5, there is little feedback on ultrasonic sensors. However, from a theoretical point of view, the impact of degraded weather is moderate. On the other hand, changes in surface condition have a much greater impact. Finally, dirt or snow accumulation on the transducer can be problematic.

In conclusion, the literature review has enabled us to obtain a score table on the robustness of sensors in degraded weather conditions. This table is in line with other literature reviews [7] [8] [9] [10] [11] [12], even if it is more exhaustive. The results are also presented graphically in Figure 5. The scores obtained for each aspect of weather have been synthesized into a single score in Table 10. This will make it possible to analyse the most relevant sensors globally in the automotive sector, but also to define the best sensor combinations into the next section.

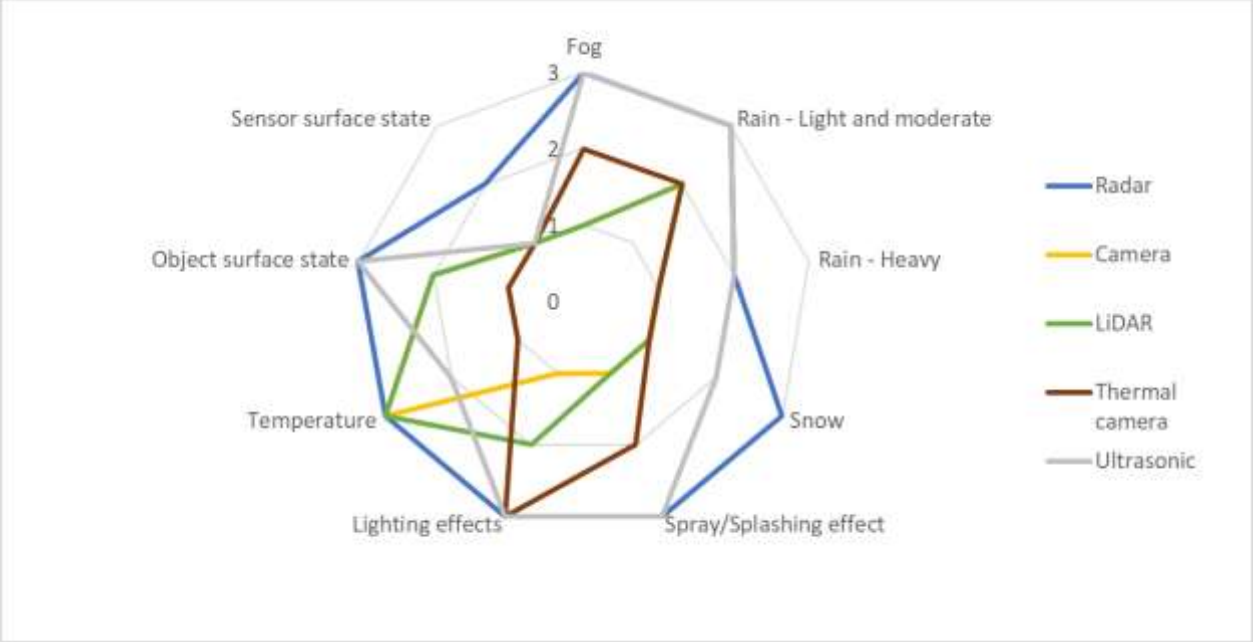


Figure 5: Impact of weather on sensors. 1 severe impact, 2 moderate impact, 3 negligible impact.

6.3 BEST ALL-WEATHER SENSOR COMBINATION

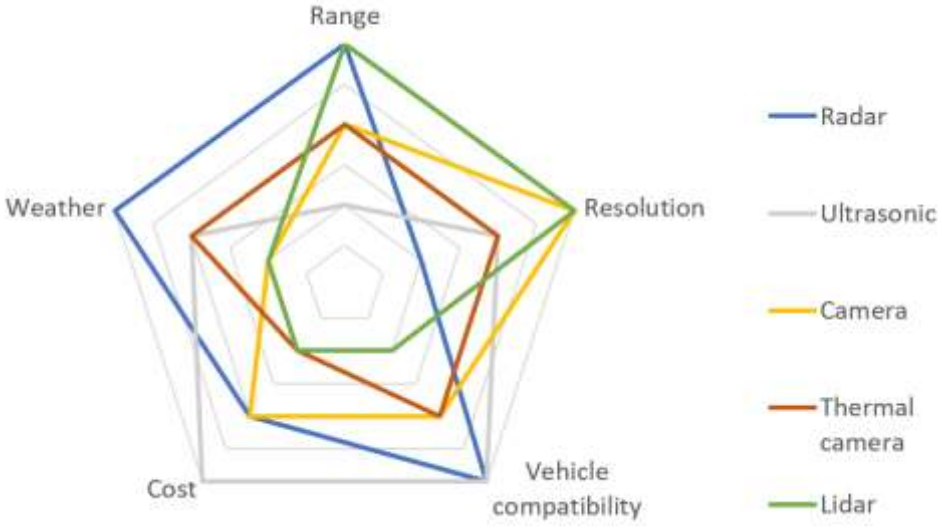


Figure 6: Summary characteristics of the various sensors for ADAS and autonomous vehicle.

Figure 6 summarises the main characteristics of sensors for ADAS and autonomous vehicles. In this figure, radar has many advantages, but lacks resolution. Conversely, the camera and LiDAR have good resolution, but their capacity in poor weather conditions is too limited. Ultrasonic sensors, although very useful for parking automation, cannot be used for a driving task because their range is far too small. Finally, thermal cameras have too few advantages over visible cameras, while their cost is high.

Based on this table, it is now possible to envisage the most appropriate combinations of sensors. No single sensor is currently sufficient. Camera and radar are clearly complementary. At the same time, there is real competition between LiDAR and radar/camera. The LiDAR is positioned between the camera and the radar. It can therefore compete with the radar or the camera. On the other hand, it is not sufficient, particularly because of the weather

conditions. In this respect, the presence of radar to manage deteriorating weather conditions is currently essential. Based on these elements, it is possible to propose a new graph showing the continuity of sensor combinations. As a reminder, proprioceptive sensors are mandatory in all cases, so that the vehicle can track itself (GPS) and receive feedback on its actions (IMU, speed, etc.).

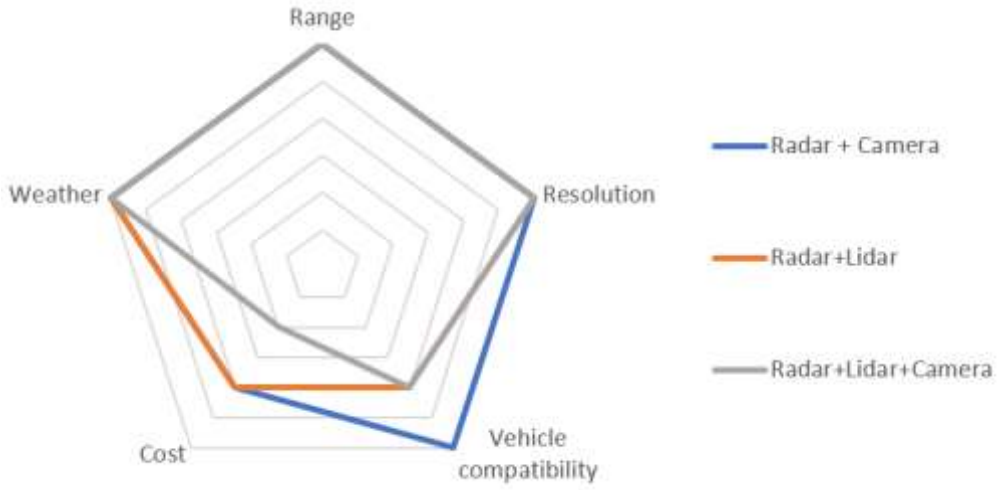


Figure 7: Summary characteristics of the best sensor combinations for ADAS and autonomous vehicle.

Based on these elements, it is also possible to discuss the likely future of sensor combinations. In our opinion, and given the sensors already present on vehicles, cameras and radars will be part of the sensor suite. These sensors already benefit from good feedback following their installation on older ADAS/ADS. Radar has already been deployed for ACC, and cameras (e.g. rear-view cameras). Some equipment manufacturers and carmakers are now offering to install LiDAR on vehicles. It is not certain that these sensors are sufficiently robust, nor that their usefulness is proven. However, current solutions for guaranteeing safety on autonomous shuttles are based on LiDAR. In the case of shuttles deployed in urban environments, LiDARs act as a last line of defence before collision, in the event of camera detection failure for example. The installation of LiDAR for the time needed to ensure the quality of camera detections may therefore be an option of choice. It's extremely unlikely that cameras will be withdrawn, as they are also indispensable for reading signs and other traffic elements. Even if we think in terms of an infrastructure that fully communicates with the vehicle, the case of work zones or accident zones will still have to be dealt with by cameras for at least a few decades. Finally, we note that the radar + LiDAR + camera combination lacks long-term interest. As things stand, however, cameras (even stereoscopic ones) and radar (even 4D ones) are still too imprecise when it comes to estimating the position of long-distance objects. Cameras lack depth accuracy, and radars lack point density. LiDAR will probably be an option to cover this gap, pending further developments. The current picture does not consider the impact of advanced data fusion methods that are currently being introduced. Indeed, by merging data at a low level, it is possible to obtain much better data than by simply combining the detections made by each of the two merged sensors [149] [150] [151] [152].
Ultrasonic sensors have been left aside. The latter are currently used as a complement to the camera for vehicle parking (low speed) because their detection range is really low (5 m). As with radar, these sensors complement the cameras. Eventually, we can imagine that this type of sensor will be phased out, if cameras become sufficiently efficient at detecting small objects. In the meantime, it is unlikely that they will be replaced by LiDAR and radar, as the latter will be installed and tuned for longer-range detection (for speeds between 30 and 130 km/h).

6.4 ASSESSMENT OF SAFETY GUIDELINES

Thanks to our literature review, we have been able to identify the most effective sensors for driver automation. This review has also highlighted their main advantages and shortcomings. A special focus on weather has been proposed in this report, with a consideration of weather-related side-effects. With these elements, it is now possible to propose critical test scenarios for each sensor. This could lead to the development of tests to verify sensor limits, and thus define their ODD. So, a few guidelines can be drawn from our analysis to carry out trials including the weather.

First, we propose to define the worst-case scenarios for the 6 sensor families we have identified in this report:

- Radar: For radar, different combinations can be critical. Firstly, in the event of extreme rain (storm) or snow on the bumper, the radar can be blocked. As the real weak point of radar is resolution, we need to combine these weather aspects with critical scenarios such as the detection of pedestrians or objects on the road. This combination of weather and resolution factors leads to the most critical scenario for radar, according to our literature review.
- Camera: For the camera, we have identified that the most critical weather-related points are lighting conditions and fog. Indeed, as the camera is a passive sensor, it is highly dependent on lighting conditions, with particular problems arising in glare or at night. Fog conditions, which reduce contrast, are also critical for cameras. In order to accentuate the weather phenomenon, objects with very low contrast to their surroundings must be included in the critical scenario. For example, a pedestrian dressed in black at night, or a vehicle of a similar colour to the test environment in daylight under glare conditions.
- LiDAR: For LiDAR, we have noted in the literature that fog conditions, or spray/splash effects, are the most penalizing meteorological conditions. Moreover, it has been shown that targets with low reflectivity (dark colours) are the most difficult to detect in these conditions. A critical scenario would therefore be the detection of a dark obstacle (pedestrian or vehicle) in spray or fog conditions.
- Thermal camera: For thermal imaging cameras, the unfavourable conditions identified in the literature are those with low temperature deltas. These conditions have a greater impact than the weather itself (rain, fog, snow). This type of scenario can be obtained in the case of a heavily covered pedestrian in snowy conditions (with cold), an object placed on the ground at room temperature, or a hot vehicle in hot summer conditions.
- Ultrasonic sensor: For ultrasonic sensors, the main source of problems can be snow or soil accumulation on the bumpers. This type of test can be combined with the presence of a large obstacle to further complicate the detection task.
- Proprioceptive sensors: Proprioceptive sensors are very little affected by the weather. There are therefore no specific measures to consider for them.

In addition to identifying critical scenarios for individual sensors, our literature review has identified several general points to consider. These elements are relevant to test vehicle functions (ADAS/ADS) under representative conditions:

- Consider dirty sensors: not doing test only with clean sensors.
- Change the colour of targets/objects (cameras/LiDARs). In the same way, use target with low radar reflectivity (tires or lost vehicle debris on the ground). And objects with ambient temperature (thermal cameras)
- Check the vehicle behaviour if a sensor is completely out of order (i.e. total occlusion of the sensor, but sensor still working).

- Always include spray effect for rain conditions.
- Fog may be another option like spray effect test

Some guidelines for testing were finally identified, the following section offers a general conclusion.

In addition to the critical scenarios identified for individual sensors, the deliverables from the WEATHERSAFE project will serve as valuable test methods for evaluating the performance of automated driving systems. These methods will not only support regulatory frameworks, such as the Automated Lane Keeping Systems (ALKS) across its full ODD.

The project's work packages 1 + 2 + 3 are complementary and are designed to systematically address safety and performance:

> **WP1** focuses on extracting the most safety-critical accident scenarios, particularly those amplified by adverse weather conditions, providing a solid foundation for our testing protocols.
>
> **WP2** reviews the capabilities of current sensors, ensuring that our guidelines reflect the latest advancements in sensor technology.

WP3 will analyse the potential benefits derived from the findings of WP1 and WP2, while also considering future advanced sensors. This comprehensive approach will help us define the most pertinent scenarios to be tested, ultimately aimed at improving road safety. These work packages together are complementary and will strengthen each other with research complemented by statistics and potential gains.

By integrating these insights and methodologies, we will develop significant guidelines for regulation, standards, and EuroNCAP assessments in the context of future evaluations. This collaborative effort will ensure that the testing framework not only reflects real-world challenges but also pushes the boundaries of safety in automated driving systems.

7 Conclusion

Advanced driver assistance systems, or even automated driving, are currently not approved under adverse weather conditions. Examples include ALKS [2] [3], collision avoidance systems AEB car to car [4] and AEB car to VRU [5] or LSS systems [5]. These systems rely on a set of sensors to perceive the environment and provide feedback on the vehicle itself (proprioceptive sensors). A review of the technical literature identified the most used perception sensors.
These include visible camera, radar, LiDAR and thermal camera sensors for high-speed functions. Ultrasonic sensors complete the range for low-speed functions (e.g. parking assist). Proprioceptive sensors complete the list of 6 sensor families that were analysed in detail. First of all, a technical description was proposed, identifying sensor variants within the family, and common points. This work resulted in a synthetic technical definition, supported by real figures from automotive datasheets. This synthetic view was summarized in the following macro criteria: range, resolution, vehicle compatibility, cost.
Having made this initial selection and analysis, it's important to consider the impact of unfavourable conditions such as low light levels, snow, fog and rain, as well as related side effects (dirt, spray effect). At present, test scenarios are not carried out under adverse weather

conditions. On the other hand, the first standards stipulate that the manufacturer can justify a more extensive ODD, for which it must provide proof. Eventually, tests and simulations will be carried out under unfavourable conditions. To achieve this, it is essential to identify the impact of adverse conditions on sensors. An in-depth literature review has identified this impact for each of the families, considering theoretical results (modelling or simulation) and feedback from real-life experience. The impact of the following weather criteria was identified: rain, spray/splash effect, fog, snow, lighting effects, temperature, objects surface state, sensor surface state. A new weather macro criterion was created based on this literature review.
Thanks to all five macro criteria, evaluated on the five sensor families, several conclusions could be drawn:

First, the best all-weather sensors were identified. The radar has many advantages including weather robustness but lacks resolution. Conversely, the camera and LiDAR have good resolution, but their capacity in poor weather conditions is too limited. Ultrasonic sensors, although very useful for parking automation, cannot be used for a driving task because their range is far too small. Finally, thermal cameras have too few advantages over visible cameras, while their cost is high.

The best sensor combinations were then identified. No single sensor is currently sufficient. Camera and radar are clearly complementary. At the same time, there is real competition between LiDAR and radar/camera. The LiDAR is positioned between the camera and the radar. It can therefore compete with the radar or the camera. On the other hand, it is not sufficient, particularly because of the weather conditions. In this respect, the presence of radar to manage deteriorating weather conditions is currently essential. Based on these elements, it is possible to propose a new graph showing the continuity of sensor combinations. As a reminder, proprioceptive sensors are mandatory in all cases, so that the vehicle can track itself (GPS) and receive feedback on its actions (IMU, speed, etc.).

Finally, critical scenarios for the EuroNCAP tests were drawn up for each of the sensors, in order to challenge them as much as possible. For radar, the real weak point of radar is resolution, we need to combine adverse weather aspects with critical scenarios such as the detection of pedestrians or objects on the road. For the camera, we have identified that the most critical weather-related points are lighting conditions and fog. In order to accentuate the weather phenomenon, objects with very low contrast to their surroundings must be included in the critical scenario. For LiDAR fog conditions or spray/splash effects are the most penalizing meteorological conditions. Moreover, it has been shown that targets with low reflectivity (dark colours) are the most difficult to detect in these conditions. For thermal cameras, the unfavourable conditions are those with low temperature deltas. This type of scenario can be obtained in the case of a heavily covered pedestrian in snowy conditions (with cold), an object placed on the ground at ambient temperature, or a hot vehicle in hot summer conditions. For ultrasonic sensors, the main source of problems can be snow or soil accumulation on the bumpers. Proprioceptive sensors are very little affected by the weather. There are therefore no specific measures to consider for them.

The literature review presented in this report is therefore new in comparison with previous ones. It offers an analysis both from a research perspective, but also considering practical aspects (automotive grade sensors, cost...). It also has the advantage of including various weather scenarios, and their all-too-often neglected side effects. Finally, this literature review has enabled us to draw up guidelines for future standardization or homologation tests in critical weather conditions.

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