A review of Cerema PAVIN fog & rain platform: from past and back to the future

Sébastien Liandrat[1]*, Pierre Duthon[1]*, Frédéric Bernardin[1], Amine Ben-Daoued[1], Jean-Luc Bicard[1]
1. Cerema, Equipe Recherche STI, 8-10 rue Bernard Palissy, 63017 Clermont-Ferrand, France
*adweather@cerema.fr

Abstract
Autonomous vehicle (AV) is less and less perceived as science fiction. AV have evolved particularly quickly these past years, but some technological locks still remain. Adverse weather is one of them, and the lack of significant progress limits the deployment of level 3 vehicle autonomy. Intelligent Transport System (ITS) development needs specific physical tests facilities combined with numerical simulations, before massive real-scale tests can be performed
and has followed the main adverse weather research and development stakes. The current paper reviews the evolution of this platform through time, pointing out each scientific step in which it was involved in: evaluation of the impact of adverse weather on human and computer vision systems, weather classification, and numerical simulation of fog and rain. This review also outlines the main upcoming perspectives of this unique facility, aiming at addressing the next mobility challenges.

Keywords:
Fog, Rain, Physical simulation

1. Introduction

Mobility issues are being transformed and the massive development of AVs or more generally Automated Driver Assistance Systems (ADAS, e.g. pedestrian and obstacle detectors) seems to become more and more a reality as regulations evolve and allow their deployment. A world with autonomous vehicles as commonplace is no longer considered as science fiction but a near future. For example, the United Nations Economic Commission for Europe (UNECE) [1] recently proposed a regulation for SAE level 3 automated driving systems [2]. In these standard proposals, the addressed conditions are limited to particular cases without complexity. However, while the world is watching demonstrations of autonomous vehicles evolving in ever more advanced scenarios, the question of driving in adverse weather conditions remains an issue to be addressed [3]. It is therefore crucial to test ADAS and AVs in these particular conditions before improving their consideration in driving.

ITS can be tested in a controlled environment at several levels of integration and realism: numerical modeling, virtual reality simulation, test bench evaluation or test track evaluation. These different steps are complementary. A large part of the developments related to ADAS and AVs must go through numerical simulation. Indeed, the validations of the embedded systems require thousands of kilometers, with combined scenarios (e.g. type of road vs. weather conditions vs. users in the surroundings). The final validations must be done on real sites, by demonstrations with fleets of vehicles. However, the presence of a test bench is essential for two reasons: (a) numerical simulators must be validated under real controlled conditions; (b) numerical simulators require data to operate that may be difficult to collect in large scale and/or in real-world environment due to road safety and regulatory constraints.

Regarding the consideration of degraded weather conditions, recent literature shows that this is a major issue for the development of AVs, but more generally for any outdoor system. Indeed, many databases are beginning to emerge with the consideration of these conditions [4] [5] [6]. Besides, multiple digital simulators have also been identified [7] [8], along with a few recent platforms, allowing to reproduce these conditions [6].

The Cerema PAVIN (INtelligent Vehicle Platform of Auvergne region) fog & rain platform [9] is one these new tests facility which is capable to artificially generate fog and rain. This platform is operated by the ITS research team of Cerema, a French public agency attached to the Ministry of Ecological Transition, which ensures its independence, confidentiality and neutrality. The platform is 30 m long, 5.5 m wide and 2.20 m high, details of fog and rain generation are described in this paper with their evolution over time. This volume allows for the reproduction of realistic road scenarios, including vehicles, pedestrians and road equipment, in day or night conditions. It is also possible to set up reference tests with targets calibrated in reflectance and thermal black bodies. The platform is mainly dedicated to the automotive (ADAS, autonomous driving, lighting) and road (marking, traffic signs, monitoring) domains but also to other advanced domains such as rail, aeronautics, maritime, construction or military.

This paper covers contribution of the PAVIN platform to research and development, mainly road safety and ITS-oriented. Such a review has never been made, and it might enhance the evolution of the platform in accordance with the progress of the stakes of ADAS and AVs. This paper is not a general review about ITS testing but a review of research work which took place in the Cerema PAVIN platform. Then, it is a back in time presentation of this unique platform and, through its history, an examination of the main research and development topics related to it. It also opens the path for the future needs in adverse weather ITS testing.

Section 2 will provide a back in past , explaining the early days of the platform which was then mainly dedicated to the analysis of human vision in a road context and under fog conditions. Section 3 will then present the transition from human vision to computer vision. At the same time, rain production was added to the platform, so this will also be detailed in section 3. Section 4 will be dedicated to recent work related to computer vision, then section 5 will present an example of current use of the platform, with the tests carried out in the context of the AWARD project. Finally, section 6 proposes a focus on the next novelties of the platform, before concluding this time travel adventure in section 7.

2. “Back to the past” – The early days of the platform: fog and human vision

Before going into the history of the platform, it is important to define what fog is. According to the definition given by the World Meteorological Organization (WMO) [10], fog is the suspension in the atmosphere of microscopic water droplets that reduce Meteorological Optical Range (MOR) on the ground to less than one kilometer. MOR, also called visibility, is the distance (in meters) through fog for which the luminous flux of a collimated light beam is reduced to 5 % of its original value. MOR varies from 0 m for a completely opaque fog to tens of thousands of meters in the absence of fog (the atmosphere is never clear). In meteorology, fog is considered to be present when the MOR falls below 1000 m. In a road context, fog becomes critical for safety when the MOR passes below 400 m (French standard NF P 99-320, AFNOR, 1998).

In addition to the MOR, which is the macroscopic parameter, it is important to check that the water droplets in suspension are of the same size than natural ones. Indeed, natural fogs contain droplets ranging from 0.5 microns to 50 microns. There are different types of fog, with different droplet size distribution (DSD). The DSD is measured with a particle size analyzer (PSA), as shown on Figure 3(c).

The platform PAVIN was built in 1983, as shown in the Figure 2 which presents the timeline of the platform. Originally it was only equipped with a fog production system. This system was on and off, with no MOR level control. At this time, the DSD was still not qualified. The platform was designed to test, evaluate and calibrate visibility sensors [10]. These visibility sensors (see Figure 3 (a) and (b)) are installed at the edge of the road to warn users of fog on their route.

Following a series of tragic accidents in France, the platform was then used to measure drivers' perception in foggy conditions. These first analysis on vehicle optics were followed by numerous studies on the cognitive psychology theme. From 2000 to 2015, the perception of the human eye in the fog has been closely examined in the platform PAVIN [11], including in the project OSMOSE [12] [13]. The latest work has been the subject of a partnership in the Lab xcellence Sustainable Solutions » (LabEx IMobS3) [14] [15].

These research items encouraged the Cerema to develop this unique fog chamber. Starting in 1993, intensive development of the fog system took place over a period of 10 years. First, the DSD was qualified and compared to natural fogs. Thus, it was shown that the fogs reproduced in the platform are similar to natural fogs [16]. Following these qualifications, the European project FOG [17] allowed to completely review the fog production system in 2003. This new system now makes it possible to reproduce two kinds of fog with small droplets (i.e. radiative/continental fog) or big droplets (i.e. advection/maritime fog). It also allows to maintain the fog density at a certain level (MOR comprised between 10 to 200m with 10% uncertainty), using a system of micro injections [18] [19] [20]. The new reproduced fogs are still faithful to natural fogs (same DSD as shown in the Figure 1) and they are metrologically repeatable [20]. The measurement is performed by a PSA, available in the platform.

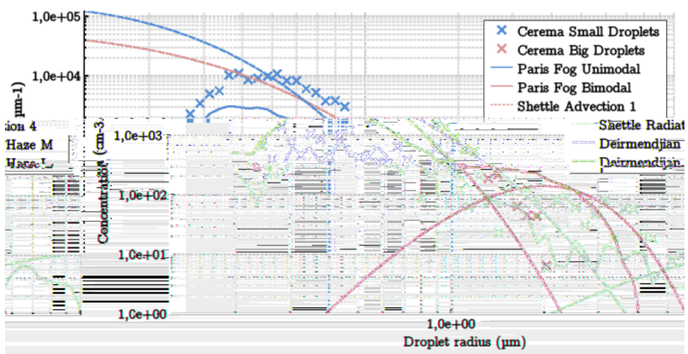


Figure 1 - Particle size distribution of the PAVIN platform fogs compared to different models found in the literature (from Duthon et al. [21])

In parallel to this work, the first numerical simulations on fog started to appear in the literature. That began with simulating a visible camera under foggy and night conditions (starting in 2000). This work will be described in section 4, after making a time leap about rain production in section 3.

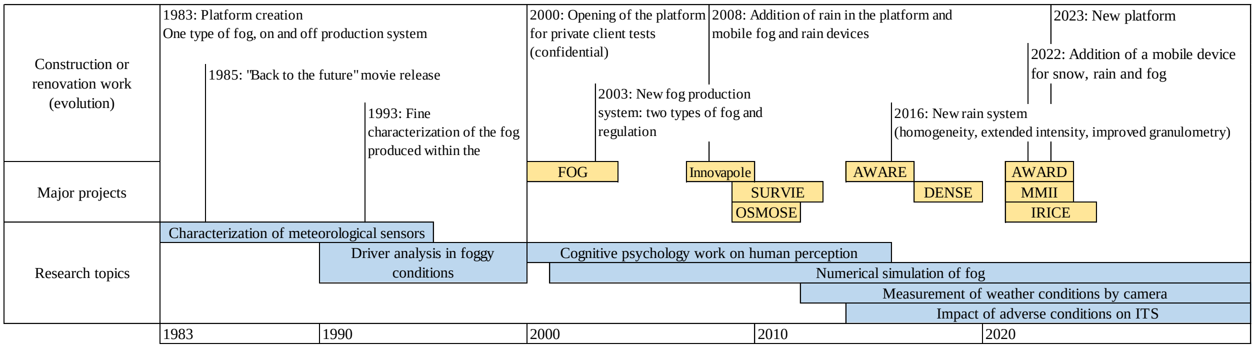


Figure 2 - History of the PAVIN platform: developments, flagship projects and research themes

3. Addition of rain in 2007 and transition to computer vision

During the CPER Innovapole project (2007-2009), Cerema was able to add a rainfall production system within the PAVIN platform. Before explaining in more detail the evolution of the platform, it is important to better define the rain phenomenon.

As for fog, rain is characterized from a microscopic point of view (droplet size) and from a macroscopic point of view (rainfall rate). The rainfall rate is the quantity that allows characterizing the rain, it is given in mm/h (1 mm/h is equal to 1 l/m²/h). Rainfall rate is calculated as the volume of water falling per unit area and time. It varies from 0 mm/h for no rain to several tens of mm/h for very heavy rain.

The NF P 99-320 (AFNOR, 1998) French standard, which proposes a classification of rainfall rate in road context, defines a rainfall rate higher than 7.5 mm/h mean value in one hour as a heavy rain. This rainfall rate corresponds to commonly encountered values in metropolitan France. However, there are much higher episodic rainfall intensities in less than one hour. Indeed, the French record of 1982 is 200 mm/h over 30 minutes and 360 mm/h over the 6 minutes of the storm's peak. The highest record in the world is 945 mm/h over 8 minutes and 2280 mm/h over one minute [22] [23]. The rainfall rate is measured with a bucket rain gauge (Figure 3(e)), while the DSD of the rain is measured with a disdrometer (Figure 3(d)).

(a) Transmissiometer | (b) Visibility meter | (c) PSA | (d) Disdrometer | (e) Bucket rain gauge

Figure 3 - Different weather sensors used in the PAVIN platform

To come back to the platform, the first rain system put in place allowed to reproduce rain from 30 to 55 mm/h. It was then completed by a rain system on windshield. The first research work related to rain focused once more on human perception and windshield wiper systems (wiper blades). The objective was to characterize by a metric the quality of visibility [24]. This work was part of the SURVIE project [25]. Comparing the performance of this first system with the highest precipitation intensity records presented earlier, it appears that increasing the capacity of the platform was a major issue. The work carried out in the framework of the European H2020 DENSE project (2016-2019) [26] extended the range of rainfall intensity (from [30   55 mm/h] to [16   165 mm/h]) [27]. The second issue concerns the representativeness of the rain. For this, work has been carried out to ensure a better spatial homogeneity of the latter on the ground, as shown in the Figure 4.

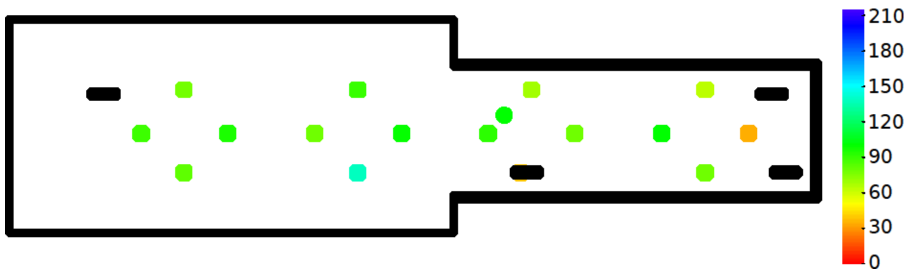


Figure 4 - Rain intensity measured within the PAVIN platform (mm/h)

Since 2011, the ability to generate rainfall within the platform has enabled research on the measurement of rainfall conditions by camera. This work allows both to estimate the impact of rain conditions on the cameras but also to characterize the rain itself [28] [29] [30]. From 2015, this initial work has been extended to include rain and fog measurements, but this is discussed in the next section.

4. Artificial vision in adverse weather conditions

Research on computer vision has become predominant since 2010, with the rise of ITS and the AV development. Concerning the use of the PAVIN platform, it can be classified into three main areas:

- measurement of the impact of adverse weather conditions on vehicle perception systems
- measurement of weather conditions by camera (artificial intelligence)
- numerical simulation of meteorological phenomena

While the platform was first used to analyze the impact of fog on human vision, it is now mainly used to evaluate computer vision systems that are installed in vehicles, whether for ADAS or AV, but also to make roadside surveillance cameras smarter.

Concerning the measurement of the impact of adverse weather conditions on vehicle perception systems, the first public work was conducted in the context of the AWARE project, from 2014 to 2017 [31]. The objective of this project was to analyze which wavelength bands are least penalized by fog. Several cameras in the visible light (VIS), Short-Wave Infrared (SWIR), Mid-Wave Infrared (MWIR) and Long-Wave Infrared (LWIR) ranges were thus compared in the platform [32] [33]. This topic was then continued in the DENSE project, from 2016 to 2019 [26] [34]. The DENSE project aimed to develop a series of all-weather sensors, allowing the automation of a particular vehicle. The conditions targeted included fog, rain and snow. The sensors set was composed of stereoscopic cameras in VIS, (Near-Infrared) NIR and SWIR domains, LiDARs (Light Detection And Ranging), radars and time-of-flight cameras. The research studies characterized the boundary weather conditions for each of the sensors [35] [36] [37] [38] [39] [40] (see

Figure 5) and used data fusion to extend the admissible conditions [41] [42] [43] [44]. This work has been continued and extended to polarimetric cameras [45] and LiDARs [46] in the context of international PhD thesis collaborations. This work was also completed in the AWARD project, which is the subject of Section 5.

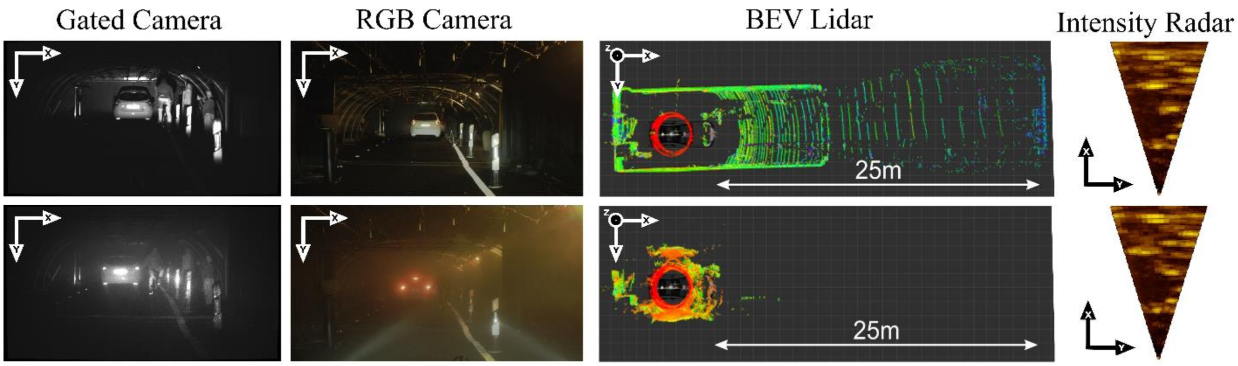


Figure 5 - Multimodal sensor response of RGB camera, scanning LiDAR, gated camera, and radar in a fog chamber with dense fog. Reference recordings under clear conditions are shown in the first row, recordings in fog with visibility of 23m are shown in the second row. From Bijelic et al. [43].

In parallel, other works to measure the efficiency of pedestrian detectors for visible-domain cameras in rain and fog conditions was conducted. They showed that the efficiency decreases strongly with the presence of fog [4]. On this occasion, a database of pedestrian images in adverse weather conditions has been published (see Figure 6) [47] [48].

Figure 6 - A selection of images from the Cerema Adverse Weather Pedestrian (AWP) database under different conditions. Top = Day conditions and Bottom = night conditions. From left to right: Normal conditions, Light fog, Heavy fog, Light rain, and Heavy rain. From Dahmane et al. [4].

Concerning the measurement of weather conditions by camera, camera-based weather measurement initially derived from work on the impact of rain on cameras. Indeed, it was shown that rain has a quantifiable impact which is proportional to the rainfall intensity on common image descriptors of the literature [28] [30]. The impact on the image features was then used to detect the actual weather conditions, including fog and rain conditions [29]. Then, the use of image features was left aside, and Deep Convolutional Neural Networks (DCNN) were successfully used in the WeatherEye solution (see results in Table 1) [49] [50] [51]. For the artificial intelligence optimisation, a first learning step can be done from images recorded in the PAVIN platform, before being transferred and fine-tuned on images that are acquired on a real site. These research items were realised in the LabEx IMobS3 framework [15].

Table 1 – Classification scores obtained on three state of the art DCNNs, on the Cerema Adverse Weather Highway (AWH) database with five meteorological class (Normal conditions, Light fog, Heavy fog, Light rain, Heavy rain). From Dahmane et al. [50].

	Architectures		
	ResNet-152	**DenseNet-121**	**Inception-v4**
Fixed scene	0.9	0.9	0.87
Random scene	0.82	0.8	0.7

Concerning the numerical simulation of adverse weather conditions, the first numerical simulation tools developed with the PAVIN platform were about fog. The work started in 2000 and continued until 2010. Authors first used visible light cameras only in night conditions [52] [53]. These researches have been resumed by the Cerema team in charge of the platform in 2020 and are currently in progress. First, some experiments have been conducted to check the impact of the wavelength and the fog DSD on the transmission of electromagnetic radiation [54]. According to the literature and as shown on the Figure 7, they show that the light transmission is not the same for all wavelengths. The objective is now to use these first results to develop a new fog numerical simulator based on radiative transfer equation and Monte-Carlo method (Figure 8) [Ben-Daoued et al. 2022, paper in process of publication]. In parallel, a digital twin of the platform is being developed and is discussed in more detail in section 6. Before jumping into the future, in section 6, we propose to focus on an example of a present use of the PAVIN platform, in section 5.

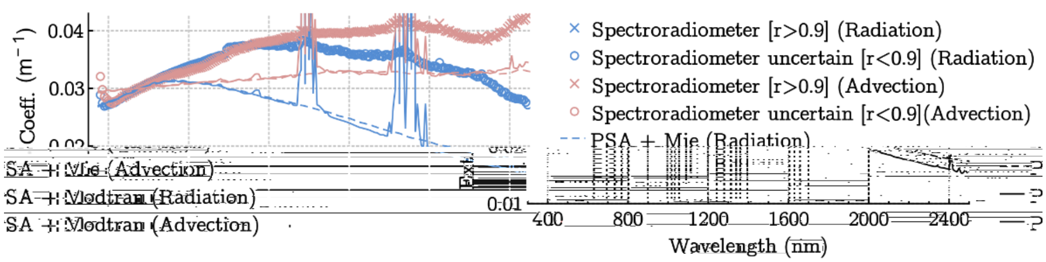


Figure 7 - Extinction coefficient as a function of wavelength for a fog's MOR = 100m. (From Duthon et al. [54])

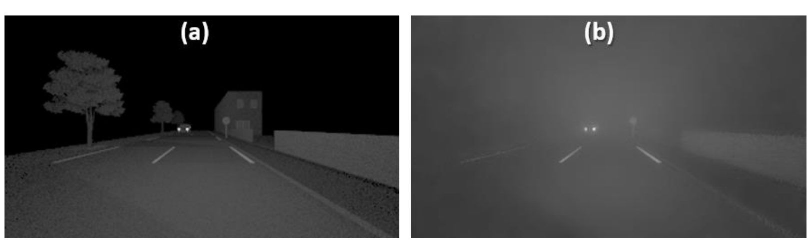


Figure 8 - Simulated road scene in the visible: (a) without fog, (b) with 3D fog with MOR = 21 m (From Ben-Daoued et al. 2022, full paper in process of publication)

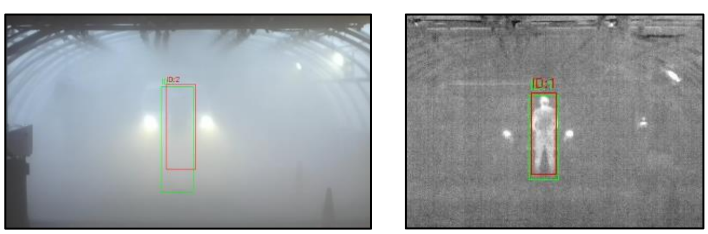
5. H2020 AWARD project: some recent use cases

The H2020 All Weather Autonomous Real logistics operations and Demonstrations (AWARD) project aims to bring major innovations to the transport industry, fleet operators and the entire logistics sector. The project will contribute to the accelerated deployment of innovative, connected and automated freight transport solutions in Europe and worldwide. The Cerema ITS research team has an important role in this project. It participates in more than half of the project's work packages (WP). Within the framework of WP3, the research team participated in the implementation of the protocols and in the realization of the tests in adverse weather conditions. The PAVIN platform was used during the development of the sensors batch and the associated analysis as well as processing algorithms.

Within the AWARD project, Easymile was able to make a benchmark of different LiDARs (spinning, Risley prisms, micro-motion and MEMS). They were compared in various artificial rain and fog conditions, in the PAVIN platform. A specific target with calibrated reflectance was used to make a first quantitative analysis. Different results were observed depending on the sensors, valuable multi-echo information, and unexpected behaviors in the analysis with artificial rain were seen where higher rain rates do not necessarily mean higher degradations on LiDARs data [55].

weather conditions. The novelty of that common work (Foresight and Cerema) was to present results of a 3D object detection operational design domain characterization: (a) on a commercially ready system, (b) using visible and thermal wavelengths, and (c) in controlled fog and rain conditions. This study shows that the use of dual visible and long-wave infrared thermal sensors in stereo is essential to the all-weather detection of pedestrians and vehicles. The thermal sensor is essential in challenging conditions such as nighttime or adverse weather conditions. Rain and low lighting conditions are not a problem for the QuadSight system. The system also performs well in foggy conditions (see Figure 9), with the only exception of compromised performance in very dense fog [Duthon et al. 2022, full paper in process of publication].

Other AWARD partners, like Navtech [56] or Adasky have also carried out tests within the PAVIN platform. Results will be published later in the future. Speaking of the future, it is time to introduce the next major evolutions of the PAVIN platform. This is the subject of section 6, which will be our last time leap before concluding.



(a) (b)

Figure 9 - Example of the pedestrian who is totally invisible on the visible light camera (a), while he is perfectly visible on the thermal camera (b).

6. Towards the future of the Cerema PAVIN platform: new building, mobile devices and numerical simulation

From its construction in 1984 until past years, Cerema fog & rain platform has always evolved in order to stay correlated with actual stakes, renewing, improving and evolving its technical capacities and offer. However, the building has achieved its maximum transformation and evolution possibilities and a complete redesign of the whole installation is inevitable.

As the current building seems to have reached its evolutionary limits, Cerema initiated a new platform project in 2018 and its construction is planned for 2023 thanks to co-financing from the Auvergne-Rhône-Alpes region (France). One of the main objectives was to increase the dimensions of the building, as 30 meters length and 5.5 meters width was a limiting aspect for more complex scenarios. Moreover, the height of the tunnel was not initially designed for a quality rain generation and is far too low [34].

Beyond the strong evolution of the dimensions of the tunnel, this new platform is also improving thermal and lighting properties of the climatic chamber. The main purpose is to provide particularly optimized stable conditions over time, especially among a testing campaign for example. It consists then in a strong optimization of thermal isolation and sun exposition of the whole building, as an active thermal regulation based on cold air addition or circulation contradictory with controlled fog characteristics.

The new building is 50 meters length, 7 meters width and 6 meters height (see Figure 10). These new dimensions will enable to consider new realistic scenarios and also to include other types of vehicles such as trucks, shuttles or even not urban vehicle (agricultural, etc.).

Figure 10 - New Cerema's PAVIN fog & rain platform

The main objective for the test chamber is to provide thermal and lighting conditions that are stable over time and homogeneous in space. For lighting purposes, both natural and artificial sources will be used with adapted goals. The main idea is to obtain a good homogeneity on ground irradiance and a minimal average value. The natural light will allow to make daytime tests with the real spectrum of the sun. This will be useful for the dimensioning of the sensors of the future which use more and more varied ranges of wavelengths (SWIR, MWIR).

The controlled thermal conditions will make possible to produce a much better-quality fog. In particular, the droplet size distribution of the different types of produced fog will be closer to the real meteorological phenomenon (in particular for maritime fog) [21]. The rain production quality will also be strongly improved thanks to the height of the test chamber; indeed the nozzles will be at about 5.50 m and then the rain will be very realistic from 3.5 m height (better falling velocity). In addition, the platform will be built with the possibility to recover all the rain generated and then be able to reuse it, thus working with very low water consumption, and much longer rain production time.

This new platform will offer the Cerema a great evolution at a larger scale to address adverse weather stakes with autonomous vehicles, and for other applications. Indeed, the internal dimensions of the test chamber offers new possibilities. First, it will be an opportunity to calibrate outside mobile adverse weather generators (rain, fog, even snow) inside the tunnel, using all the meteorological devices of the platform on them. Then, the increased length of the tunnel and the positioning of the whole building in the continuity of its access road will enable to consider dynamic tests with vehicle entering or exiting of the tunnel, at realistic speed.

The building of this new adverse weather platform will be correlated with the development of fog modelling with the objective to get a numerical twin of the facility. Then, the Cerema will propose both physical and numerical simulations of fog and rain visibility conditions.

All these evolutions of the Cerema offer will set up from 2023 with the building of the new PAVIN fog & rain platform. One of the final purposes will be to propose a full standardized testing platform for ITS within adverse weather conditions.

7. Conclusions

The context of autonomous mobility is evolving fast, making a lot of various ADAS and AV technologies continually emerging and trying to address remaining scientific locks. Considering adverse weather is one of them and both numerical and physical simulations seem to be necessary tools to make relevant progress.

The Cerema PAVIN fog and rain platform is a unique facility
to propose realistic harsh weather conditions reproduced in controlled environment. As it focused on fog at the beginning, it produced only basic single kind of uncontrolled and unmeasured fog conditions. The first evolutions consisted in a fine characterization of fog such as DSD and MOR, followed by a proper fog regulation and the possibility to produce both radiative and advection fog. Then the possibility to produce rain was added, firstly with a unique rainfall rate and then with a larger range, with a fine characterization of DSD and rainfall rate uniformity. From almost the beginning, both fog and rain conditions were checked to be as realistic as possible. Over time, it became an important issue to ensure the metrological stability and representativeness of the reproduced adverse weather conditions. In fact, this will remain a strong need, as the legislation of ADAS (and AVs) will introduce a specific test procedure with environmental controlled parameters.

During the last decades and through its various evolution, the Cerema PAVIN fog and rain platform always offered updated services to the partners and private customers of the transport sectors. It was then involved in many major research and development projects, which established the new benchmarks. In the meanwhile, the platform was used to evaluate more than 50 different sensors from various companies from about 15 countries all around the world, allowing to keep the platform equipments up-to-date regarding all the upcoming new technologies. Thanks to its French agency status, Cerema can easily work with many kinds of partners such as industrial, SME, startup and academic research laboratories.

During these 40 years of loyal service, the platform has also been a key tool for the Cerema ITS research team. Numerous research projects have been carried out, first on human vision, then on artificial vision. Today, this renewed team works mainly on three aspects: the evaluation of the impact of the weather on vision systems, the measurement of weather conditions by camera and finally the numerical simulation of weather conditions.

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