PRISSMA Project
Plateforme de Recherche et d'Investissement pour la Sûreté
et la Sécurité de la Mobilité Autonome
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[L3.1] WP3 STATE OF THE ART AND INVENTORY OF THE EXISTING SITUATION

Etat de lieux et recensement de l'existant

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Abstract.

The aim of this deliverable is to make an inventory of existing "controlled" test environments in France and abroad, in the field of autonomous mobility. It will focus in particular on "vehicle in the loop" test tracks and benches, as well as current experiments on this type of test facility and the AI functionalities that can be evaluated there. This inventory will be based in particular on the report by Philippe Anrigo (PFA), which will be updated during the project via a scientific monitoring process. This will make it possible to identify gaps (particularly in the systems aspect, often overlooked in current homologation activities) and needs in this category of testing, in line with the expectations of the project and in particular the recommendations of WP1 from a national or European perspective.

Résumé.

Ce livrable a pour but de faire un état des lieux et un recensement des environnements de test « contrôlés » existants en France et à l'étranger, dans le domaine de la mobilité autonome. Elle portera notamment sur les pistes et bancs « vehicule in the loop », ainsi que sur les expérimentations en cours sur ce type de moyens d'essais et les fonctionnalités d'IA pouvant y être évaluées. Ce recensement s'appuiera notamment sur le rapport de Philippe Anrigo (PFA) qui sera actualisé durant le projet via un processus de veille scientifique. Ceci permettra d'identifier les manques (notamment sur l'aspect système de systèmes souvent oublié des activités actuelles d'homologation) et les besoins pour cette catégorie d'essais au regard des attentes du projet et notamment des recommandations du WP1 dans une perspective nationale ou européenne.

Contents

1 INTRODUCTION

The needs for evaluation of autonomous vehicles pertain to:

- Smart autonomous transport grids
- Infrastructures
- Network and connectivity, IOT
- Autonomous vehicles

The evaluations can be performed in controlled environment at different levels of integration and realism:

- Numerical modeling (components and whole vehicle, dynamics, etc.)

- Virtual reality simulation
- Test bench evaluation
- Test track evaluation

It is necessary to ensure a continuous adaptive pattern of evaluation from POC to development to validation and homologation; all levels of integration are useful for that purpose.

This document focuses on existing test benches and test tracks. These testing facilities allow the evaluation of physical vehicles and components, which provides a higher level of realism than simulation testing.

2 TEST BENCHES

Test benches are defined as an infrastructure where part of or the whole vehicle is tested in simulated conditions, without the vehicle moving in reality. Different levels of integration exist for test benches:

1. Sensor test benches: these devices evaluate components of the autonomous vehicle. It is necessary to apply a realistic testing scenario in order to evaluate the sensor in representative conditions.
2. Function test benches: these testbeds can host a functional part or the whole vehicle. Their purpose is to evaluate a given function (for example, pedestrian detection can be evaluated in such test benches, either as a function of the smart camera or of the whole vehicle with the integration of different sensors. It is also possible to evaluate driving assistance functions in this type of test benches, by integrating the driver into the evaluation protocol. For example, HMI tests can be performed on function test benches.
3. Vehicle test benches: this final type of testbeds is the most realistic version of testbeds. They host a vehicle as a whole and aim to evaluate all of its functions in realistic scenarios. This is the step closest to actual test track driving tests, and it has the advantage of potentially reproducing a large variability of scenarios and conditions.

All these levels of integration are relevant to cover different stages of development. The vehicle test bench is a transitional infrastructure getting close to the realism of test tracks.

3 TEST TRACKS

Test tracks are the ultimate controlled environment before real-road testing. It provides a high representability but comes at a higher cost and has limited variability because of the cost of implementing new scenarios. It is for example hard to recreate all climatic and lighting conditions.

Test tracks also present different levels of realism but also focus on different interest areas for vehicle evaluation.

1. Combined vehicle and track, connectivity testing: This type of testing track is designed to test smart city or IOT connectivity and the functioning of the vehicle as connected to the track.
2. Vehicle function testing, performance evaluation: This is the generic vehicle testing track, it is designed to evaluate the performance of the vehicle as a whole in generic representative conditions.

3. Safety mode testing: This type of testing tracks are specifically designed to evaluate the triggering and functioning of the vehicle safety modes, such as emergency braking or ABS.
4. Test tracks representative of final exploitation site: For vehicles designed for a specific environment (such as agricultural vehicles or city shuttles), this type of testing track is designed to evaluate the performance of the vehicle in a realistically representative environment.
5. Human-Machine Interface evaluation in realistic scenarios: This is a subcategory of functionality testing, but it is considered separately as it demands the presence of a human on board, which implies more safety concerns.
6. Testing on the final exploitation site: For vehicles that are designed for a particular limited exploitation site, such as a closed-site shuttle, supervised testing can be performed in real conditions.
7. Testing for certification and homologation (Euro NCAP and others): These tracks are designed in accordance with requirements specified by the standards used for homologation and certification of the vehicle.

The type of test track will be indicated in the description of the examples in the following sections.

4 CONNECTIONS BETWEEN CONTROLLED AND SIMULATED ENVIRONMENT FOR TESTING

Autonomous drive and advanced driver assistance software have shown an outstanding development in the last decade. The performance of this software is nowadays reaching and maybe going beyond the level of human drivers' skills. This is bringing a drastic change in the automotive industry. Despite this outstanding progress, few of the recent research developments have been applied to prototype vehicles and extremely few have been transferred to commercial applications. This is mainly due to the lack of convenient testing tools and validation procedures. In fact, testing advanced automotive software takes lots of effort, engineering time and money. It involves complex prototypes and dedicated test sites.

Even though testing and validating autonomous vehicles components in simulation is a powerful tool, extensively exploited by the community, pure simulation cannot suffice and there is a clear need to experiment on real platforms to bridge the gap between virtual and real world and ensure a proper validation. Nevertheless, nowadays, the main metric to assess the performance of such software remains the average distance run without an error or a disengagement, and the most common validation procedure currently used in industry is to drive a fleet of prototype vehicles for millions of kilometers, hope that no fatality occurs and wait for an a posteriori validation. However, the most interesting scenarios to test are often extremely rare events on the roads and particularly dangerous to reproduce even in a controlled environment with real traffic actors (cars, pedestrians, bikes, etc.), and in this case the use of simulated environments show its clear contribution, to safely recreate risky and critical scenarios.

An interesting solution is to combine these two procedures of testing and analysis for validation purposes, by considering simulated scenarios and real experiments either separately but for similar tests or simultaneously, in a context of hybrid scenarios.

An example of how real tests in a controlled environment can be exploited to support an analysis performed in simulation has been shown in [1]. This work presented an approach based on

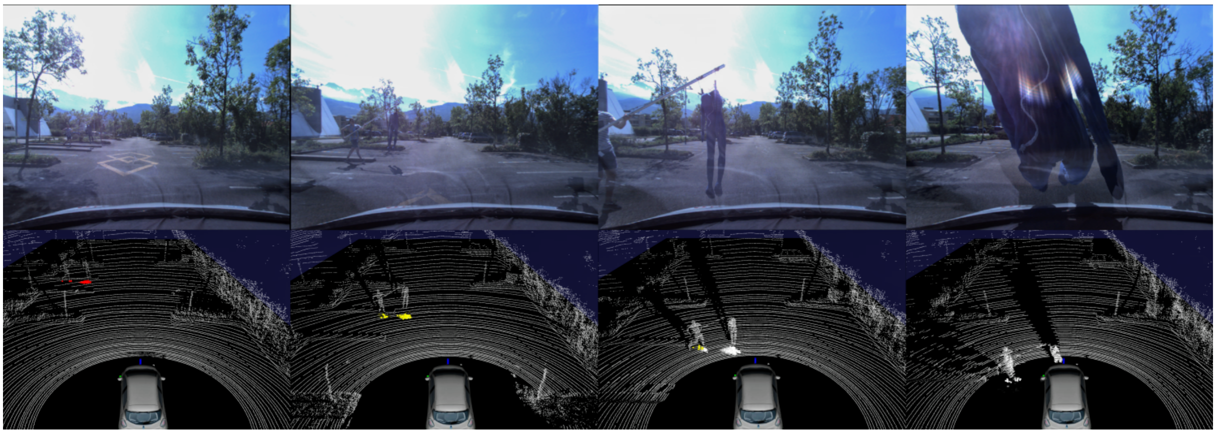


Figure 1: Illustration of one of the experiments performed with INRIA's autonomous car. The scenario reproduces the car colliding with a pedestrian (mannequin) crossing the street. Top: camera view from the car. Bottom: the environment as seen by the LiDAR and the CMCDOT collision risk grid. The sequence from left to right represents different time stamps. Colors represent probability of collision in $3s$ (red), $2s$ (yellow) and $1s$ (white).

Statistical Model Checking (SMC) [2], [3] to validate the collision risk assessment generated by a probabilistic perception system. SMC represents an intermediate between test and exhaustive verification by relying on statistics and evaluates the probability of meeting appropriate Key Performance Indicators (KPIs) based on a large number of simulations. As a case study, a state-of-the-art algorithm was adopted to obtain the collision risk estimations [4]. This algorithm provides an environment representation through Bayesian probabilistic occupancy grids [5] and estimates positions in the near future of every static and dynamic part of the grid. Based on these estimations, time-to-collision probabilities are then associated with the corresponding cells. SMC is strongly based on the use of a very large number of execution traces, and in this work the CARLA simulator [6] was adopted to generate them, considering both collisions and almost-collisions in realistic urban scenarios.

In the real world, it is clearly infeasible to generate a statistically significant number of traces to evaluate the KPIs and an SMC approach for validation is less suitable. It is possible and meaningful, however, to analyze how close the simulation traces are to real experiments. In [1], several real traces were collected by imitating the collision of the ego-vehicle (an equipped Renault Zoe) with a pedestrian (by using a mannequin as in Fig. 1) and with another vehicle (by throwing a big ball). In these experiments, the authors did not have access to real non-ego vehicles velocities and positions, therefore only timestamps, CMCDOT risk values and the ego-vehicle speed were recorded. The real-world traces were then compared with simulated ones of analogous scenarios, where the ego-vehicle's speed was in the range $[v - 0.5m/s, v + 0.5m/s]$, with v being the real car's speed.

To compare the risk evolution over time, the authors used a partial curve mapping metric (PCM) [7] as a measure of similarity. The PCM maps each data point of one curve onto another and the similarity estimates the volume between mapped curves as $s = \Sigma_{i=1}^{n-1}((d_i + d_{i+1}) * l_i/2)$, where n is the number of data points on the curve, d_i is the distance between the i^{th} points of mapped curves, and l_i is a relative length of the i^{th} curve segment. Curve mapping makes this metric unaffected by having a separate point at timestamps that may not coincide in different traces. Also, for traces of different length, PCM chooses an offset that gives the best mapping of curves.

The traces recorded during the real experiments had been finally compared with the ones

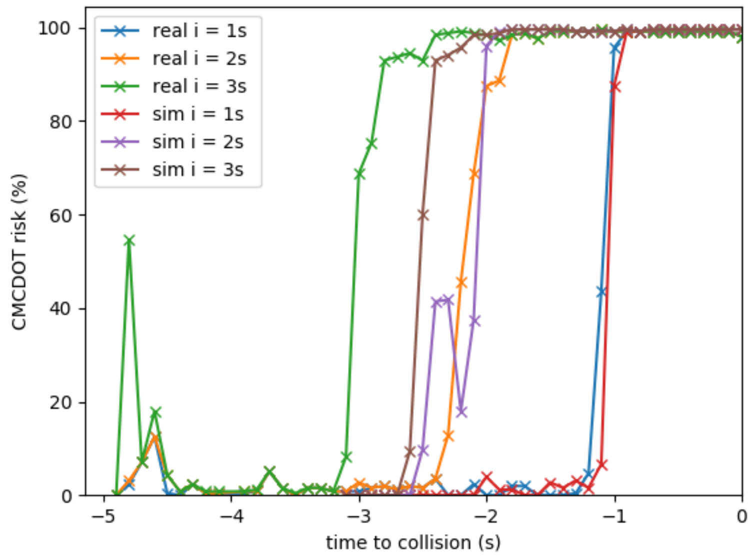


Figure 2: Comparison of real-world and simulated estimations. Curves show CMCDOT risk in i seconds for real and simulated traces.

corresponding to similar scenarios simulated in CARLA. While recreating real tests with clear collisions or no-collisions scenarios is easy, the near-miss scenarios are more challenging to reproduce. These cases are much more sensitive to several factors, such as changes in the velocities of the vehicles, and finding a reliable way to conduct experiments clearly matching simulated scenarios was not possible. For this reason, this work did not consider this class of scenarios for this analysis.

For all except one real-world trace, the authors were able to obtain a PCM metric below 1 with respect to a simulated trace. Fig. 2 shows the evolution of the collision risk for the real trace and the simulated one for an instance where all the three pairs of curves for 1, 2 and 3 seconds had low PCM metric, specifically below 1 for the 1-second curves and below 2.5 for 2- and 3-seconds predictions. Considering all the possible sources of noise and instability in velocities, a perfect match between the two curves cannot be expected. However, the obtained results showed that in most of the cases the collision risk estimated by CMCDOT over time in simulation closely reproduced the real world. Another relevant discovery is that in the real-world traces, the risk raise happens earlier than in simulated traces. This could suggest that the risk raise delay noticed in simulated traces might be exclusively caused by delays in the simulator.

But besides the specific results on the collision risk evaluation obtained by the considered perception algorithm, this work showed a way to exploit real experiments in controlled environments where few critical scenarios were reproduced to support and complete a larger validation analysis conducted in simulation.

4.1 TESTS IN HYBRID REAL-SIMULATED FRAMEWORKS

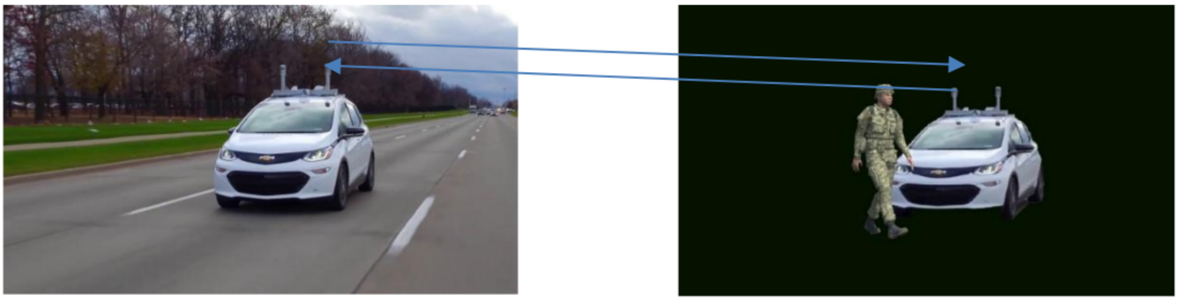
Another alternative to exploit the richness of virtual simulated data with the constraints of a real vehicle is to consider hybrid systems for testing. Vehicle-in-the-loop (ViL) frameworks, that provides a validation environment for real vehicles in combination with virtual environment simulations, allows the execution of complex and safety-critical scenarios on the vehicle level [AR]. The idea is therefore to combine the test vehicle with a synthetic test environment, and thus gain the advantages of both methods. ViL has been adopted for automotive testing over the last decade and is now a widely-used method to work as a transition phase between Hardware-in-the-loop (HiL) testing and full on-road testing. Various implementations have been realized and designed for different purposes. ViL always involves the software under test, the computer and the whole vehicle in motion. The state and actions of the actual vehicle are updated in a virtual environment which is then perceived by emulated sensors that replace the actual sensors of the vehicle. While the test can happen entirely in the virtual environment, the actual vehicle may be standing on a test bench [8], [9] or driving in a controlled environment [10], [11]. As the environment remains purely virtual, the testing is still somehow limited by the simulator realism, the emulation of the sensors and the diversity of the virtual scenes.

In [8] the authors test an active safety light system. When an accident is imminent the system illuminates the path the driver should take to avoid the accident. This system can be considered as an ADAS helping the decision making of the human driver. To evaluate the impact of their system on the safety of the car and its driver the authors use a ViL-based method. Their ViL setup is composed of a Volkswagen Passat CC immobilized on a test bench and its virtual twin inside the virtual environment of a simulator. The car is linked via its CAN bus to the simulator. The human driver can drive the car in the virtual environment using the real commands of the car (steering wheel, throttle, brakes, etc.). To visualize the virtual environment, the driver is equipped with an Head-mounted display which displays the environment of the simulator as if viewed by the driver inside the simulator. The driver's head is precisely localized in real time during the tests to compute its view of the virtual environment. With this system, the authors ran several tests of one scenario : at an intersection an opponent car, coming from the right, wrongfully cross the intersection in front of the ego car. To avoid the collision the driver must follow the path illuminated by the active safety light.

In [9] the authors propose a ViL framework with different levels of X-in-the-loop, where X can mean Vehicle, System, Subsystem, Software depending on how much virtual the test is. It allows flexibility in what is virtual or not depending on the objective of the test. The tested vehicle is put on a test bench and linked to the simulator Simulink (from Matlab), which is used for the simulation of the vehicle and its components. They apply their method to test the energy management strategy of an hybrid vehicle in a stop and go situation (for example in dense traffic). They measure the fuel consumption of the the real car combustion engine. A screen in front of the vehicle displays a simulation of a dense traffic while a human driver drives the vehicle in the virtual environment using the real commands (throttle and brake pedals, steering wheel). They measure the rotation speed of the wheels and the steering angle to control the virtual twin of the car. They test different energy management strategies and show that an efficient strategy can effectively reduce fuel consumption.

In both studies ViL allows to easily acquire a lot of data by performing many test while being directly connected to the CAN bus of the car. The test are realized by a human driver, so the behavior of the vehicle and the response of its driver are more realistic than during fully simulated test. Even if The vehicle is immobilized on a test bench ViL tests are easier to perform and safer for the subject of the tests (e.g. the human driver, the vehicle, the obstacles, etc.)

In [11], the authors show that a human driver behave similarly when following a real car or a virtual car. A human driver put a see through head mounted display. The car is linked to a simulator, in this simulator the car is located and is moved according to the real motion of the vehicle. The position and orientation of the driver's head is tracked to display through the headset what the driver would see in the virtual environment. The headset is see-through so the virtual view overlaps the driver's view of the real world, the driver sees a fusion of both



(a) (b)

Figure 3: Image from [12]. An illustration of a test conducted with the help of augmented reality. (a) A real vehicle is moving on a real road without any obstacles. (b) A virtual obstacle is added to the vehicle's environment and the sensor information used for testing is a combination of real and virtual objects.

worlds. During the test, the driver must follow a virtual car and drives in virtual lanes (road markings are virtual), the test is performed on a large and empty test track. The behavior of the driver is compared to its behavior when following a real car, the authors show that the behaviors are same. They conclude that this method could be used to test ADAS by connecting it to the simulator so it can perceive the virtual obstacles. Like the two previous studies the authors show that ViL testing is less costly method but also that the ViL system can be directly embedded in the tested vehicle. Thus, the vehicle can be mobile. Also, this method is still safe for the vehicle and the driver, every other actors or obstacles of the tests are virtual.

In [10], the authors proposed a ViL system that uses the realistic traffic simulator. They used a fully autonomous Smart Fortwo as a tested ego vehicle and Matlab for the simulation of virtual environment. They used the open source traffic simulator SUMO, which is compatible with Matlab. They performed a test scenario in car park, the ego vehicle must follow a leading vehicle which is virtual, the leading vehicle performs an emergency brake and the ego vehicle must avoid the collision. The environment and the two vehicles are modeled and simulated with Matlab, the virtual leading vehicle is controlled by SUMO and the real ego vehicle is synchronized with its virtual twin through its CAN bus. The ego vehicle is equipped with a LiDAR sensor, the LiDAR data from the real car are ignored and replaced by the data from the LiDAR of the virtual car. With this experiment they show that costly and complex test with real road traffic of AVs can be replaced by a ViL system where the ego vehicle drives in a real environment while the other actors of the scenario evolve in a virtual reproduction of this environment. This method is safer as it avoids real collision, also, more various traffic configurations can be tested.

More recently, several works made significant improvements to go beyond ViL in combining virtual and real-test environments. These methods offer safe and efficient testing with virtual elements but also a rich, dense and representative real environment.

In [13], Chen et al. presented a mixed reality test framework where the vehicle under test receives a unified perception of the environment without emulation of the sensors, where virtual and real perception are fused at object level. During the test scenarios, the virtual actors are simulated by a system embedded in the vehicle, they use the simulator Gazebo. The virtual environment is a reconstruction of the testing field road topology, the authors propose a method to reconstruct the road topology using the scans of the 3D LIDAR of the tested AV. The facility does not need to be a complex reproduction of a traffic situation (road marking, signs, objects...) in fact, these elements can be added in the virtual environment then sent to the AV to simulate a complex scenario. Conversely, the data from real sensors are used and are not altered, so elements already in the real environment does not need to be virtually added. The method is tested with a real vehicle in a dedicated empty facility, with existing real road network. They add virtual actors to the scenario and an opponent car crossing an intersection of front of the ego vehicle. This method could be used in any testing field, in fact their method allows scanning of the real environment and its rendering in the simulator. Many scenarios can be easily generated and performed. The data of the real sensors are still used by the AV, so the vehicle sensors are not excluded from the test.

In [14], the authors propose to run test scenarios for connected and automated vehicles (CAV) in a dedicated testing facility using augmented reality. The facility is a connected infrastructure, the CAV are connected with it, they can communicate information with each other or with the infrastructure and vice versa. In their method the authors add virtual actors to the scenarios (e.g. obstacle cars, pedestrians or virtual CAVs). A virtual twin of the infrastructure is simulated by the infrastructure itself. The CAVs are precisely localized in the simulation thanks to an RTK GPS and the virtual actors are controlled by a realistic road traffic simulator. The real CAVs perceive the virtual actors through their connection with the infrastructure. Either the infrastructure communicates information in its name to the vehicle (infrastructure to vehicle communication) or in the name of virtual actors (simulated vehicle to vehicle communication). The authors implement their method at the Mcity facility in Michigan USA. They achieve realtime communication between the infrastructure systems (sensors, traffic signals, simulated actors, etc.) and the real CAVs. This method allows testing of CAVs and their communication systems with non connected AVs or pedestrians and also tests interactions between CAVs.

In [15] the author proposes a new testing and validation framework called Scenario-in-the-loop (SiL) as an improvement of Vehicle-in-the-loop (ViL). SiL improves the integration of the virtual elements and data of a scenario into the real world (the infrastructure and the real vehicles of the scenario). SiL proposes a wider gradient in what is virtual and what is real in the test compared to ViL. Its objective is to test one AV, the ego vehicle or vehicle under test, in a dedicated facility (the vehicle is actually moving, not fixed on a test bench) through scenario-based testing. Also, SiL puts the emphasis on connected infrastructures and vehicles, real vehicles upload data to the infrastructure through wireless communication (like 5G). Then the infrastructure relay both the data from its own sensors and the data vehicles communicated by the vehocles. In the case of virtual vehicles, they are managed by the infrastructure so the infrastructure has full access to their data. Virtual elements are injected in the autonomous driving system of the AV at object level, before the decision making layer. Raw sensor data are not altered with data from simulation. The author apply this method on the ZalaZONE testing facility, located in Hungary, by performing two scenarios: 1) a pedestrian crosses the street in front the tested vehicle and 2) the tested vehicle follows then overtakes a leading car. Both scenario were performed with a virtual obstacle and then a real one. The tested vehicle is an autonomous vehicle, they observe no difference of the AV behavior between real and virtual obstacle. They conclude that the SiL testing method is valid for AV validation and an improvement of previous ViL methods.

Then Hildebrandt et al. introduced the concept of World-in-the-Loop [16]. WiL has been implemented for the monocular camera of a drone. It is one the best examples of AR implementation at sensor level. However, WiL runs a parallel simulation of the vehicle under test which only exchanges perception with the real one. WiL requires filtering and adjusting the perception to compensate for this weak connection between reality and simulation. They use a motion capture system to track the drone. They perform several tests to compare testing in simulation, reality and WiL. They use 3 scenarios: 1) the drone must fly trough a ring gate, 2) the drone follow a person and 3) the drone must avoid another drone. In WiL only the drone is real, the other elements (gate, person and other drone) are virtual. They conclude that in a WiL scenario the drone behaves closely to reality compared to the drone in simulation. WiL allows more realistic testing than fully virtual testing and a reduced cost compared to real testing. Also failure is less costly, during real tests the drone get damaged when passing through a gate and damaged the gate.

5 EXISTING CONTROLLED ADVERSE WEATHER TESTING FACILITIES IN THE WORLD

The use of numerical simulation is essential in order to test ADAS and autonomous vehicles. However, it is not sufficient. It is necessary to have data acquired under controlled conditions in order to verify the validity of the simulations. This is particularly true for adverse weather conditions that deserve a special focus [17]. This section provides a review of test sites that can reproduce adverse weather conditions (fog, rain, snow). Previous literature reviews have been identified, but they seem to be incomplete because they focus on particular regions of the world [17, 18]. As this type of equipment is rare, we propose here a worldwide review of test sites allowing to simulate road scenarios, in artificially simulated weather conditions. Some test beds have therefore been deliberately left out:

- Test chambers to measure the durability of vehicles. These test chambers are very small in size, allowing only the vehicle to be put inside (few square meters). They allow the vehicle to undergo cycles of heating, cooling, exposure to salt spray (to check corrosion), and possibly exposure to rain and wind (to check drainage and waterproofing). However, these chambers do not allow the implementation of road test scenarios, due to their small size.
- Small mobile systems that can be used to add a local effect to an initially unequipped track are also discarded, these last ones produce indeed more a cinema effect, than real test conditions.
- Test tracks that include a wet road area are not included in this list. These tracks are wetted by sprinkling or flowing at ground level only (to create a thin film of water on the road), so the disturbances of rain in the atmosphere are absent. Only the skid resistance conditions are impacted on this type of track, the perception systems are not impacted.
- Test tracks where natural weather conditions must be expected are also not included in this review. For example, many snow test tracks are installed at sites near the poles, where the occurrence of snow is very high throughout the year. However, these do not allow for on-demand weather, nor do they provide control and repeatability conditions during testing.
- Finally, private platforms not accessible to the public are not included either, as they do not allow a third party evaluation of the systems, nor the publication of the results.

There are very few test centers that meet the above mentioned selection criteria. Indeed, there are only 7 around the world, 2 in USA, 2 in Europe, and 3 in Asia. The following table summarizes the platforms identified.

Most of the test centers offer both fog and rain, except for the DENSO center with rain only. There are 2 outoor test tracks and 5 indoor centers. The first advantage of the test tracks

Table 1: Adverse weather facilities for automotive testing

	Fog range (m)	Rain range (mm/h)	Snow*	Real sunlight	Artificial daylight	Nightlight On Demand	Natural conditions	Facility	Country	Operator	Weather area (m)	Total area (m)
PAVIN	10 - 1000	20 - 180		x	x	x	x	Indoor	FR	Cerema	7x50**	7x50**
CARISSMA	20 - 200	16, 32, 66, 82, 98			x	x	x	Indoor	DE	THI	4x50	32x123
JARI	10 - 80	30, 50, 80			x	x	x	Indoor	JP	JARI	15x100	15x200
CRPG	30	50 - 100	x	x				Outdoor	KR	KICT	5x400	30x3000
DENSO	No fog	4 - 50			x	x	NA	Indoor	JP	DENSO	10x50	10x200
VSR	3 - 90	2 - 63	x	x				Outdoor	US	VTTI	5x800	10x3500
WSMR	NA	13 - 600			x	x	NA	Indoor	US	US Army	7x22	7x22

* if favourable conditions ; ** in 2023, 5x30 now.

is that they allow for dynamic, high-speed testing scenarios. The second advantage is that on these tracks, if the outdoor conditions are very favourable (very cold winter), it is possible to reproduce snow. On the other hand, the conditions reproduced are very dependent on the outside weather, especially the wind. The weather conditions produced on these test tracks are therefore not well calibrated and are difficult to repeat. Moreover, the lighting conditions of the runway depend on the sunshine. Concerning indoor test centers, their dimensions vary from 2 to 3 lanes wide, with a total length of 50 to 200m. On the other hand, the areas of production of adverse weather are all restricted to 50m, except for the JARI center with 100m.

For fog, the PAVIN and JARI centers seem to be the most developed, with a calibration of droplet size distribution and a wide density range (down to 10m visibility fog). Concerning rain, the PAVIN and CARISSMA centers seem to be the most relevant, with the consideration of rainfall rate uniformity, droplet size distribution and large ranges (up to 180mm/h for PAVIN). The WSMR, which is smaller, have the maximum rainfall rate with 600mm/h. Concerning lighting conditions, the indoor centers can reproduce day and night conditions on demand. However, among the indoor centers, only the PAVIN one allows the use of both artificial lighting and direct sunlight, allowing a light spectrum identical to that of the sun. The following subsections give a short description of each platform, with some pictures.

5.1 Cerema's PAVIN Fog and Rain Platform, Clermont-Ferrand, FRANCE

Cerema's PAVIN Fog and Rain Platform is a unique tool for reproducing extreme fog and rain in a spacious enclosure. The facility takes the form of a 30 m long covered track, specifically fitted out and instrumented with different equipment: rain and fog generator, advanced weather sensors, reference vision sensors. Opposite the control station, the track is structured in two parts (hard tunnel and greenhouse with removable opaque cover), making it possible to carry out tests under day and night conditions, according to a wide variety of scenarios. In 2023, the platform will be completely rebuilt. The future building will be a homogeneous tunnel of 50m length and 7m width. Openings all along the tunnel will allow for day and night conditions on demand. Into the weather chamber, a lot of natural weather conditions can be reproduced :

- Dense to light fog by dissipation (not stabilised), meteorological visibility from 10 m to 1,000 m,
- Dense fog in stabilised stages, meteorological visibility from 10 m to 200 m,

Figure 4: Cerema's PAVIN Fog and Rain Platform

- 2 types of fog particle size, radiation (0.8 microns) and advection (0.8 to 8 microns),
- Heavy rain in stabilised stages, rain intensity from 20 mm/h (duration of up to 100 minutes) to 180 mm/h (duration of up to 9 minutes).

The weather conditions are repeatable and representative of natural conditions. The Intelligent Transport Systems research team, with more than 30 years of experience (since 1983) and involved in multiple national and international projects (H2020, ANR, etc.), is responsible of the platform to assist in the design and execution of the tests. Independence, confidentiality and neutrality are ensured, related to Cerema's status of public institution.

5.2 CARISSMA, Ingolstadt, GERMANY

The Technische Hochschule Ingolstadt (THI) research and test center CARISSMA (Center of Automotive Research on Integrated Safety Systems and Measurement Area) is a 123 meters long building which was opened in June 2016 [19]. With 4,000 square meters of floor space, it houses an indoor test facility in which fog and rain can be reproduced. The indoor rain facility consists of three parallel strands that generate rain on an area of 50 x 4 m. It is possible to generate artificial rain with intensities from 16 to 98 mm/h. The droplet size distribution of the rain is controlled and is representative of a natural rain. The replicated fog consists only of clear water to ensure the same physical characteristics as real fog regarding scattering and absorption. In contrast to the rain facility, the fog facility is located laterally above the test area and pushes the fog onto the test area. However, the droplet size distributions of the indoor fog differs from the natural one. The simulated fog consists mainly of drops smaller than 1 microns. Nevertheless, the droplet sizes of the natural fog are mainly between 3 microns to 6 microns, which shows that the facility produces too many small drops.

Figure 5: Carissma

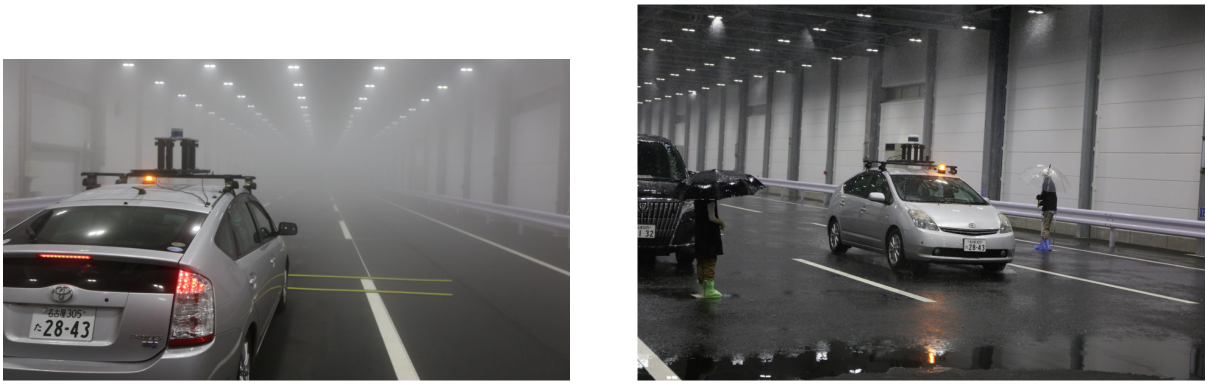


Figure 6: JARI's chamber

5.3 JARI's chamber, Tsukuba, JAPAN

The Japan Automobile Research Institute (JARI) weather experimental facility is a 200m long and 15m wide indoor weather chamber with 3 straight and marked lanes (each 3.5 wide as per Japanese regulations), regularly flat, with fences, traffic lights, controlled illumination and ventilation, and multiple sprinklers for fog and rain [20]. For fog emission, this weather chamber has 7.5 microns particle size and controllable visibility of 10m up to 80m, with fog emitted over the complete 200m track. For rain emission, there are two different sprinklers with particle size of 0.64 mm and 1.4 mm, and 3 precipitation levels: strong (30 mm/h), intense (50 mm/h), and very intense (80 mm/h). Rain is emitted only for half of the track (100 m).

5.4 Center for Road Weather Proving Ground, Yeoncheon, KOREA

The Center for Road weather Proving Ground (CRPG) is a testing facility that can recreate hazardous weather conditions such as snow, rain, and fog. The center is situated on a site measuring 700,000 m^2 in Yeoncheon. It's operated by the Korea Institute of Civil Engineering and Building Technology (KICT). It can mimic poor weather conditions, producing fog limiting visual range to 30 m, heavy rainfall of up to 50 mm - 100 mm per hour, and heavy snowfall of up to 5 cm per hour. A nighttime environment testing facility featuring track-mounted lighting equipment reproduces nighttime driving conditions.

Figure 7: Center for Road Weather Proving Ground

Figure 8: DENSO's Nakuda Test Center

5.5 DENSO's Nakuda Test Center, Okazaki, JAPAN

DENSO's Nakuda Test Center was established in 1984. Since 2013, it includes a facility that can evaluate the performance of sensors for ADAS. This facility reproduces nighttime and rainy weather. There is a course with a total length of 200m and a width of 10m inside the building, and it can run at a speed of 60 km/h. In addition, 500 watering nozzles are installed on the ceiling to bring the particle size of artificial rain and the distribution of rainfall closer to those of natural rain. The hourly rainfall can be adjusted from 4 to 50 mm.

5.6 Virginia Smart Roads, Montgomery County, Virginia, USA

The Virginia Smart Road is a 3.5km long two-lane road. It is operated by the Virginia Tech Transportation Institute (VTTI) [21, 22, 18]. This road is made available for research for various transport applications (lighting, communication, pavement...). It has fog and rain production systems. For production, 75 towers with nozzles are spread over 800m along the way. They allow producing fog if conditions are favourable (no wind and low temperature). The visibility range offered is 3 to 90m and the droplet size distribution is not measured. Proposed rainfall rate ranges from 2 to 63mm/h. The rain is produced by nozzles positioned on the same towers as fog. No data could be found in the spatial uniformity of the rainfall rate, droplet size distribution or drop velocity.

Figure 9: Virginia Smart Roads

Figure 10: White Sands Missile Range Climatic test facilities

5.7 White Sands Missile Range (WSRM) Climatic test facilities, New Mexico, USA

White Sands Missile Range (WSRM) Climatic test facilities , operated by U.S. Army, has the capability to perform a wide variety of climatic tests. Salt-fog testing is performed in accordance with MIL-STD-810. The tests are performed in the multi-purpose Hot Chamber. The facilities can produce salt concentrations of 5-20%. Rain testing is performed in accordance with MIL-STD-810, with rain rates of 13 to 600 mm/h produced at the ETA-II rain pad. Blowing rain is generated utilizing three portable wind generators capable of producing 40 mph winds.

6 EXISTING CONTROLLED ENVIRONMENT PHYSICAL TESTING FACILITIES IN FRANCE

The purpose of this section is to present the current testing facilities in France, their strengths and weaknesses and what protocols they can cover.

6.1 Transpolis

vehicle function testing, performance evaluation, test tracks representative of final exploitation site

Transpolis operates two testing facilities, both located in the Ain: in Fromenteaux and in La Valbonne. A third facility near the Saint Exupery airport, that was focusing on collision testing, is no longer in operation since 2018.

The Valbonne facility provides testing of **safety and comfort** in an environment simulating an **empty rural area**, including heavy vehicles.

Figure 11: The Transpolis facility in Fromenteaux

The Fromenteaux facility, operating since 2018, features a **full-scale city model** that allows the testing of urban mobility solutions.

These facilities provide testing for all physical validations of road and infrastructure, as well as driving assistance (ADAS) systems.

6.2 Altran Arémis (Car2Road)

test tracks representative of final exploitation site

This large testing facility provides high velocity testing tracks simulating a rural roas and motorways, as well as some interesting interconnectivity with simulated urban areas (intersections).

Figure 12: The Altran Arémis facility in

6.3 Pavin

vehicle function testing, performance evaluation, test tracks representative of final exploitation site

Pavin is a network of vehicle evaluation platforms in the Auvergne region in France.

Pavin Cészeaux is specialized in urban areas with low velocity (30km/h) and interfaces between different transports. It aims to help guide development of lightweight fully autonomous vehicles for urban mobility. A digital twin of the facility is also available for simulation testing.

Figure 13: Pavin Ceszeaux facility

A second Pavin facility is focused on fog and rain testing. It consists of a closed tunnel that is capable of reproducing degraded meteorological conditions with a high degree of accuracy (different types of fog and rain). More details on this facility are provided in section 5

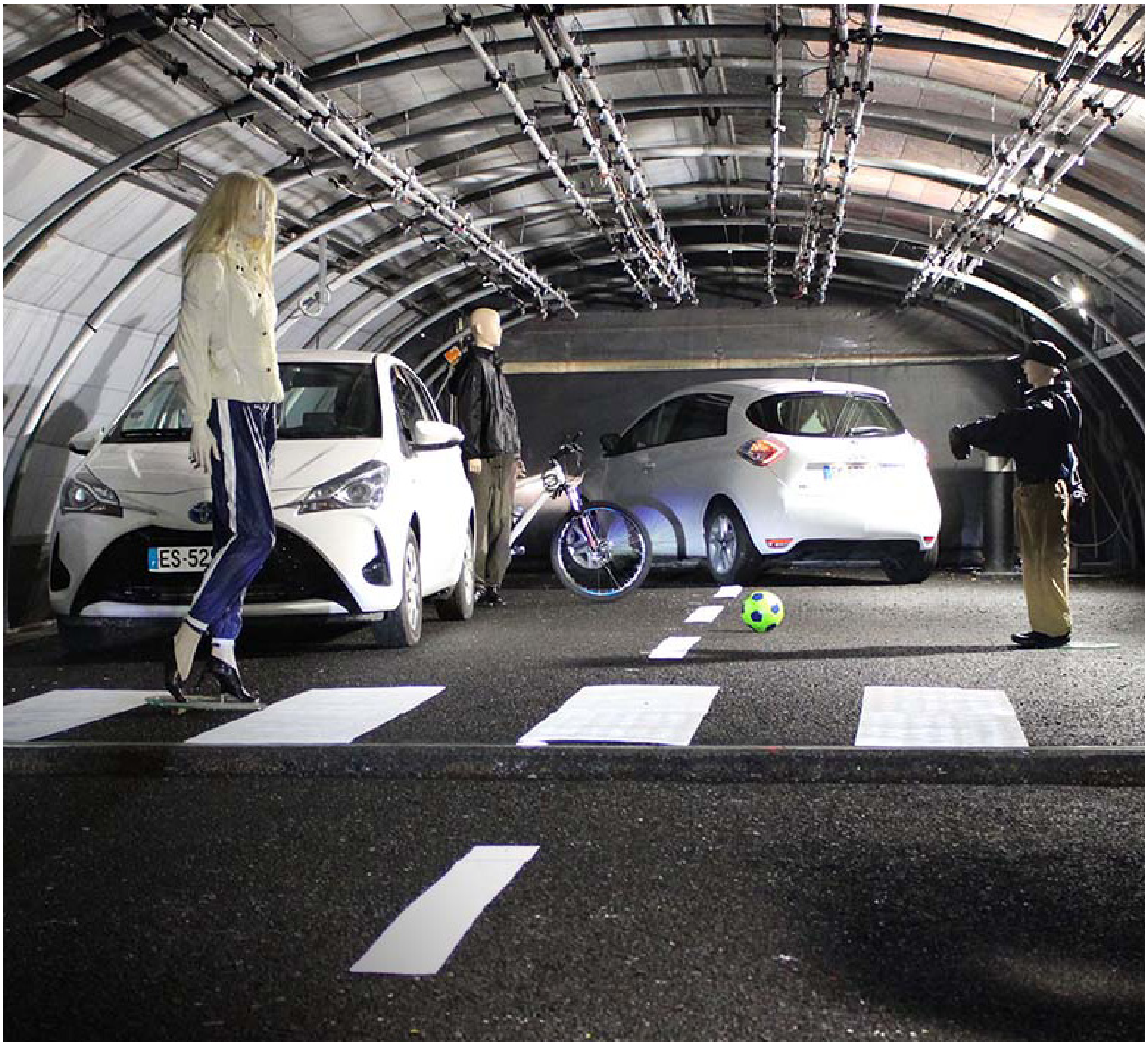


Figure 14: Pavin rain and fog facility

Finally, the last Pavin testbed, located at Montoldre and developed with the AgroTechnoPole, specializes in natural environment mobility. It allows the testing of heavy industrial or agricultural vehicles and evaluation of driver assistance in offroad conditions.

6.4 IFFSTAR

vehicle function testing, performance evaluation, safety mode testing

IFSTTAR provides two testing facilities:

The first is near Versailles and it is a set of small tracks for autonomous vehicle evaluation.

The second is located in Nantes, it is specialized in road adherence testing and geolocalization.

The full track is about 4km long and includes a curve with a 250m radius. The track features in over 15 different road coatings, which allows to test the vehicle adherence on different terrains.

Figure 15: The IFFSTAR testing facility in Nantes

6.5 UTAC CERAM

combined vehicle and track, connectivity testing, testing for certification and homologation

The main UTAC testing site is located in Monthlery, it is large and has a strong specialization in autonomous vehicles.

Figure 16: UTAC CERAM testing facilities in Monthlery and in Mortefontaine.

6.6 MICHELIN LADOUX

The Michelin Ladoux testing facility is specifically designed for autonomous vehicles and allowing evaluation of LAS, active security and adherence.

Figure 17: Michelin Ladoux testing tracks

6.7 BOSCH JUVINCOURT

Test tracks representative of final exploitation site The Bosch testing track is a 1.8km long, 50m wide piece of road. It is useful for recreating some interactions on high-speed highways.

Figure 18: Bosch testing tracks in Juvincourt

6.8 LA FERTE VIDAME

Vehicle function testing, performance evaluation, test tracks representative of final exploitation site The Citroën testing tracks in La Ferte Vidame are not specifically designed for autonomous vehicles. This medium-size testing facility has sections representative of different road types.

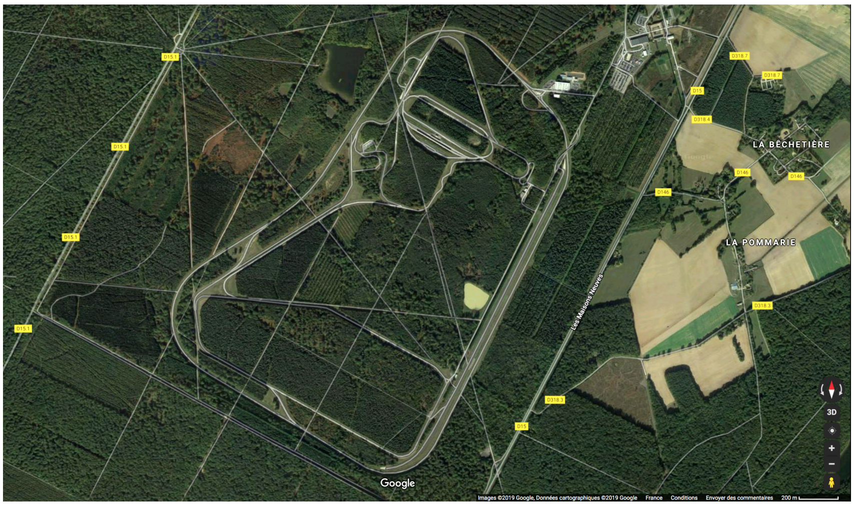


Figure 19: Citroën testing tracks in La Ferte Vidame

6.9 FRANCAZAL

vehicle function testing, test tracks representative of the final site The Francazal testing facility consists of short demonstration tracks (city and connections) and is designed for Proof of Concept testing.

7 CONCLUSION

Autonomous vehicle evaluation can be performed using testing beds, simulated environments or controlled environment testing tracks. Several testing tracks have been referenced in this document and categorized according to their type. An emphasis was put on adverse weather testing facilities, and a section of the document develops the advantages of hybrid testing in simulated and controlled environments.

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