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AIthena

D4.2 Report on physical set-up, digital twin and hybrid testing approaches

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Control Sheet

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1. Introduction

1.1 AITHENA concept and approach

Connected, Cooperative, and Automated Mobility (CCAM) offers significant potential to enhance urban transportation by reducing accidents, improving traffic efficiency, and lowering CO_2 emissions. Achieving this vision depends on the integration of intelligent infrastructure, including smart Roadside Units (RSUs) and Vehicle-to-Everything (V2X) communication technologies.

To accelerate the development and deployment of CCAM functionalities, effective and cost-efficient testing environments are essential. In line with this need, the concept underpinning this deliverable is the integration of physical and virtual testing methodologies into a unified hybrid approach. This approach enables thorough validation of AI-based CCAM systems across a broad range of scenarios. By combining real-world data collection with high-fidelity digital simulations, this methodology supports the early detection of system issues and fosters the continuous improvement of AI functionalities. Ultimately, it ensures comprehensive evaluation of AI processes, enhancing the trustworthiness and reliability of CCAM solutions.

1.2 Purpose of this deliverable

Deliverable 4.2 focuses on designing and developing tools as part of a toolchain architecture (Figure 1) that integrates the outputs of WP2 and WP3 for application in the use cases defined in WP5. This work package establishes a comprehensive framework that supports both physical and virtual testing environments. It encompasses vehicle configurations, infrastructure elements, and the preparation of simulation environments to enable hybrid testing approaches, including X-in-the-loop methods such as Hardware-in-the-Loop (HiL).

Additionally, this deliverable outlines the technical specifications necessary for preparing test vehicles and setting up controlled testing environments, as well as simulation platforms. The objective is to ensure that each component contributes effectively to the validation of the targeted AITHENA use cases.

1.3 Work package objectives

Work Package 4 (WP4) is dedicated to defining and implementing a toolchain architecture that supports the seamless integration of developments from WP2 and WP3 into the use cases executed in WP5. The primary aim is to establish a unified infrastructure and platform that enables the comprehensive execution of all AITHENA use cases. This includes vehicle and infrastructure setup, as well as preparation of simulation environments that blend the physical and virtual worlds through hybrid testing approaches.

A cloud-based infrastructure and platform solution will also be defined and configured to support the validation process, offering scalability, ubiquitous access, and high-performance computing capabilities.

The main objectives of WP4 are:

- **Toolchain Architecture:** Define the necessary toolchain architecture to facilitate the development and testing of trustworthy AI-based CCAM solutions.
- **ICT Framework:** Develop an ICT framework for data management, AI lifecycle management, and tool deployment.
- **Physical Testing Tooling:** Specify the infrastructure and software tools required for the generation of real and virtual datasets.
- **Vehicle Setup:** Prepare and make available reference vehicles with advanced architectures and sensor setups to support the development and validation of AI-based CCAM technologies.
- **Physical Infrastructure:** Establish and provide access to controlled testing environments and infrastructure for safe and effective physical testing.
- **Virtual Tools**: Set up and configure existing simulation platforms to support digital testing and validation activities.
- **Cloud Infrastructure:** Deploy cloud infrastructure and MLOps tools to support scalable, efficient, and robust testing and validation processes.

2. Structure of the deliverable

This deliverable is structured around three interdependent tasks within WP4 that together form a robust testing framework for AI-based CCAM systems (Figure 1).

Task 4.2 focuses on physical testing preparation by equipping test vehicles with sensor configurations designed to meet stakeholder requirements and collecting driving data on real roads as well as in controlled facilities to support the use cases defined in WP5.

Task 4.3 is dedicated to developing an advanced simulation infrastructure that leverages digital twin technology to replicate a range of driving scenarios—including challenging environmental conditions and system variations—using proven simulation toolchains.

Task 4.4 bridges the physical and virtual domains by deploying XiL (X-in-the-loop) setups, which integrate physical components such as sensors and ECUs with simulation models, enabling early prototype validation through Driver-in-the-Loop and Vehicle-in-the-Loop configurations.

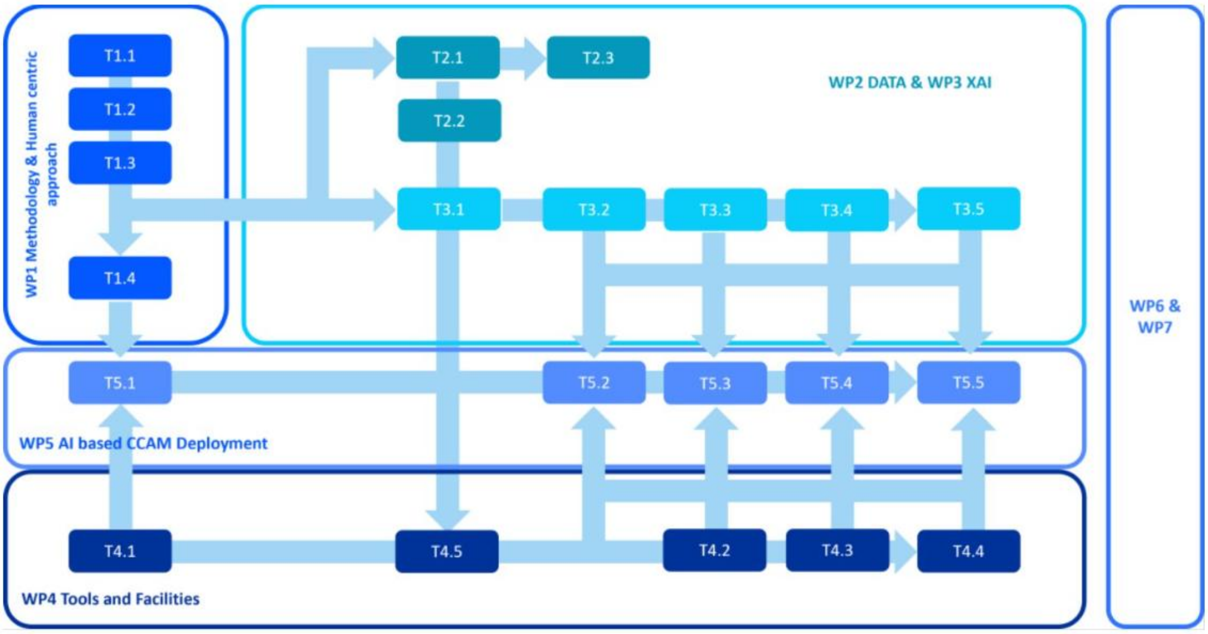

Figure 1: AITHENA architecture, showcasing the relationship of tasks T4.2, T4.3, T4.4 with WP5.

3. Physical testing preparation

3.1 Design and test vehicle setup

The selection of the test vehicles used within the AITHENA project reflects the diverse Use Cases requirements, which were essential for addressing the specific needs of the project stakeholders. Each vehicle was chosen based on its suitability for the development of AI-based CCAM functionalities, including perception, control, and V2X communication, across various testing environments. More specifically, Siemens-BE selected the Kia EV6 primarily due to its ability to draw power directly from the vehicle's battery, providing energy supply to the perception sensors installed on the roof rack as well as to the data acquisition system. The sensors chosen were selected according to the requirements defined based on the partner's feedback in deliverable D2.1.

Similarly, the Ford Fusion, utilized as VIF's demonstrator test vehicle, was selected due to its adaptability for hardware modifications and its capability to support scenario-awareness functionalities, both essential for testing advanced perception systems. VIF's hardware configuration was explicitly designed to enable real-time measurements and processing capabilities, which are necessary for accurately localizing the demonstrator vehicle and precisely tracking its surrounding actors.

A Volkswagen Multivan eHybrid was selected as the basis for ika's test vehicle. The vehicle was chosen on the basis of various criteria. Firstly, it will be used in Use-Case 3 where the possibility of software-based vehicle guidance with closed-loop control is a prerequisite. With its Drive-by-Wire interface it. offers this possibility. In addition, the hybrid powertrain allows sufficient electrical power output to operate sensors and computing hardware while the vehicle provides enough space to integrate additional measurement technology and computing hardware.

Finally, IDIADA selected the Kia Niro HEV primarily because of its practicality, existing familiarity, and verified compatibility in accessing the CAN bus. IDIADA's test vehicle was configured in such a way to facilitate functionalities related to Perception, Control, and V2X communication, thus enabling accurate understanding of the surrounding environment, controlling the trajectory of the CAVRide, and supporting communication with other vehicles.

3.1.1 Vehicle Setup (SIEMENS-BE)

The test vehicle selected by SIEMENS-BE during the AITHENA project was a Kia EV6 model (Figure 2). This choice was influenced by multiple factors, such as the ability to draw 230V power from the car battery or the trunk area, facilitating the installation of large AV equipment. Another reason was that previous Kia models have demonstrated suitability to be transformed into an experimental full AV.

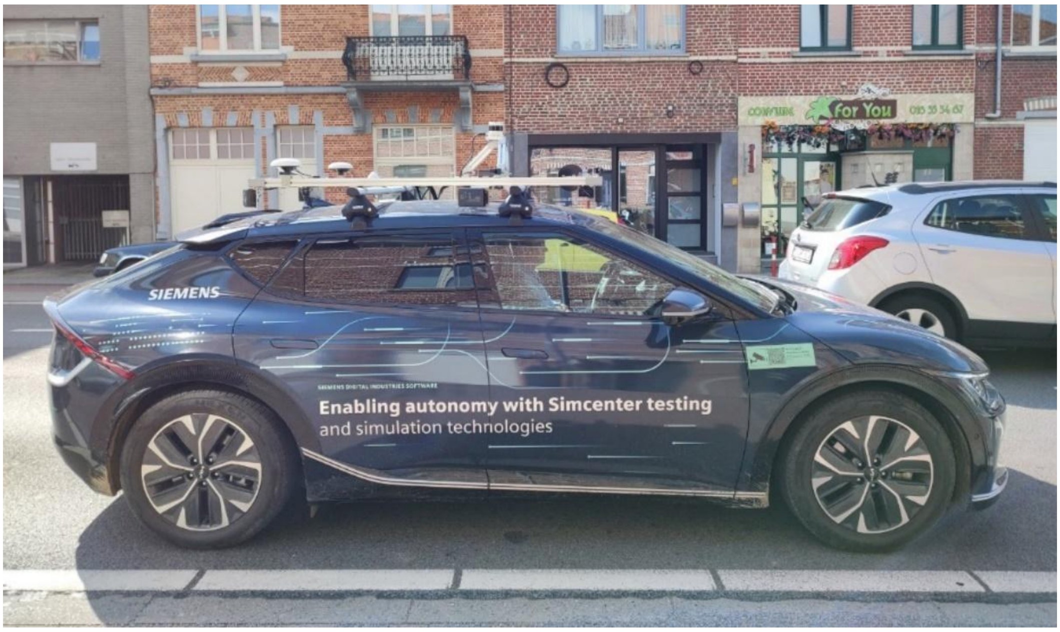

Figure 2: SIE-BE KIA EV6 test vehicle

The vehicle is extended with a vehicle roof rack for supporting perception sensors, as well as a device rack in the trunk for auxiliary equipment. A laptop tray has been integrated into the back seat that allows control of the setup from the back seat, as the front one is typically occupied by test occupants.

The 230V power supply is split and transformed through a transfer switch into three separate power flows at 12 V, 25.6 V, and 230 V. This is necessary to power all the different sensors and the data acquisition system. Non-critical loads can be switched off in case of peak load delivery. The integrated power circuit has the possibility to switch between in-vehicle power and external shore power to not drain the battery at a prolonged standstill.

With this vehicle setup, SIEMENS-BE can generate multiple types of measurements, such as vehicle dynamics and environmental data. For the vehicle dynamics, two 3D accelerometers are utilized, one attached at the seat rail and one on the roof rack, with sampling frequency at 120Hz.

The vehicle surroundings are measured using a robust combination of several sensors (Figure 3). Six cameras are mounted on the roof rack, ensuring a 360-degree field of view. Five radars are utilized for relative velocity/acceleration estimation of any external moving object, as well as for increasing the robustness of the perception stack in case of limited visibility from the other sensor modalities. A solid-state and a mechanical spinning LiDAR are used for precise object detection and tracking of actors in the environment. A high-precision GPS device is also used for accurate localization of the ego vehicle.

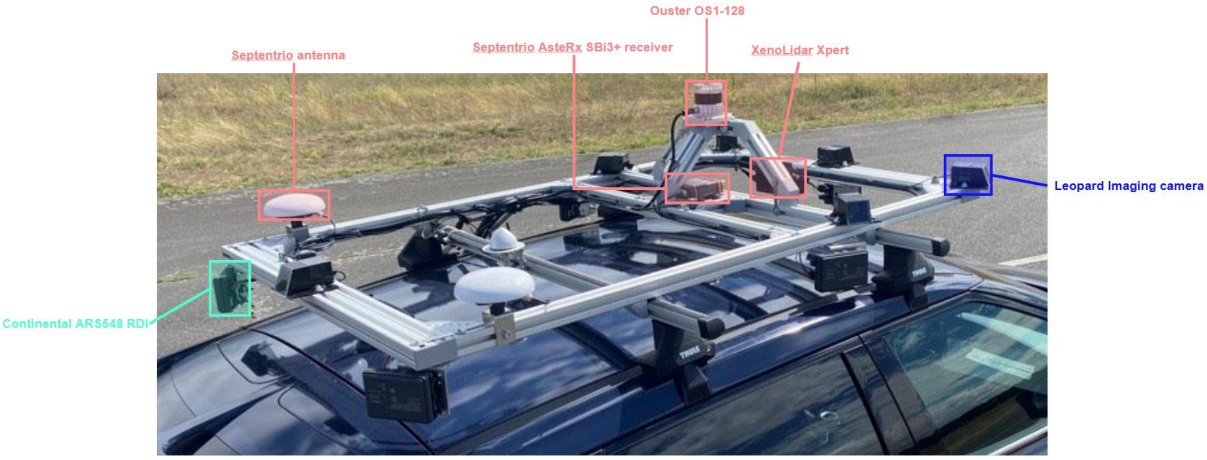

Figure 3: Perception sensors mounted in the SIE-BE roof rack

Two data acquisition systems were utilized for the setup described in the previous paragraph. An overview is given in Table 1. The AV Siemens data acquisition system stores all the perception and GNSS/IMU data as MCAP files while the Simcenter SCADAS device is used to capture the 3D accelerometer data from the roof rack and the seat rail and they are saved as ldsf files. The data from both the two data acquisition systems are stored in data storage disks using 100GbE and USB connection and they can be merged based on the corresponding timestamps in a single MCAP file.

A grand master clock device, using GPS as its time reference, orchestrates the timing pulses across the various components. The time synchronization between the different sensors and acquisition systems is achieved using PTP (Precision Time Protocol). The Septentrio Asterx Sbi3+ GNSS/INS unit is serving as the master clock by transmitting the time information via SBF messages to the SIEMENS-BE data acquisition system. Once synchronized, the data acquisition system then forwards the time reference to the other sensors via PTP, ensuring accurate timestamping across all data streams.

Sensor	Transfer mode	Logging device	Time synchronization
Camera (Leopard Imaging)	GMSL2/10- GBE	SIE data acquisition	PTP
Radar (Continental ARS548)	BRR/10 GBE	SIE data acquisition	PTP
Lidar (OS1-128)	10 GBE	SIE data acquisition	PTP
GNSS (Septentrio AsteRx Sbi3+)	1 GBE	SIE data acquisition	(time reference)
XenoLidar Xpert	10GBE	SIE data acquisition	PTP
Accelerometers	Analog	SCADAS	IRIG-B

Table 1: Overview of the sensor communications with the logging devices.

A detailed technical specification of each sensor installed on the SIE-BE test vehicle during the AITHENA project is provided in Table 2, defining the sensor configuration employed during data collection and testing activities.

Cameras	
Model	5x LI-IMX424-FPDLINKIV-065H 1x LI-IMX424-FPDLINKIV-120H
Resolution (H x V Pixels)	3849 x 1929
Pixel Size (H x V)	2.25 µm x 2.25 µm
Frame Rate	20
Field of view (Horizontal)	5 x 65º + 1 x 120º
Ouster Lidar	
Model	Ouster OS1-128
Dimensions (Diameter / Height)	85 mm (3.34 in) / 73.5 mm (2. 9 in)
Weight	447g
Vertical Resolution	128 channels
Horizontal Resolution	1024
Field of View (Vertical / Horizontal)	45.5º (+22.5° to -22.5°) / 360º
Range (Minimum / Maximum)	1 m / 120 m
Range Resolution	0.3 cm
Rotation Rate	20 Hz
Laser Wavelength	865 nm
Points Per Second	2,621,440 (128 channel)
Data Per Point	Range, signal, reflectivity, near-infrared, channel, azimuth angle, timestamp
Timestamp Resolution	< 1 µs
Data Latency	< 10 ms
Continental ARS548 RDI	
Dimensions	137 x 90 x 39 mm
Min/Max Range	0.2-301m
Range resolution	0.22
Range accuracy	0.15m
Azimuth FOV/resolution/accuracy	100/0.1/±0.1- ±0.5 deg
Elevation FOV/resolution/accuracy	30/0.1/±0.1 deg
Min/Max speed	-400/200 kph
Doppler resolution	0.35 kph
Speed accuracy	±0.03 m/s

Output rate	20 Hz
XenoLidar Xpert	
Detection range	Up to 150m
Field of view	30 x 10 deg
Angular resolution	0.15 x 0.15 deg
Output rate	20 Hz

Table 2: Technical specifications of each perception sensor mounted on the SIE-BE test vehicle.

To enable accurate sensor fusion within the AITHENA project, a calibration process was established. Since the perception sensors on the SIE-BE vehicle are based on diverse technologies, the calibration procedure was specifically tailored to account for the unique perception principles of each sensor separately. Furthermore, the sensors were strategically positioned on the vehicle to ensure optimal coverage and high performance in both perception and data recording (Figure 4). A single calibration target, detectable by all sensors, was also utilized to ease calibration process across the entire sensor suite.

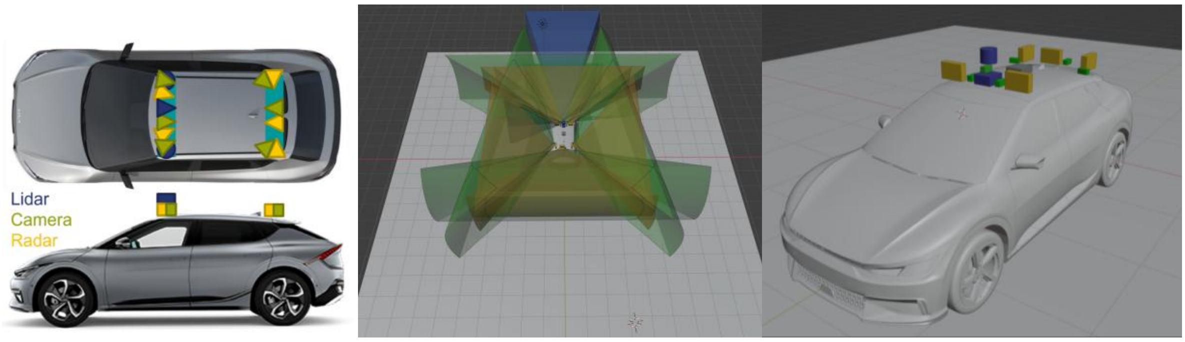

Figure 4: Sensor positions and the corresponding field of views of the SIE-BE test vehicle

3.1.2 Vehicle Setup (VIF)

The demonstrator vehicle VIF selected for this project is a Ford Fusion, chosen due to its suitability for modifications that accommodate additional hardware components. The modifications involve the implementation of a comprehensive hardware and software architecture, specifically designed to enable advanced perception and scenario-awareness functionalities. The following sections detail the hardware configuration necessary to achieve the UC2.2's scenario awareness-related objectives.

Intended use and scope

The VIF demonstrator vehicle primarily focuses on evaluating scenario-awareness functionalities, underpinned by a comprehensive perception system. Consequently, the described hardware setup is designed to facilitate real-time measurement recording and processing, crucial for accurate localization of the demonstrator vehicle and detailed tracking of its surrounding environment.

Vehicle modifications and sensor placement

The vehicle has been equipped with a roof rack to accommodate additional sensors critical for perception tasks. Specifically, this includes four lidar sensors (three Ouster OS0-64 and one Ouster OS2-128 units in total) and six TIER IV C1 camera units, strategically placed to ensure comprehensive 360-degree environmental coverage and optimized field-of-view performance. Further radar sensors (eight units) have been mounted around the vehicle, comprising short-range radars (four Smartmicro), long-range radars (two Smartmicro and Continental ARS408), and a high-performance radar (Continental ARS548). The placement of all sensors can be seen on Figure 5, while a detailed technical specification of the aforementioned sensors is provided in Table 3.

This extensive sensor set-up is a standard practice in advanced autonomous vehicles, providing redundancy and reliable perception capabilities even under challenging environmental conditions.

Additionally, a display visible (see Figure 6) to the driver and passenger was added to provide real-time visualization of the surrounding environment via point cloud representation, significantly enhancing scenario-awareness.

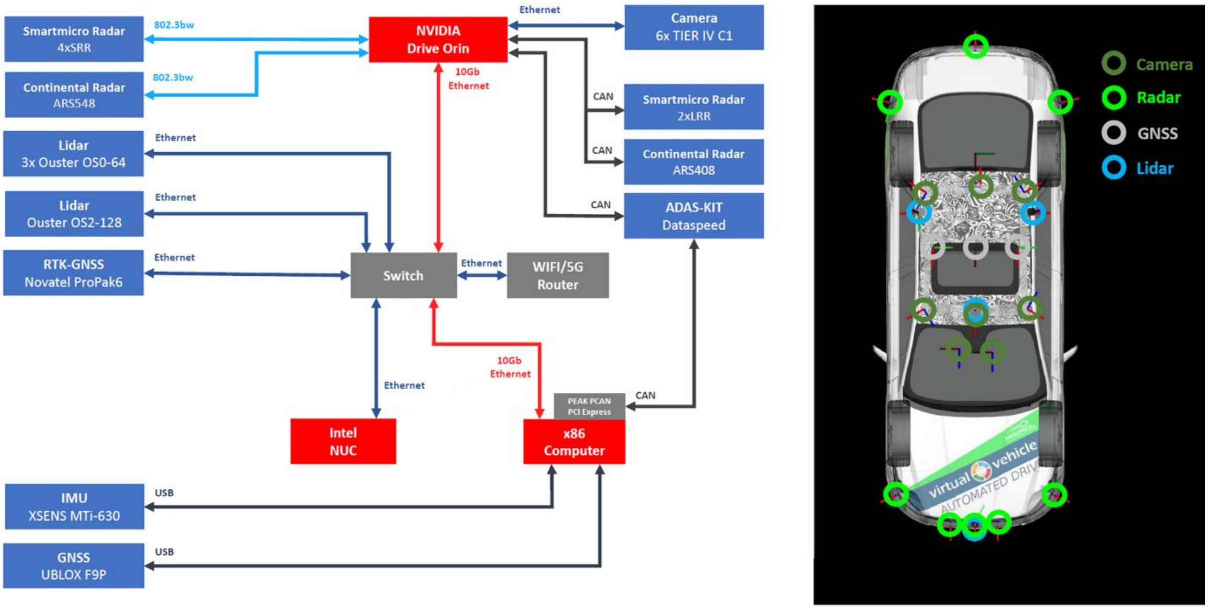

Figure 5: Hardware overview

Figure 6: External and internal set-up of the demonstrator vehicle

Camera	
Model	Tier IV C1-085
Camera size [mm]	38.5 x 38.5 x 43.21
Field of View (FoV) [°]	LDC off 85; on 78
Output frame rate [fps]	Up to 30
Output image size [px]	1920 x 1280
Radar	
Model	Continental ARS548 / Continental ARS408 / Smartmicro UM11 / Smartmicro UM96
Operational frequency [GHz]	77 / 77 / 24 / 77…81
Outline dimensions [mm]	137 x 90 x 39 / 138 x 91 x 31 / 110 x 99 x 31 / 97 x 76 x 17.7
Range (Minimum – Maximum) [m]	0.2 – 300 / 0.2 – 250 / 1 – 180 / 0.15 – 19.3
Range resolution [m]	0.22 / 0.39 / 2.06 / <0.3
Range accuracy [m]	±0.15 m / ±0.1 m / < ±0.25 / < ±0.15
FoV in Azimuth [°]	±60 / ±60 / ±50/ ±65
FoV in Elevation [°]	±4 at 300 m; ±14 at <100m / 14 at far range; 20 at near range / ±12 / ±7.5
Speed range (Minimum – Maximum) [km/h]	-400 – 200 / -400 – 200 / -320 – 320 / -400 – 140
Speed resolution [km/h]	0.35 / 0.43 / 1.26 / 1.08

Speed accuracy [km/h]	±0.1 / ±0.1 / <±1 / <±0.54
Lidar	
Model	Ouster OS0-64 / Ouster OS2-128
Dimensions (Diameter; Height) [mm]	87; 58.35 / 119.6; 98.9
Weight [g]	430 / 1100
Vertical resolution [channels]	64 / 128
Horizontal resolution	512, 1024 or 2048 (configurable)[1]
FoV vertical (Minimum – Maximum) [°]	-45 – 45 / -11.25 – 11.25
FoV horizontal [°]	360
Range (Minimum – Maximum) [m]	0.3 – 207 / 0.8 –350
Range resolution [m]	0.1 / 0.001
Rotation rate [Hz]	10 to 20
Laser wavelength [mm]	865
Points per second	1,310,720 / 2,621,440
Data per point	Range, Signal, Reflectivity, Near-infrared, Channel, Azimuth angle, and Timestamp
Timestamp resolution [µs]	< 1
Data latency [ms]	<10

Table 3: Technical specifications of each perception sensor mounted on VIF's test vehicle.

Power supply

All components draw power from the vehicle's low-voltage system (12V). No additional batteries or high-capacity generators have been integrated. Depending on individual component requirements, power is sources from the vehicle's board net (~9-14V) with constant 12V or 24V outputs.

Localisation and ground truth

For accurate localization and ground truth validation, the vehicle integrates three GNSS units, including an RTK-GNSS (Novatel ProPak6) and a standard GNSS module (UBLOX F9P). Additionally, an XSENS MTi-630 IMU supports inertial data integration, enabling precise positioning and orientation measurements.

Computing infrastructure

The trunk of the demonstrator vehicle houses a central control and computing infrastructure. This includes:

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[1] Note: Specification values that are same for all models are noted only once in the table.

- NVIDIA Drive Orin: Used primarily for sensor interfacing (especially CAN and Automotive Ethernet)

  Intel NUC: Responsible for data recording and visualization for the rear seats.

- x86 Computer: Main computing platform running the full autonomous driving stack. Responsible for executing perception algorithms and processing all sensor data. Also serves as the system's time synchronization source.

Communication and networking

Data communication between sensors and computing infrastructure is primarily facilitated via Ethernet, including high-speed 10Gb Ethernet for data-intensive streams, and CAN bus for lower-bandwidth sensor interactions. The vehicle also includes a Wi-Fi/5G router for remote data access and diagnostics.

Time synchronization is managed by the x86 computer, which acts as the central time source. Components within the vehicle are synchronized using PTP and NTP, while the x86 system itself is synchronized via internet-based time services.

Data recording and processing

The system operates entirely within the ROS 2 framework and the data is recorded using ros2 bag record and stored in the MCAP format with timestamps. The architecture supports the recording of both raw sensor data (e.g., images, point clouds, CAN messages) and processed outputs (e.g., object lists, planned trajectories, control signals).

3.1.3 Vehicle Setup (IDIADA)

For the implementation and testing activities within the scope of the AITHENA Project, IDIADA selected a Kia Niro as the primary development platform. The choice of this vehicle was driven by a combination of technical and practical factors. Most notably, IDIADA had prior experience and access to tools enabling low-level access to the vehicle's internal communication network (CAN bus). This access was made possible through existing decoding protocols and support, notably facilitated by prior collaboration and technical insights from Toyota, which provided compatibility references useful for interpreting CAN messages in the Kia platform.

To reflect its role as a Connected and Automated Vehicle (CAV) demonstrator, the vehicle was internally designated "CAVRide". This naming convention symbolizes its dual role as both a platform for testing automated driving technologies and a representative prototype in the broader context of CAV research and development.

The Kia Niro HEV underwent a comprehensive transformation to align with the technical objectives and requirements of the project. This adaptation process encompassed the design and integration of a modular software and hardware architecture, deployment of a range of sensors, and implementation of a robust data logging infrastructure.

The platform is developed considering three different sub-systems: Perception, Control and V2X communication. The purpose of which is to perceive the operational domain/ environment, control the CAVRide's trajectory and to communicate with other vehicles.

Most of the equipment is installed on the rack in the trunk of the car, except the perception components like the Lidar, cameras and Radar which are on the roof and the front of the vehicle respectively.

The electrical architecture of all the systems is directly supplied by the vehicle and capable of providing 12 V DC up to 1000 W power consumption without needing any external power supply. Both the electrical and communications architecture have been designed to withstand a very noisy environment where many sensitive sensors and power electronics must coexist.

The CAVRide is also equipped with high-speed Wi-Fi enabled by Idiada's own 5G network and public cellular networks.

Two Full HD screens have been installed in the rear seats of the test vehicle for the test engineers to display both perception and control related data in real time, making prototyping tasks much easier.

The CAVRide is capable of C-V2X communications, enabling it to send and receive Cooperative Awareness Messages (CAMs) to and from other vehicles.

To validate the perception system having a Ground Truth is vital, so the CAVRide is also equipped with a high precision Differential GPS (DGPS) that can connect to the Idiada Proving Ground reference stations and to other vehicles equipped with DGPS to obtain relative positioning.

The following subsections detail each component of this adaptation:

CAVride architecture

The CAVRide system architecture was designed to support modular integration of perception, decision-making, and actuation layers. The architecture comprises the following main subsystems:

- On-board computing platform: Industrial-grade automotive PC (BRAV-750) running middleware (e.g., ROS) for data handling and algorithm execution.
- CAN gateway interface: Custom interface enabling bidirectional communication with the vehicle's CAN bus for both reading sensor and actuator data and injecting control commands.
- Power management system: Ensuring stable power supply to added sensors and computing units without interfering with OEM electrical systems.

CAVride sensor specification

To enable perception and positioning capabilities required for Connected and Automated Vehicle (CAV) functionalities, IDIADA's CAVRide has been equipped with a set of carefully selected sensors (Figure 7). These sensors support object detection, environment mapping, and precise localization. The full sensor suite installed on the vehicle is as follows:

- **Ouster OS128 LiDAR (Ouster OS2 long-range):** a high-resolution 3D LiDAR sensor providing 128 channels for dense point cloud generation. It is used for environment perception, object detection, and spatial mapping.

- **ARS408 Radar:** an automotive-grade radar unit supporting robust detection of dynamic objects under various weather and lighting conditions. It enhances vehicle awareness in mid- to long-range scenarios.

- **Basler Cameras (a2A1920-51gcPRO Basler):** three industrial-grade cameras are mounted on the vehicle, 2 lateral-facing cameras for peripheral object tracking and lane detection, 1 front-facing camera for forward vision tasks, including scene understanding and traffic sign recognition.

- **Mobileye EyeQ8:** an advanced vision processing unit that provides real-time perception capabilities such as lane keeping, vehicle and pedestrian detection, and semantic understanding of the driving scene.

- **OxTS RT3000 GNSS/INS:** a high-precision GNSS receiver integrated with an Inertial Navigation System (INS), used for accurate vehicle localization and trajectory tracking. This system ensures high fidelity ground truth data for validation purposes.

Figure 7: IDIADA's CAVRide sensor setup.

IDIADA's main contribution to this task has been to provide recorded sensor data to project partners SIE-NL and VICOMTECH, for use in the development and validation of their algorithms. The data has been collected using the sensors and formats specified in Table 4.

Sensor	Data Type	Transfer Mode	Time Synchronization
Ouster Lidar OS128	Pointcloud	Ethernet	PTP from PC
Front & Lateral Cameras	Video	Ethernet	PTP from PC
RT3000 GNSS/INS	Position and kinematics of the ego and target vehicle	CAN	Master Clock to PC with NMEA

Table 4: CAVride sensors and format used for the AITHENA project.

Time synchronization across all sensors was managed using PTP (Precision Time Protocol). The RT3000 GNSS/INS unit acted as the master clock, distributing time via NMEA messages to the recording PC. The PC, once synchronized, distributed the time reference to other sensors using PTP, ensuring coherent timestamping across all data streams.

Table 5 provides detailed technical specifications of each sensor installed on the CAVRide vehicle used during the AITHENA project. These specifications define the sensor capabilities used during data collection and testing activities.

Cameras	
Model	Basler a2A1920-51gcPRO ace 2 GigE camera
Size (L * W * H) / Weight	62.2 * 29 * 29 mm / < 105 g
Resolution (H x V Pixels)	1920 x 1200
Pixel Size (H x V)	3.45 µm x 3.45 µm
Frame Rate	Up to 24 Hz (depending on light conditions – exposure time)
Field of view (Vertical / Horizontal)	54.3º / 79º
Lense	C125-0418-5M-P f4mm
Lidar	
Model	Ouster OS2-128
Dimensions (Diameter / Height)	119.6 mm (4.71 in) / 98.9 mm (3.89 in)
Weight	1100
Vertical Resolution	128 channels
Horizontal Resolution	1024
Field of View (Vertical / Horizontal)	22.5º (+11.25° to -11.25°) / 360º
Range (Minimum / Maximum)	1 m / 240 m
Range Resolution	0.1 cm
Rotation Rate	10 Hz
Laser Wavelength	865 nm
Points Per Second	2,621,440 (128 channel)
Data Per Point	Range, signal, reflectivity, near-infrared, channel, azimuth angle, timestamp
Timestamp Resolution	< 1 µs
Data Latency	< 10 ms

Table 5: Detailed technical specifications of each sensor installed on the CAVRide for the AITHENA project.

The placement of the sensors on the CAVRide vehicle has been carefully designed to ensure optimal coverage and performance for perception and data recording purposes. Figure 8 illustrates the physical location of the LiDAR and camera sensors on the vehicle. Squares represent the positions of the installed cameras (Basler units) and the Circle represents the location of the LiDAR sensor (Ouster OS128).

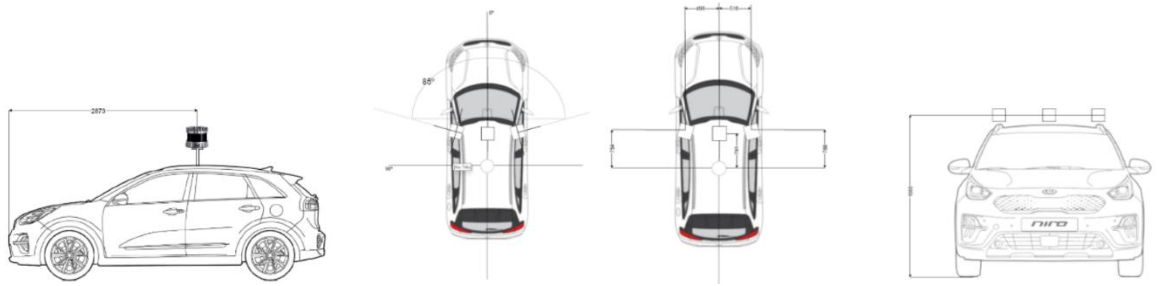


Figure 8: IDIADA's CAVRide sensor placement

CAVRide logging system

The data logging system implemented by IDIADA for the CAVRide vehicle is based on the Robot Operating System (ROS1) framework. All sensor data was recorded using standard ROS1 message types, ensuring compatibility and ease of integration with partner systems and tools.

The logging system was configured to capture data streams in real time, adhering to the message types and frequency rates outlined in Table 6 below.

Sensor	Message Type	Rate (Hz)	Description
Camera (front and lateral)	sensor_msgs/CompressedImage.msg https://docs.ros.org/en/noetic/api/sensor_msgs/html/msg/CompressedImage.html	24	Camera image
Camera (front and lateral)	sensor_msgs/CameraInfo.msg https://docs.ros.org/en/noetic/api/sensor_msgs/html/msg/CameraInfo.html	24	Information about the camera
Lidar	sensor_msgs/PointCloud2.msg https://docs.ros.org/en/noetic/api/sensor_msgs/html/msg/PointCloud2.html	10	Lidar Pointcloud
RT3000	gps_common/GPSFix.msg https://docs.ros.org/en/jade/api/gps_common/html/msg/GPSFix.html	100	GPS data

Table 6: CAVRide logging specifications.

Table 7 describes the messages that have also been recorded.

Message Type	Description
tf2_msgs/TFMessage.msg https://docs.ros.org/en/noetic/api/tf2_msgs/html/msg/TFMessage.html	Transformed Frames, for sensor relative positions to each other
std_msgs/String.msg https://docs.ros.org/en/noetic/api/std_msgs/html/msg/String.html	Test type, to indicate to which test the recording belongs.

Table 7: CAVRide logging specifications.

The rate for these ones has not been written because they were only transmitted once and at the beginning of the recording.

All sensor data described above was originally recorded using ROS1 in the form of rosbag files. To maintain consistency across the project and ensure interoperability with other partners' tools and workflows, the common data format adopted by the project is MCAP. To address this difference, IDIADA developed a conversion tool leveraging the MCAP Python library. This tool automates the transformation of raw. rosbag recordings into the standardized. MCAP format, preserving all relevant messages and timestamps for seamless integration.

Figure 9 illustrates the workflow of this conversion process.

Figure 9: IDIADA conversion pipeline from. rosbag to. MCAP format.

This approach ensures that data collected by IDIADA can be readily shared and processed by all project partners.

3.1.4 Vehicle Setup (ika)

In Phase II of the AITHENA Cycle, there has been a notable change compared to ika's initial project plan: Due to age and technical limitations, ika's research vehicle, a VW Passat CC, was replaced by a modern vehicle, which has been converted into a research vehicle for various CCAM applications.

The new test vehicle is based on a Volkswagen Multivan eHybrid. The vehicle was selected with respect to various criteria: most important was the ability to manipulate the lateral and longitudinal dynamics of the vehicle through automated driving software. Next to this the vehicle offers the possibility of sufficiently high electrical power drawn from the on-board electrical system. For this reason, the plug-in hybrid drivetrain was selected, which also makes it possible to operate the vehicle purely electrically.

Finally, the vehicle offers sufficient space to install measurement equipment, additional energy storage and processing hardware. The Multivan meets these requirements and enables the additional hardware to be mounted properly thanks to the built-in mounting rails. The vehicle is called *karl*., hence this name will be used in the following. In the following sections, the installed hardware and components will be briefly explained.

Intended use and scope

karl. is intended to be used as demonstrator of the AITHENA Use-Cases 1 and 3. Especially for UC3 the possibility to run the developed Algorithms in a closed control-loop, meaning that the software controls the vehicle dynamics, is a necessary requirement. Next to a drive-by-wire system, *karl*. is equipped with various devices for energy supply, processing, internal and external communication as well as sensors for environmental perception. The vehicle setup is explained in the following sections.

Environmental sensors and localization

Figure 10 shows the sensor-rack of *karl*. which is used to mount various sensors for environmental perception as well as antennas and a rooftop-box. The rack holds four Ouster OS1 360° LiDAR Sensors mounted on all corners of the rack for 360° coverage. In addition, the rack holds 8 StereoLabs ZED X stereo-cameras for 360° field of view. For energy supply and signal-distribution of the sensors, a sealed stainless-steel box is mounted in the center of the rack. The box contains two NVIDIA Jetson Orin for image pre-processing, a network switch and various components for energy supply of the sensors.

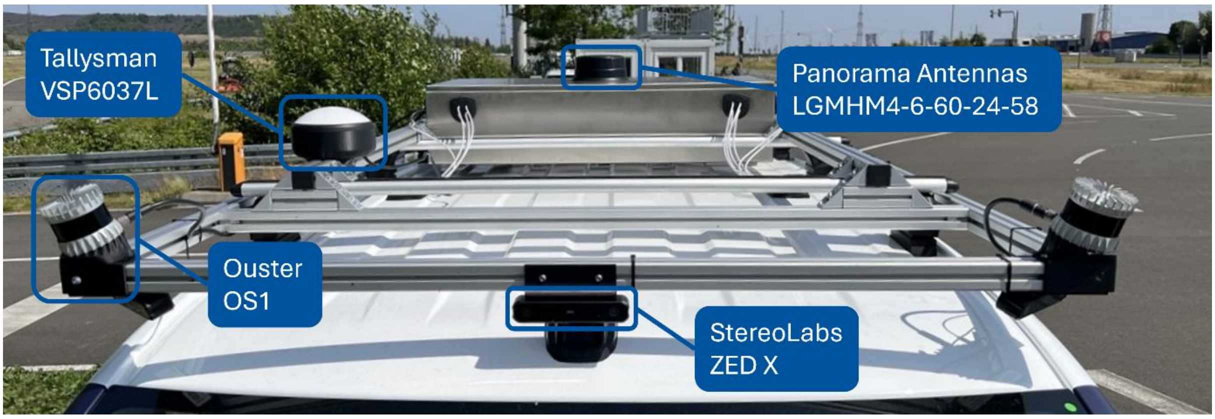


Figure 10: Sensor-Rack with various environmental sensors, antennas and rooftop-box for power- and signal-distribution.

In addition to the roof-mounted sensors, *karl*. is equipped with five radar sensors in total, one front facing Altos V2 imaging radar, two smartmicro DRVEGRD 169 in the corners of the front bumper and two smartmicro DRVEGRD 152 in the corners of the rear bumper.

For localization and vehicle state estimation, an SBG Systems Ekinox Micro INS is mounted in the trunk of the vehicle. Two GNSS antennas are mounted on the sensor rack.

Data processing and networking

For sensor data processing and execution of the various modules of the automated driving system, a computer is installed in the trunk of the vehicle. The computer is connected to an ethernet switch, connecting the rooftop switch, devices for external communication, the INS and the radar sensors. For energy supply of the additional vehicle hardware, a lithium iron phosphate battery with inverter and corresponding charging hardware was installed in the trunk. The secondary battery can be charged both from the vehicle's electrical system and from shore power, allowing continuous operation of the additional hardware.

External communication

For external communication, e.g. with other road-users, digital infrastructure or cloud-servers, *karl.* is equipped with two additional devices: An Ericsson Cradlepoint R1900 is used for cellular communication and general connectivity of the vehicle, while a Cohda Wireless MK6 on-board unit is used for V2X communication via ITS-G5 and/or C-V2X. Both devices are connected to a combination antenna mounted on top of the stainless-steel box on the vehicle roof (cf. Figure 10).

3.2 Data collection and testing infrastructure

3.2.1 Proving ground

Applus+ IDIADA operates a 370-hectare multi-user proving ground where safety and confidentiality are paramount. The facility features first-class test tracks, fully equipped confidential workshops, and delivers the highest level of customer support to ensure seamless execution of testing programmes.

Located near the Mediterranean coast, the proving ground benefits from a favourable climate that enables all-year-round testing. Warm summers support hot climate testing, while mild winters allow development activities to continue without interruption, making Applus+ IDIADA the preferred choice for a wide range of testing needs.

IDIADA brings extensive experience in vehicle testing and validation, leveraging world-class proving grounds and specialized facilities across Spain. These include multiple proving tracks designed to replicate diverse real-world driving conditions, facilitating comprehensive assessment of automated and connected vehicle technologies.

3.2.2 Test Scenarios

The test scenarios described in Table 8 have been recorded by IDIADA within the scope of this project to support development, validation, and demonstration activities.

Regulation or Protocol	Target Type	Test Scenario
Regulation UN Nº 152	Car to Car	CCRs
Euro NCAP 2023 Car to Car	Car to Car	CCRs offset -50
		CCRs offset -75
		CCRs offset 75
		CCRs offset 50
Regulation UN Nº 152	Car to Car	CCRm
		CCRm offset -50
		CCRm offset -75

		CCRm offset 75
		CCRm offset 50
		CCRb
		CCRb offset -50
		CCFtap
Regulation UN Nº 152	Pedestrian	CPNC
Euro NCAP 2023 VRU	Pedestrian	CPNCO
		CPFA
		CPNA25
		CPNA75
Regulation UN Nº 152	Cyclist	CBNA
Euro NCAP 2023 VRU	Cyclist	CBFA
		CBNAO

Table 8: IDIADA recorded proving ground scenarios for the AITHENA project [UN-ECE 2023][Euro NCAP 2025].

All recorded data has been securely stored in the AWS bucket established as part of Task 4.5. The datasets are available in the project's standard MCAP format to ensure compatibility across partners.

Each recording follows a standardized naming convention designed to facilitate easy identification and retrieval. This convention encodes key information such as the test date, sensor suite, test scenario, and version number. A comprehensive document accompanies the dataset, providing detailed descriptions of each recording's name, content, and metadata.

This structured approach guarantees transparent data management and supports efficient use by all project participants.

3.2.3 Public measurements

SIEMENS-BE captured a diverse range of realistic and operational design domain (ODD) scenarios across Flanders, Belgium. Recording on public roads inevitably introduces significant variability, making it nearly impossible to replicate controlled test scenarios like in closed proving grounds. In urban environments, driving conditions usually create a superposition of driving scenarios that reflect the complexities of real-world situations.

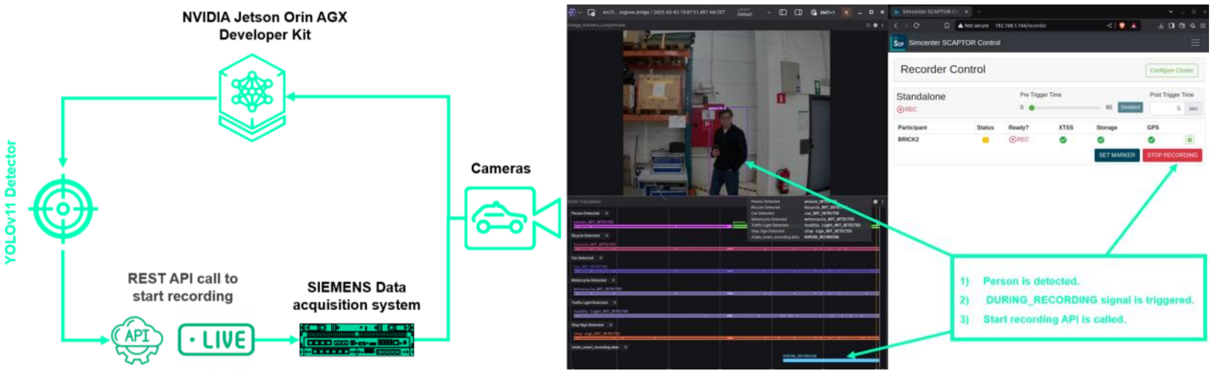
Thus, in the measurement campaign SIE-BE focused on comprehensive data collection in urban environments rather than targeting specific scenarios. This approach allowed us to capture a wide range of driving behaviours and incidents, without the constraints of reproducing identical test scenarios. The resulting dataset serves as a base for developing scenario detection algorithms, which in a later stage will differentiate the varied scenarios to a specific category.

3.4 Smart recording approaches

3.4.1 Smart triggering (SIEMENS-BE)

Integrating intelligent triggering mechanisms into an autonomous vehicle's data acquisition system is a crucial step towards maximizing resource optimization and strengthening overall system performance. More specifically, these smart triggering mechanisms can improve data selection and reduce data storage usage, allowing AV systems capturing only corner cases that are considered vital for training and validation of AI-based CCAM systems. By utilizing camera-based perception algorithms, which include detection of static or dynamic actors, or infrastructure works such as traffic cones or roadworks, AV systems can identify and respond accordingly to safety-critical events.

In Task 4.2, Siemens-BE developed an intelligent data recording system architecture using Siemens data acquisition system (see Figure 11). The smart triggering mechanism consists of NVIDIA Jetson Orin AGX Developer Kit which is employed to run a YOLOv11 object detection model and make the API calls for starting or stopping a recording of Siemens data acquisition system. The YOLOv11 model can detect pedestrians, cars, trucks, traffic signs and lights, motorcycles, and bicycles. The NVIDIA Jetson Orin device has a dedicated camera which is utilized for this task in addition to the sensor setup described in section 3.1.1. A visualization of the described procedure is shown in Figure 11. First, a person (or a pedestrian) is shown in the scene. Then, YOLOv11 detects the person and triggers a DURING_RECORDING flag which makes a REST API call to start a recording in the data acquisition system. The data recording continues as long as the object remains within the camera's field of view. Once the actor goes out of the scene, a STOP_RECORDING flag is triggered, and a second REST API call is made to stop the recording.



1) Person is detected.
2) DURING_RECORDING signal is triggered.
3) Start recording API is called.

Figure 11: schematic diagram of the smart recording pipeline and a demonstration of the smart triggering tool when an actor is detected in the scene

4. Simulation infrastructure, generation of digital twin including adverse conditions and complex scenarios

4.1 Virtual validation of AI-based CCAM systems and synthetic data generation using simulation environments

4.1.1 Virtual testing environment for UC 3 and Digital Twin of IKA's Research Vehicle

Virtual testing and validation of CCAM systems is an essential step in the development process. The following paragraph describes ika's activities regarding simulation mainly contributing to the works done in WP3 and WP5 and especially UC3.

The resulting simulation environment, which was implemented as part of T4.3, has already been explained in Deliverable 5.2 - Report on initial use case evaluation, section 5.1. Therefore, the aspects described there are only briefly summarized in the following paragraph.

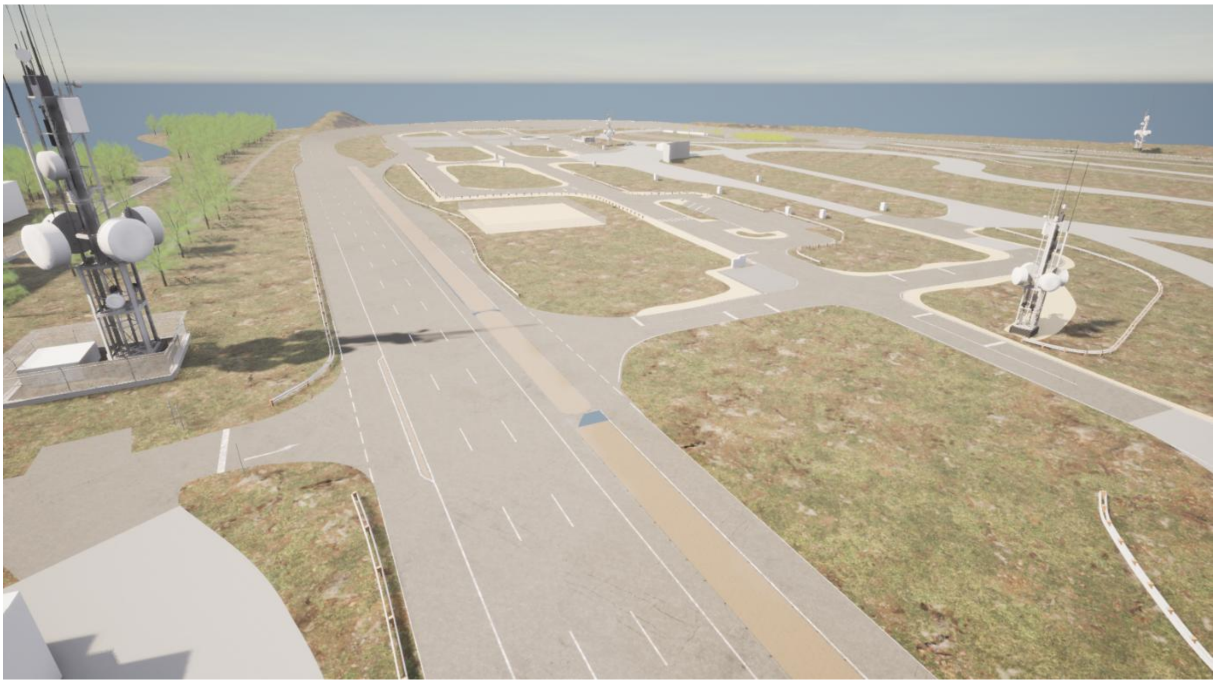


Figure 12: Aldenhoven Testing Center modelled in CARLA

Closed-loop simulations are crucial for the development of algorithms for behaviour planning and vehicle guidance. Especially AI-based approaches show difficulties in closed-loop performance. As adevelopment, testing and verification environment we use the open-source simulator CARLA [Dosovitskiy 2017]. Since the utilized driving stack is implemented based on a microservice architecture, we make use of CARLOS[2] [Geller 2024] providing a containerized framework building upon CARLA as simulation core. The simulation framework alongside the required modules of the driving stack related

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[2] https://github.com/ika-rwth-aachen/carlos

to UC3 has been provided to members of T3.5 and UC3 respectively. In addition to the implementation and provision of the simulation framework, the Aldenhoven Testing Center (ATC) was modelled as part of T4.3 to be able to simulate the UC3 scenarios accordingly (Figure 12).

In addition, a digital twin of *karl*. (cf. Figure 13) was created and integrated into CARLA as part of T4.3. The corresponding simulation model is to be used for the aforementioned closed-loop simulation in UC3. In addition, the digital vehicle model was used, for the simulation-based design of the position and orientation of sensors on the vehicle roof. It additionally served as a foundation to derive synthetic test-data for UC1, in order to facilitate the integration of the developed perception-models into the real-world vehicle.

Figure 13: Real-World vehicle (left) and its corresponding digital twin (right

4.2 Software toolchains for verification and validation of AV systems

4.2.1 Scenario virtualization

The collaboration between IDIADA and SIE-NL focused on the virtualization of the data recorded by IDIADA. To enable this process, IDIADA provided SIE-NL with the necessary input data, which included:

- MP4 video files from the cameras (front, right, and left perspectives).
- A timestamped CSV file containing GPS data (details summarized in the table below).
- Detailed sensor specifications.
- Exact sensor positions in the vehicle.
- Comprehensive descriptions of the testing scenarios.
- An Excel document serving as an index and metadata description of all provided files.

Using these inputs, SIE-NL was able to generate the corresponding OpenScenario and OpenDrive files from the measurement data, essential for accurate scenario virtualization and simulation.

To enable the virtualization process by SIE-NL, IDIADA extracted specific data from the original MCAP recordings. This extraction process is illustrated in the pipeline shown in Figure 14.

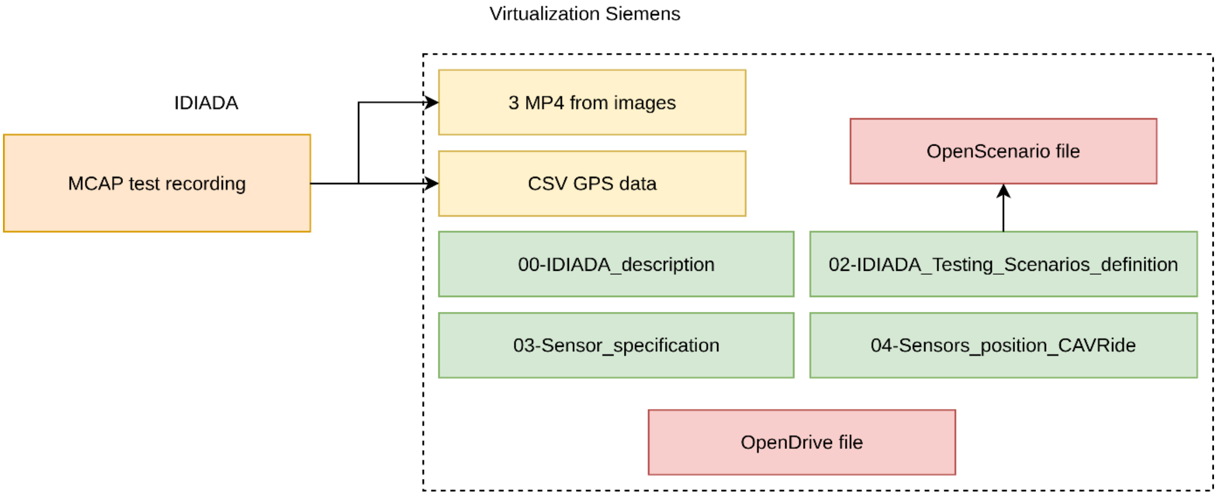


Figure 14: Virtualization process pipeline. In orange, the input data is in MCAP format. In yellow, the extracted data from the MCAP files. In green, the input data from IDIADA to be used for the OpenDrive and OpenScenario file generation on SIE-NL side.

Video frames were extracted from the image topics of the MCAP files and encoded into MP4 format. The frame rate was selected individually for each recording to balance quality and data volume, with an average value of approximately 13 frames per second (fps). GPS and motion data were extracted in CSV format, with each row representing a unique timestamp and associated measurement. Data was provided for both the ego and target vehicles.

The structure of the CSV file is described below in Table 9.

Field	Unit	Description
Timestamp	ns	Nanosecond timestamp of the measurement
Speed	m/s	Vehicle speed
Latitude	degrees	Geographical latitude
Longitude	degrees	Geographical longitude
Altitude	m	Altitude above sea level
Pitch	degrees	Vehicle pitch angle
Roll	degrees	Vehicle roll angle
Heading	degrees	Vehicle heading (yaw)
Vehicle	-	Vehicle role (Ego/Target)

Table 9: Data structure input for scenario virtualization.

This structured data enabled SIE-NL to faithfully reproduce and virtualize the recorded scenarios in simulation environments through the generation of OpenScenario and OpenDrive files.

The scenario selected for demonstration purposes within the scope of this collaboration was the CCFTap (Cut-In, Cut-Out Following Traffic application). This scenario was used to validate the virtualization process and demonstrate the integration of recorded real-world data into a simulated environment

The relevance of virtual testing and implicitly synthetic data is highlighted in the New Assessment and Test Method document published by UN-ECE [UN-ECE-2022]. Therefore, SIE-NL virtualized the real-world scenarios considering the following main steps:

- The real-world scenario/data have been visualized (see Figure 15).
- The ego vehicle and target vehicle trajectories have been exported (see Figure 16).
- The static environment of the operational design domain has been defined (see Figure 17 and Figure 18) in the simulation environment.
- The ego and target vehicles, including the attached sensors have been specified in the simulation environment.
- The ego vehicle and target vehicle trajectories have been imported into the simulation environment.
- After the scenario is prepared, the simulation is initiated, and the virtual sensor data is saved (see Figure 17 and Figure 18).

In the current case, the following virtual sensor data are available: camera, LiDAR and radar. All sensor parameters, a detailed description of the synthetic data structure [Forrai_2025_1] as well as the generated synthetic data have been shared with the consortium partners and are stored on the project shared folder.

Two different static environments have been considered – one very simple as specified in the EuroNCAP and another according to a possible operational design domain “Deurenseweg” in Helmond, The Netherlands.

The virtual verification and validation environment, built around Simcenter Prescan simulation tool, allows us to consider different illumination and weather conditions. Therefore, the safety, performance, and robustness of different AI-based CCAM solutions can be tested effectively and efficiently before real-world tests and deployment.

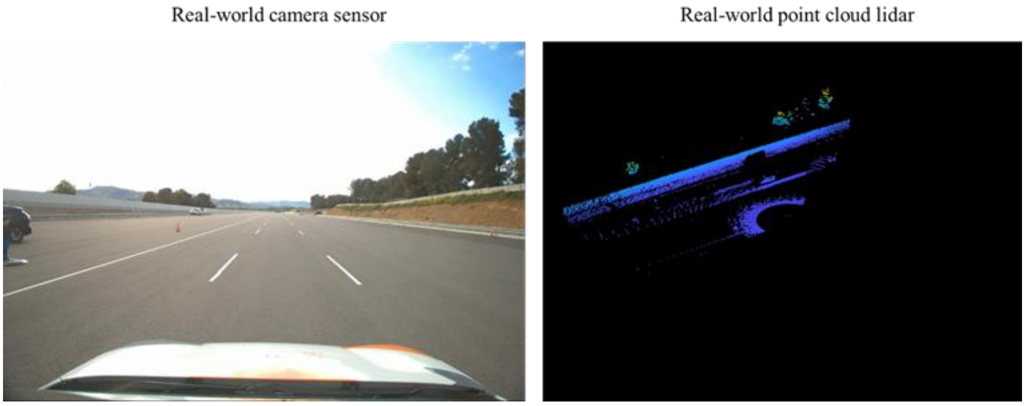


Figure 15: Real-world sensor data – EuroNCAP scenario

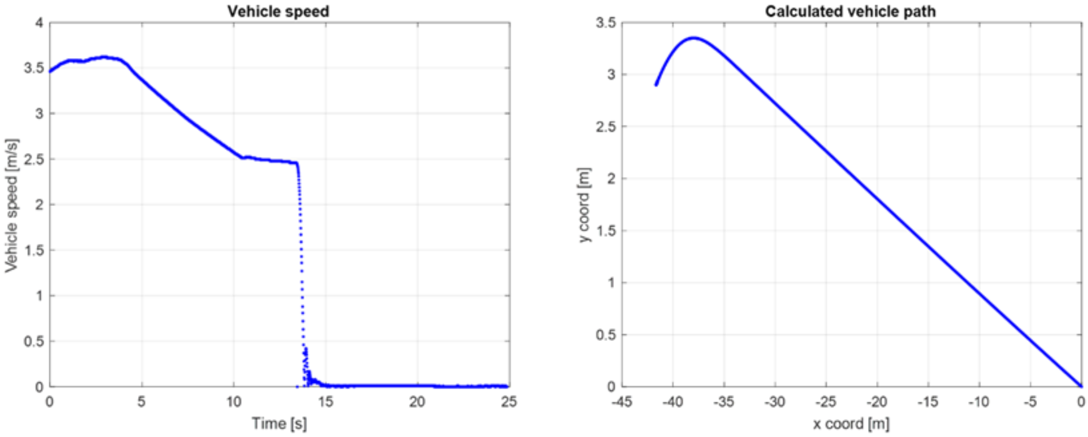
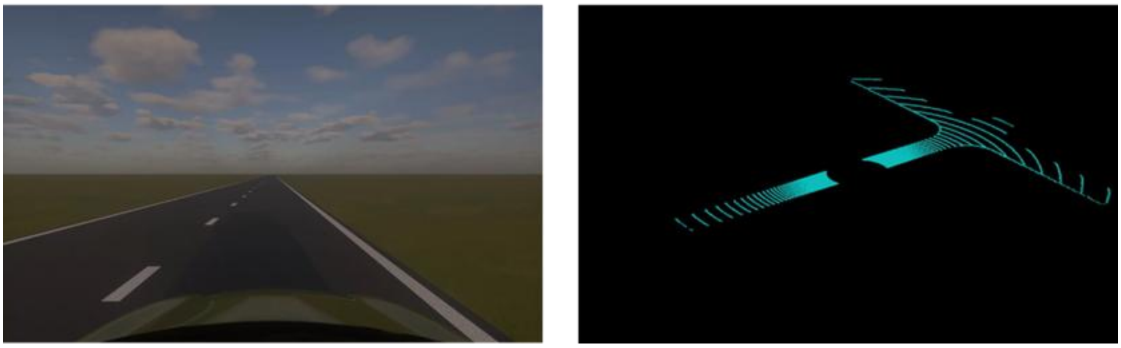


Figure 16: Ego vehicle trajectory - real-world sensor data – EuroNCAP scenario


Physics-based camera sensor

Physics-based point cloud lidar

Figure 17: Virtualized EuroNCAP scenario and sensor data


Physics-based camera sensor

Physics-based point cloud lidar

Figure 18: Virtualized real-world scenario and sensor data

Related to the illumination conditions and weather variations, we considered only five different time moments during the day, and we have three distinctive seasons from sun position perspective: spring or autumn, summer and winter [Forrai 2025_2]. These are summarized in Table 10.

Spring or Autumn					
Time [hour]	07	10	12:30	17	18
Azimuth [deg]	95	140	180	220	265
Elevation [deg]	7	30	38	30	9

Summer					
Time [hour]	06:30	10	12:30	16	20
Azimuth [deg]	60	117	180	250	300
Elevation [deg]	8	48	60	45	8
Winter					
Time [hour]	08:30	10	12:30	15	17:30
Azimuth [deg]	120	145	180	210	220
Elevation [deg]	0	7	15	9	0

Table 10: Considered sun positions: season and time.

In terms of weather, based on the season we defined 4 different weather types during the year, as shown in Table 11.

Spring or Autumn				
Weather	Clear	Rain	Light_Fog	Dense_Fog
Summer				
Weather	Clear	Rain		
Winter				
Weather	Clear	Rain	Snow	Snow_and_Light_Fog

Table 11: Weather types, function on season

Using the integrated simulation environment, a synthetic data set is generated using a combinatorial testing approach and is made available for consortium partners [Hotait 2023]. Combinatorial or t-way testing is a proven method for more effective testing at lower cost. Studies by NIST research showed that most software bugs and failures are caused by one or two parameters, with progressively fewer by three or more, which means that combinatorial testing can provide more efficient fault detection than conventional methods. As conclusion the synthetic data contributes to effective and efficient verification and validation of AI-based CCAM solutions. Hereby, we remark that the generated camera and radar data have been successfully used by Continental Automotive France for testing object detection algorithms as well as for sensor fusion. The LiDAR sensor settings have been aligned according to the sensor specifications defined by Idiada.

4.2.2 Generation of adverse weather conditions in simulation environment

Regarding the work of Continental Automotive France, they worked in the generation of adverse weather conditions in simulation environment divided in two parts: scenario generation and scenario coverage.

Scenario simulation is an essential part of testing since not all DL errors lead to hazards, and most of the time, the physics of such autonomous systems need to be considered when searching for hazards [Ferreira 2022].

In this part, we apply a library called SIMOOD [Ferreira 2022] that is dedicated to testing perception functions built with DL that are integrated within the CARLA simulator.

SIMOOD applies image perturbations during simulation instead of using it over static datasets as usually done in the literature [Ferreira 2021].

Since each image perturbation has several parameters, the number of possible simulations to find a hazard grows exponentially and the time to simulate even a tiny part of these simulations grows quickly as well.

Integrating SIMOOD into our framework helps to tackle the two problems mentioned above when generating graphical scenarios for tests.

It uses a two-step approach. First, it performs unit testing of the ML model using a genetic algorithm [Mirjalili, 2019] on the same dataset applied to train the ML model.

It determines which combination of image perturbations with their respective intensity levels increases the number of incorrect predictions.

Second, the selected perturbations are applied to the simulation to verify if they are leading to hazards in the system.

That is, SIMOOD takes a set of existing scenarios injects image perturbations selected by a genetic-algorithm-on-data approach, and posteriorly tests them on simulations, proving itself capable of turning safe scenarios into unsafe ones, which can be analysed to improve the system's safety.

Since SIMOOD tries to find corner cases only in the space of pixels, we still need to perform the coverage of the other parts of the simulation, as explained below.

For scenario coverage, effective testing of ADAS requires a wide range of scenarios with different weather conditions, traffic densities, road types, and other environmental factors. For this part, we develop two main modules:

- Scenario generation coverage: Manual scenario creation is time-consuming and prone to oversight. Therefore, we use genetic algorithms (GAs) [YANG 2014] to automate the generation of diverse and challenging driving scenarios in the CARLA simulator.
- Scenario coverage evaluation: Evaluating the coverage strategy presented above can be achieved using various algorithms that quantify how well the generated scenarios cover the desired space of driving conditions and edge cases. The result is a score between 0 and 1, where 0 indicates no coverage and 1 indicates full coverage. We apply a weighted sum of multiple metrics. This method combines multiple metrics to provide a comprehensive coverage score by combining diversity, parameter space coverage, and edge case inclusion into a single score.

4.3 Traffic Simulation Tools, Data Generation and Automation for Traffic Management Modelling

4.3.1 Simulation Tooling

For this project, PTV VISSIM was selected as the micro traffic simulation platform due to its robust and configurable traffic modelling capabilities. VISSIM supports both human-driven and automated vehicle

(AV) behaviour through built-in driving models. To support AV simulation, the EU Horizon 2020 CoEXist Project previously introduced built-in AV behaviour models, adapted from the Wiedemann 99 model.

As of VISSIM 2025, a more advanced AV driving behaviour model has been introduced, incorporating Adaptive Cruise Control (ACC) and Automatic Lane Change (ALC). This updated model offers improved realism and accuracy for simulating AV dynamics, making it particularly suited for the objectives of this study. The ACC and ALC models in VISSIM 2025 builds on the work executed in the CoExist project. This project will use the built-in AV model from VISSIM 2025 exclusively, focusing on traffic behaviour rather than low-level vehicle dynamics or perception.

Although co-simulation frameworks (e.g., coupling VISSIM with tools like Carla or Prescan) allow for detailed sensor modelling and environmental perception, these go beyond the scope of this project. The emphasis will be on behavioural modelling within VISSIM to analyse AV and CAV impacts on traffic flow.

4.3.2 Data Generation

For the VISSIM simulation, intersection data was used as a starting point, supplemented with real-world datasets from road operator databases, including live traffic systems data and non-AV data. A two-hour simulation period was created to reflect realistic traffic conditions, consisting of a 30-minute warm-up phase, a one-hour full demand period, and a 30-minute cool-down phase. These datasets were prepared and configured to accurately replicate observed traffic patterns within the simulation environment.

4.3.3 Simulation

To efficiently manage the complexity and scale of the simulation scenarios, a Python-based automation script was developed. The script orchestrates the execution of multiple simulation runs, each representing a unique traffic mix. Every traffic mix consists of a combination of human-driven vehicles, autonomous vehicles (AVs), and connected autonomous vehicles (CAVs). AVs are further categorized into behavioural profiles—cautious, normal, and aggressive—and differentiated by trust levels, with some AVs capable of collaborative behaviour and others operating independently.

Each traffic mix is simulated ten times using different random seeds to account for variability and ensure statistical robustness. Within the simulated road network, a traffic incident is introduced: a vehicle comes to a complete stop, blocking its lanes. The following vehicles must respond to this disruption. Human-driven vehicles and trusted AVs can overtake the stopped vehicle using the opposite lane, while AVs without trust are initially unable to do so. However, after a predefined delay, these AVs are allowed to initiate an overtaking maneuver.

The automation script not only executes all simulation scenarios but also monitors the network during runtime. It detects stuck AVs and programmatically adjusts their behaviour after the specified delay, enabling realistic modelling of trust-dependent overtaking logic. This level of automation significantly reduces manual workload and ensures consistency and repeatability across all simulation runs.

4.3.4 Result handling

The simulation generates various output files containing detailed information on traffic delays, vehicle behaviour, and overall network performance. To efficiently process and analyse these results, a series of Python scripts were developed. These scripts systematically extract and consolidate data from multiple simulation runs, allowing for automated post-processing and statistical evaluation.

Key performance indicators—such as average delay per vehicle, level of service (LOS), total number of vehicles, and vehicle delay hours—are calculated across all traffic mixes and random seeds. By aggregating the data from repeated runs, the scripts provide robust statistical summaries that enable comparisons between different traffic scenarios and vehicle compositions.

The automated result handling ensures consistency in the analysis, reduces the potential for manual errors, and enables rapid iteration and evaluation of simulation outcomes. This structured approach supports data-driven insights into the impact of AV behaviour, trust dynamics, and incident response on overall traffic performance.

5. XiL infrastructure, tools and software preparation for data generation and validation support

5.1 XiL testing approaches for AI-based CCAM validation protypes

SIEMENS-BE has executed the task through the setup and initial deployment of a hybrid testing framework. This framework combines virtual simulation environments with physical components to enable front-loaded, iterative validation throughout the development process. A XiL (X-in-the-Loop) testing environment has been established, incorporating Driver-in-the-Loop (DiL) and Vehicle-in-the-Loop (ViL) configurations (Figure 19), enabling the integration of real human operators, sensors, and Electronic Control Units (ECUs) with high-fidelity digital twin simulations. This setup allows for realistic, real-time interaction between virtual and physical systems, providing a versatile platform for evaluating vehicle and AI-based behaviour and system responses under a wide range of scenarios.

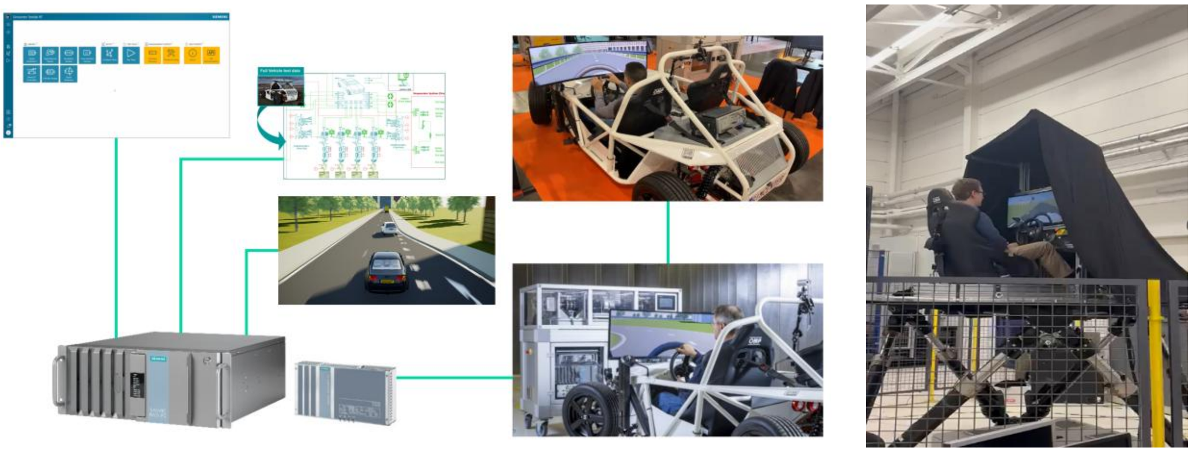


Figure 19: Left figure presents the Driver and Vehicle in the loop testing setup, while the right figure showcases a Driver in the loop demonstration with an AI-based controller.

The XiL environment was designed with the specific goal of supporting the development and validation of AI-based CCAM functionalities, such as perception, decision-making, and control systems. A proof of concept has been successfully demonstrated, showcasing the potential of this approach to test and validate subsystems and control strategies well before full vehicle integration is available. This early-stage validation helps identify performance issues, inconsistencies, and unexpected behaviour in a controlled yet realistic setting, accelerating the development cycle while enhancing safety and reliability.

However, while the proof of concept confirms the feasibility and value of the approach, further extensions and refinements are necessary to fully realize its potential. These include expanding the scope of testing scenarios, improving the fidelity and responsiveness of the digital twin, integrating additional physical components, and enhancing the automation and scalability of test case execution. Additionally, the environment needs to support more complex CCAM interactions, such as edge case handling in highly dynamic urban environments.

In conclusion, the established XiL test environment represents a significant milestone in the development of robust and trustworthy AI-based CCAM systems. It lays a strong foundation for more extensive and automated validation campaigns in the future and positions the project to contribute meaningfully to the advancement and eventual certification of safe, intelligent mobility technologies.

5.2 ViL testing

The entire test vehicle or Dynamic Vehicle-in-the-Loop (DynViL) system is designed for testing automated driving functions (ADF) by integrating a real vehicle with a virtual environment. This integration enables the evaluation of ADFs in a wide range of simulated scenarios, offering a complementary approach to traditional testing methods.

IDIADA implementation follows the DynViL architecture detailed in this report, utilizing a real vehicle integrated with a virtual environment for ADF testing.

5.2.1 System Architecture

The DynViL system architecture is characterized by the following key elements:

- A real vehicle operates within a physical test environment, typically on an empty track.
- The vehicle's movements are simultaneously replicated in a virtual environment.
- The virtual environment generates data about the vehicle's surroundings, which is then fed back to the vehicle's control system.
- The vehicle's control system processes the virtual environment data, enabling the real vehicle to respond to virtual scenarios as if they were real.
- The simulation and control systems are located on an external test bench, separate from the vehicle itself.
- Data exchange between the vehicle and the test bench is limited to vehicle control commands (accelerator, brake, steering) and vehicle positioning data, utilizing wireless communication.

This design minimizes the computational load on the vehicle and allows for efficient communication, even in complex scenarios with many virtual elements.

5.2.2 Key Components and Communication

The DynViL system comprises several interacting components:

- Virtual Environment: The CARLA simulator is used to create a virtual environment, including virtual traffic participants and scenarios.
- Sensor Model: An ideal sensor model processes ground truth data from the simulator to generate an object list representing the vehicle's perceived surroundings.
- System Under Test: This includes the Automated Driving Function (ADF) and vehicle control algorithms, implemented using the Robot Operating System (ROS).
- Vehicle Control: The ADF calculates the necessary control inputs (steering, acceleration, braking). Then, these commands are sent wirelessly to the real vehicle. Finally, actuators on the

vehicle (linear and rotational) translate these commands into physical actions on the steering wheel and pedals.

- Vehicle Feedback: A GNSS/IMU system captures the vehicle's position, orientation, velocity, and acceleration. This data is transmitted wirelessly back to the simulation to update the vehicle's virtual representation.
- Communication: Wireless communication is used for data exchange between the vehicle and the external test bench, enabling real-time interaction.

5.2.3 Vehicle Dynamics

The DynViL system incorporates a real vehicle, capturing its actual dynamics, rather than relying on a simulated vehicle dynamics model. This is important because real-world vehicle behavior can be complex and difficult to model accurately. This approach contrasts with relying on simulated vehicle dynamics models.

5.2.4 Automated Driving Function (ADF) and Control

A simplified prototype ADF is used, designed to control the vehicle longitudinally along a desired path at a specified speed.

The ADF generates a path-line and calculates the necessary speed and acceleration profiles.

It also incorporates a basic collision avoidance system that triggers deceleration based on the distance and relative velocity of nearby objects.

The vehicle controller uses PID control to translate the ADF's commands into actuator inputs for steering, acceleration, and braking.

This task has been executed by developing a framework to support Vehicle-in-the-Loop tests. The main goal of this framework is to reduce the costs and risks involved in field tests where the ego vehicle interacts with external elements, from pedestrians to cars. Furthermore, a wide range of simulated scenarios is available at no cost, offering a complementary approach to traditional testing methods.

In the proposed testing setup, a real vehicle operates within an empty physical test environment while its surroundings are generated by a simulator. By incorporating a real vehicle, capturing its actual dynamics, rather than relying on a simulated model, we ensure that the physical response of the system is accurately represented in the tests. Generating an accurate vehicle model is not a trivial task, and the ViL infrastructure bridges the gap between simulation and reality by embedding the physical vehicle into the simulation, exploiting the flexibility of a digital environment without compromising the accuracy of the vehicle representation.

The architecture of our implementation (Figure 20) can be divided into two parts.

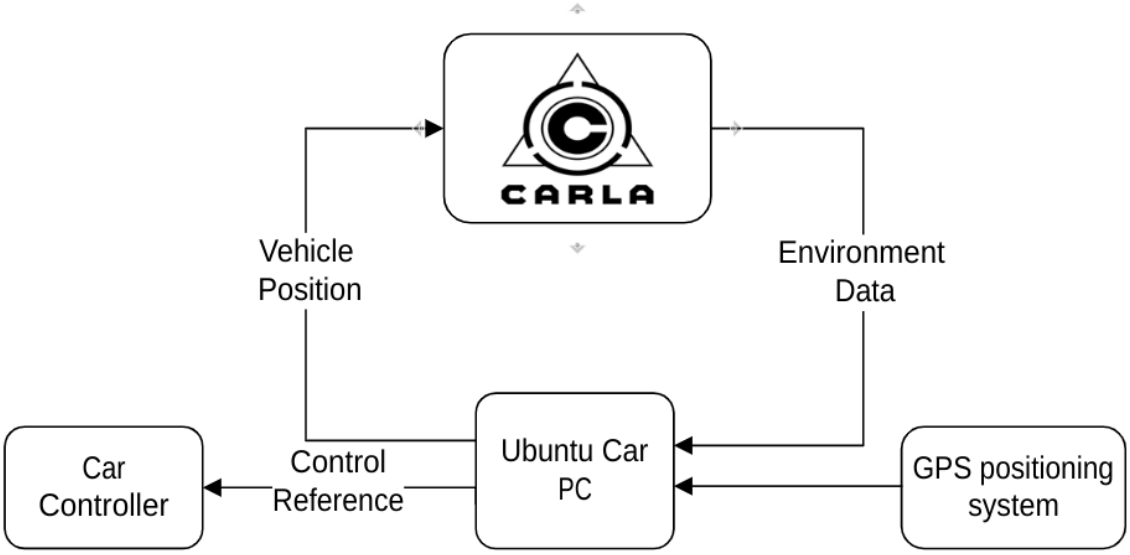


Figure 20: Architecture of the implementation.

On the one hand, a simulated environment is designed on top of an empty testing track within IDIADA proving grounds. This digital space mimics the scenario under study and can be created using CARLA, which is a state-of-the-art open-source simulator for testing and simulating autonomous vehicles in various urban and rural scenarios. Additionally, any perception algorithms are either bypassed by perfect information or executed with the data generated by virtual sensors.

On the other hand, a real vehicle is equipped with localization and control capabilities, allowing it to develop navigation algorithms without dealing with complex system models or putting others at risk. The information of a localization module is used to move the vehicle in the simulated environment, providing an accurate representation of the vehicle dynamics.

Figure 21 illustrates the physical compared to the simulated scenario.

Figure 21: Physical vs Simulated scenario.

Communication between the vehicle and simulator has been done using ROS2, which allows us to execute the simulator either locally on the car PC or offload it onto an external device. Furthermore, this setup simplifies the communication between onboard modules, such as the control and localization units. At the moment all the tests have been performed with the onboard computer, but complex scenarios may imply a computational burden beyond the capabilities of the car PC. In the next iterations of the framework, we plan to evaluate the impact of having a wireless communication layer, as it implies dealing with delays in the data collection of the control unit.

We are in the initial stages of the deployment of the framework, which motivated the design of a study case to benchmark the system. To do so, a simple physical test has been used as a baseline scenario to evaluate the behaviour of the framework. We used GNSS data from a field test where an autonomous ego vehicle navigates a road adjusting its velocity to a target vehicle driving down the lane. Both agents were later embedded in the ViL framework to evaluate if the same test could have been performed only using a single physical vehicle.

In Figure 22, both digital and physical sensor arrays have been displayed, showing how the testing environments present similar capabilities. It’s worth noting that even though the virtual scenario is not a high-fidelity representation of the testing grounds, our main objective was to validate the mapping of physical coordinates onto the simulator and study the behaviour of the simulator-vehicle interaction.

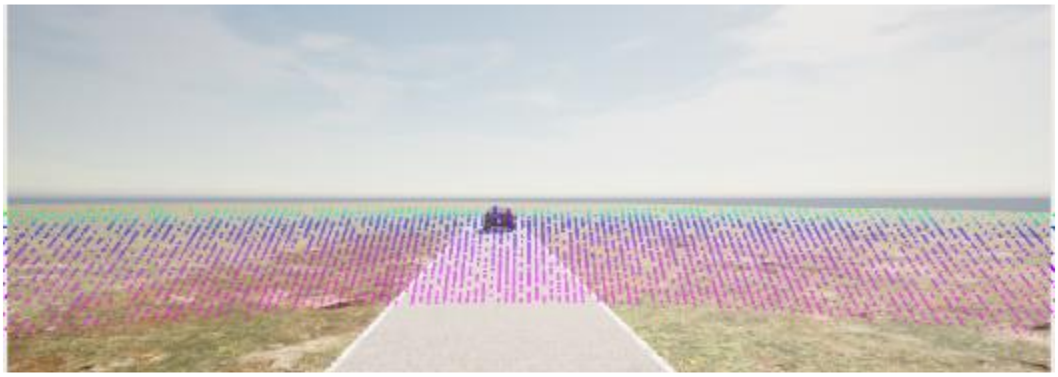


Figure 22: Vehicle detection in simulation

In conclusion, we managed to implement the proposed ViL architecture in a real test case, validating the system developed and opening the door to further tests. The designed test environment establishes a solid ground to develop novel navigation algorithms safely and with minimal deployment costs. However, further developments are required to enhance the realism of virtual test cases, such as 3D models of the IDIADA vehicle fleet and tools to bridge the gap between the physical proving grounds and the digital scenarios to be tested.

6. Conclusions

Automated driving systems need to navigate safely through different traffic and environmental conditions. To test all possible scenarios in the virtual and real world require a considerable amount of time, engineering effort and financial resources. In case of automated driving systems (especially level 3 and level 4 of automation) the scientific community realized quickly that only real-world testing - using a mileage-based coverage - is not feasible, from economical and technical point of view. One of the main reasons is that during real world-driving, safety relevant events, happen very rarely. Therefore, it became obvious that virtual testing will play a key role in the development and certification of automated driving systems.

According to a Roland Berger study [Berger 2023], vehicles are becoming computers on wheels and the automotive industry in moving in direction of software defined vehicle approach, driven by sustainable development, increasing complexity, etc. Therefore, we tried to answer the question: in case of AI-based CCAM systems, how do we verify the correctness of the software and how to assess the test coverage?

Since our focus is on automated driving systems and CCAM we approach this topic from the perspective of scenario-based software testing, which is a software testing activity which uses scenarios (hypothetical or real stories) to help the tester work through a complex problem or test system.

In this deliverable a comprehensive overview was provided regarding the hybrid testing framework developed of AI-based CCAM systems. Various methodologies and early results were presented, associated with the preparation of physical testing environments, the establishment of advanced simulation infrastructures with different illumination and weather conditions, and the integration of these approaches by means of XiL (X-in-the-loop) setups.

For each of the three tasks, physical testing preparation, simulation infrastructure development, and hybrid integration, the deliverable offers a detailed description of the background, the adopted methodologies, and preliminary performance outcomes in line with stakeholder requirements. An evaluation of the advantages and potential limitations of the proposed testing strategies is also provided, keeping in mind human-centric AI principles and the overall objectives of the project.

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