WHITEPAPER

IABG Mobility Innovation Campus

Testbed for Automated and Connected Mobility

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Executive Summary

This document provides an overview of a cutting-edge testbed for the development and validation of automated and connected mobility solutions.

Located in Ottobrunn/Munich, Germany, the IABG Mobility Innovation Campus (MIC) offers a controlled yet highly flexible environment for testing connected and automated vehicles (CAVs) and innovative mobility solutions in complex urban traffic scenarios.

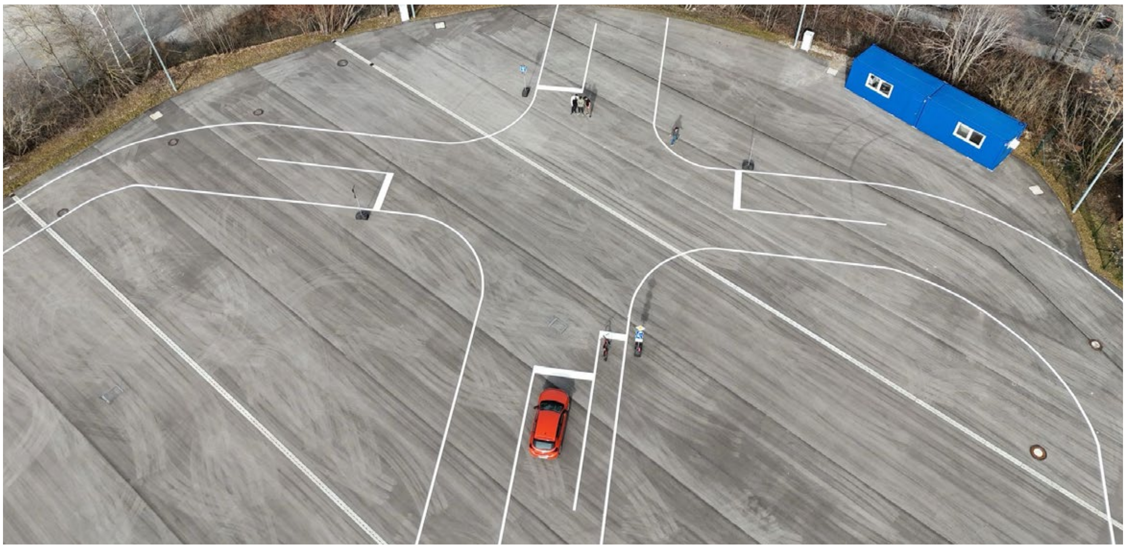
The testbed plays a crucial role in evaluating automated driving technologies, vehicle-to-everything (V2X) communication, and adaptive urban infrastructure. Equipped with advanced LiDAR sensors, a dedicated and private 5G communication network, and modular road layouts, it enables industry experts, researchers, and policymakers to develop and refine mobility solutions efficiently and safely. Ensuring road safety and traffic efficiency is essential for a successful deployment of CAVs.

The testbed allows for real-world validation of automated mobility solutions, particularly their interaction with vulnerable road users (VRUs) such as pedestrians and cyclists. It also provides a controlled environment for studying vehicle behaviour, communication protocols, and emerging transportation technologies. This white paper outlines the key infrastructure and technical capabilities of the testbed, supporting the transition towards safer, more efficient, and more sustainable urban transportation systems.

Background and Problem Analysis

The transportation sector is undergoing a paradigm shift, driven by advancements in automation, electrification, and connectivity. However, the successful implementation of these innovations depends on addressing and overcoming several key challenges. One crucial concern in urban mobility is ensuring the safe interaction between CAVs and vulnerable road users (VRUs), such as pedestrians and cyclists. Urban environments are characterized by complex, dynamic, and often unpredictable traffic conditions, making it imperative to validate automated mobility solutions in a setting that accurately reflects real-world constraints.

Another major challenge is the interoperability of diverse mobility technologies. Automated vehicles must be able to communicate seamlessly with each other, with roadside infrastructure, and with central traffic management systems. This requires rigorous testing of V2X communication protocols, such as ITS-G5 or C-V2X, to ensure data reliability, cybersecurity, and low-latency transmission. The IABG Mobility Innovation Campus (MIC) provides a fully connected, modular test ecosystem to evaluate these aspects under highly controlled yet realistic conditions, bridging the gap between laboratory research and real-world application.



Solution Approach

The testbed is located on the IABG campus in Ottobrunn, south of Munich, Germany. It is a joint venture by the Chair of Traffic Engineering and Control at the Technical University of Munich (TUM), the Industrieanlagen-Betriebsgesellschaft mbH (IABG).

The facility comprises an asphalted open-air test area measuring 105 by 80 meters, a two-story parking garage, and a simulation centre equipped with offices and meeting rooms. Unlike many other test environments, the MIC testbed is specifically designed to replicate complex urban mobility scenarios. It emphasizes the interaction of CAVs with a broad range of different road users, particularly VRUs such as pedestrians and cyclists.

Designed as a highly flexible research environment, the testbed supports a wide array of experimental setups. Its key capabilities include:

Stationary and Mobile LiDAR Sensors

The testbed is equipped with a full and redundant sensor system, ensuring full coverage and a 100 % detection rate - even in the presence of multiple visual obstructions such as buildings, trees, or vehicles. A total of twelve LiDAR sensors, mounted at various positions and angles, provide a robust perception.

Each sensor station is equipped with two LiDAR units:

- One Ouster OS1 64 Gen2 long-range LiDAR, offering 360-degree coverage, a vertical field of view of 45 degrees below the horizon and 64 scan lines with an angle speed of 10-20 Hz.
- One RoboSense Bpearl blind-spot LiDAR, also with 360-degree coverage, a vertical field of view of 90 degrees, 32 scan lines with the same angle speed of 10-20 Hz. This sensor specializes in detecting objects directly adjacent to and below the sensor installation point.

Sensor placement consists of four stationary units, each located at the midpoint of the outer testbed edges and mounted at a height of around 4 meters.

Additionally, two mobile rover stations are available, equipped with telescopic poles that allow adjustable sensor heights between 2.30 and 5.30 meters. All six sensor stations combine long-range and blind-spot LiDARs. Sensor fusion of the point clouds at each station ensures seamless 360-degree coverage of their respective surroundings.

The aggregated point clouds from all sensor stations are processed in real time to classify and track all traffic participants across the entire testbed such as cars, trucks, motorbikes, bicycles and pedestrians. The result is a continuously updated fused object list available for real-time evaluation and system integration.

The exclusive use of LiDAR sensors offers a significant advantage in terms of data privacy. Unlike video-based systems, LiDAR provides detailed spatial data without capturing personal identifiers. This approach ensures full compliance with the EU's General Data Protection Regulation (GDPR, Regulation EU 2016/679), balancing the increasing demand for sensor data in traffic research with the need to protect individual privacy.

Stationary and Dynamic Inductive Charging Lanes

The testbed features inductive charging infrastructure for both stationary and dynamic use cases. The Park & Charge area on the western edge includes three parallel lanes:

- Two lanes each contain three individual inductive charging spots for stationary charging.
- One lane functions as a continuous inductive charging lane, approximately 17 meters in length, enabling vehicle charging also during vehicle movement.

In addition, the Drive & Charge lane is another 17 meters-long continuous charging lane, centrally located within the testbed. This lane supports dynamic charging, allowing vehicles to be charged while in motion. It can also be integrated into use cases such as inductive charging of buses at bus stops during passenger boarding or charging of vehicles in front of stop lines.

All inducive charging spots and lanes support charging with 22 kW, making the infrastructure suitable for a broad range of electric vehicles and use scenarios.

Traffic Signal System

The testbed includes a flexible, state-of-the-art traffic signal system that can be fully adapted to changing test scenarios. All signal poles and signal heads are modular and movable, allowing dynamic rearrangement according to different layout requirements. The system consists of:

- Four vehicular signal heads with three lamps each.
- Eight pedestrian signal heads, each with two lamps.

All signals use Yunex Silux2.VLP (Very Low Power) LED technology, featuring interchangeable 200 mm symbol inserts, a 24V/DC power supply, and a luminous intensity of 200 cd. The signal heads are connected to a Sitraffic sX "Advanced Version" signal controller, which supports:

- Sitraffic Canto and the OCIT-O V2.0 communication protocol.
- Up to four partial nodes, 64 signal groups and 250 (virtual) detectors.

The controller includes an API for custom control algorithms, data connections and V2X (Vehicle-To-Everything)-based data provision to third party systems. It is also enabled to receive and incorporate R09-telegrams.For V2X communication, the traffic signal system incorporates a hybrid Road-Side Unit (RSU), the Yunex Traffic RSU2X. This unit features:

- Dual-radio, dual-stack architecture supporting both IEEE 802.11p/DSRC and C-V2X (3GPP Rel. 14/15).
- Two Toplink 5.9 GHz modules and one Toplink LTE 4G module, offering a communication range of up to 2,500 meters.
- Capacity to process up to 4,000 message verifications and 130 message signatures per second, ensuring scalability even at high penetration rates.

For time synchronization and positioning, the RSU2X is equipped with GNSS, offering 2.0 m CEP accuracy and WAAS support across GPS, Galileo, GLONASS, and BeiDou systems. To enable traffic-actuated signal control, the system also includes four Yunex Traffic Sivicam CI-2 MOS video cameras (black and white), each capable of creating virtual detection loops for eight zones with a detection range of 50 meters. Due to data protection regulations, resolution is limited to 640×480 pixels.

5G Campus Network Coverage

The testbed is equipped with a dedicated private 5G network, consisting of the two main components: The Radio Access Network (RAN) and the Core Network. The RAN includes one Base Band Unit (BBU) and one ViCell 5G Remote Radio Heads (RRHs) connected to the BBU. This setup forms a 5G base station (gNodeB) serving the whole open-air testbed. The network operates in the n78 frequency band (3700 – 3800 MHz), which is specifically allocated for 5G campus networks in Germany.

Due to its open interfaces and customizable architecture, the network serves as a platform for advanced research, including the development and testing of 5G+ and future 6G technologies. The infrastructure also supports experiments involving signal spoofing and jamming (e.g. GNSS, V2X messages), which are crucial for assessing the robustness and resilience of connected and automated vehicles (CAVs) in adverse conditions.

Future Parking Garage

Directly connected to the testbed is the dedicated multi-story parking garage, measuring approximately 25 x 30 meters. The two levels are connected by a 180-degrees circular ramp and feature extra-high ceilings (2,95 meters) to accommodate tall vehicles, such as automated shuttles or vehicles equipped with roof-mounted sensor arrays. Thanks to its dimensions and flexible layout, the facility supports a wide range of test scenarios, particularly those based on the Automated Valet Parking (AVP) standard ISO 23374-1:2023 (Intelligent transport systems – Automated Valet Parking Systems AVPS). It is also ideally suited for testing cooperative parking systems.

Adjacent to the building is a 25 meters long ramp, 3.20 meters wide, with sections of 15 % and 7.5 % inclination, ending in an elevated platform that includes a vehicle inspection pit.

The parking garage is equipped with:

- One inductive charging spot per level.
- Three 22 kW conductive charging stations.
- Two parking spaces preconfigured for robotic arm charging systems with up to 100 kW.

Part of the energy demand is met sustainably through IABG's own 53 kWp photovoltaic system, which covers the entire rooftop of the structure.

Power and Cable-based Network Connectivity

The testbed offers comprehensive infrastructure for power supply and data connectivity, enabling flexible and high-performance integration of test equipment and systems. A total of nine above-ground access cabinets are distributed around the test area and connected via a redundant fibre ring. In addition, four underground access terminals are embedded directly into the asphalt surface, providing discrete yet robust connectivity within the test field.

Each access point is equipped with:

- Several 230 V power outlets and high current power outlets (16 A, 32 A).
- Four to eight LC duplex fibre connections.
- Four to eight RJ45 Gigabit Ethernet ports.

This setup ensures stable, high-speed communication and reliable power distribution across the entire testbed, supporting a wide range of sensors, communication devices, and test systems in stationary or mobile configurations.

Additional Equipment and Simulation Infrastructure

The testbed is equipped with a wide range of modular and mobile infrastructure components that support highly flexible scenario creation for research and development in automated and connected mobility.

One element is a movable and dimensionally adjustable bus stop platform. It consists of 250 rectangular modules (30 × 30 cm, 14 cm height) that can be arranged individually to meet specific experimental requirements. The platform is bordered by curb elements designed to distribute lateral loads from bus tires evenly, ensuring structural stability. These curbs feature longitudinal retroreflective strips, improving visibility under all lighting conditions. The curb elements can also be deployed independently as roadside elements for other test configurations.

Flexible lane and pavement markings, like those used in construction zones, allow for dynamic and reversible layout designs and scenarios. A variety of traffic signs is available to simulate different static traffic control scenarios.

To replicate real-world sensor and visibility challenges, the testbed includes mobile artificial obstacles such as buildings, trees, and hedges mounted in mobile planters. These elements introduce visual obstructions for both human drivers and onboard vehicle sensors (e.g. cameras, LiDAR).
To enable V2X-based cooperative mobility for all traffic participants, a retrofittable V2X unit is available. This dual-mode unit supports both DSRC/IEEE 802.11p and C-V2X (3GPP Rel. 14/15) communication standards. It can transmit and receive Cooperative Awareness Messages (CAMs), which are displayed on an integrated screen. With a range of up to 2,500 meters and support for 4,000 message verifications and 130 message signature operations per second, the system is robust even in high-density traffic scenarios.

Adjacent to the testbed is the simulation centre and office building, offering a direct line of sight to the entire outdoor test area. The simulation centre includes a suite of human-in-the-loop simulators, such as:

- A tram simulator.
- A bicycle simulator.
- A cargo-bike simulator.
- An e-scooter simulator.
- A wheelchair simulator.
- A pedestrian simulator.
- A state-of-the-art driving simulator with six degrees of freedom.

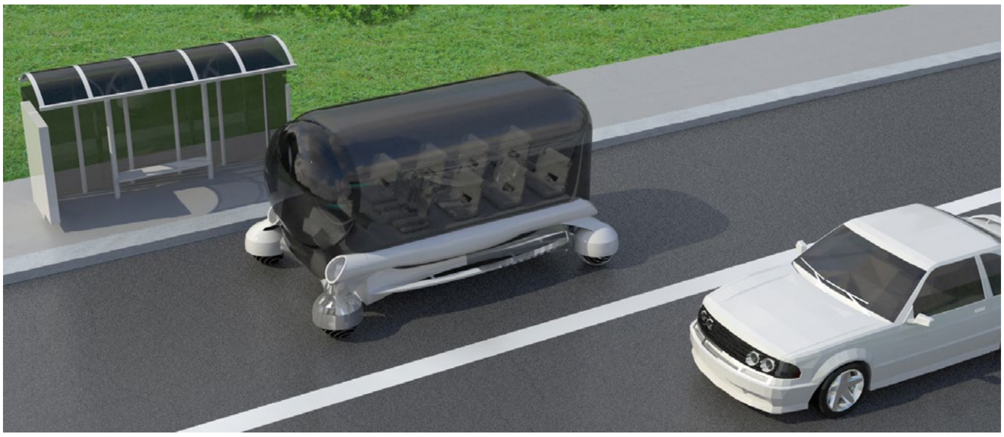
Thanks to a direct fibre-optic connection between the testbed and the simulation centre, low-latency co-simulations are possible, enabling realistic, synchronized interactions between virtual and physical participants in complex mobility scenarios.

Experimental Vehicle Fleet

The testbed includes a diverse fleet of vehicles to support a wide range of research and development activities in connected, automated, and inclusive mobility. These vehicles cover both conventional and specially equipped research platforms with advanced sensor and communication systems, that are available for experimental use on site. The available fleet includes:

- Regular bicycles, electric bicycles, and cargo bikes.
- E-bikes with integrated inductive charging capabilities.
- A wheelchair for inclusive mobility scenarios.
- An electric bicycle rickshaw with trailer, designed for Ride-Parcel-Pooling scenarios.
- A Boreal Bike, equipped with C-V2X onboard unit, 360-degree LiDAR, surround-view cameras, GNSS, and behaviour monitoring sensors.
- An e-scooter with an inertial measurement unit (IMU) capturing acceleration, deceleration, orientation, and angular velocity.
- A modified BMW i3, outfitted with inductive charging technology.
- A BMW iX1 research vehicle for augmented reality (AR) testing.
- A connected and automated electric rickshaw (three-wheeled), equipped with LiDAR, radar, and cameras for automated and teleoperated operation.
- EDGAR, the automated research vehicle developed by the Technical University of Munich (TUM).
- Two automated people-mover NAVYA shuttles for TUM research projects.

This diverse vehicle pool enables extensive testing of multimodal, cooperative, and inclusive mobility solutions, both in isolated scenarios and in complex, mixed-traffic environments.



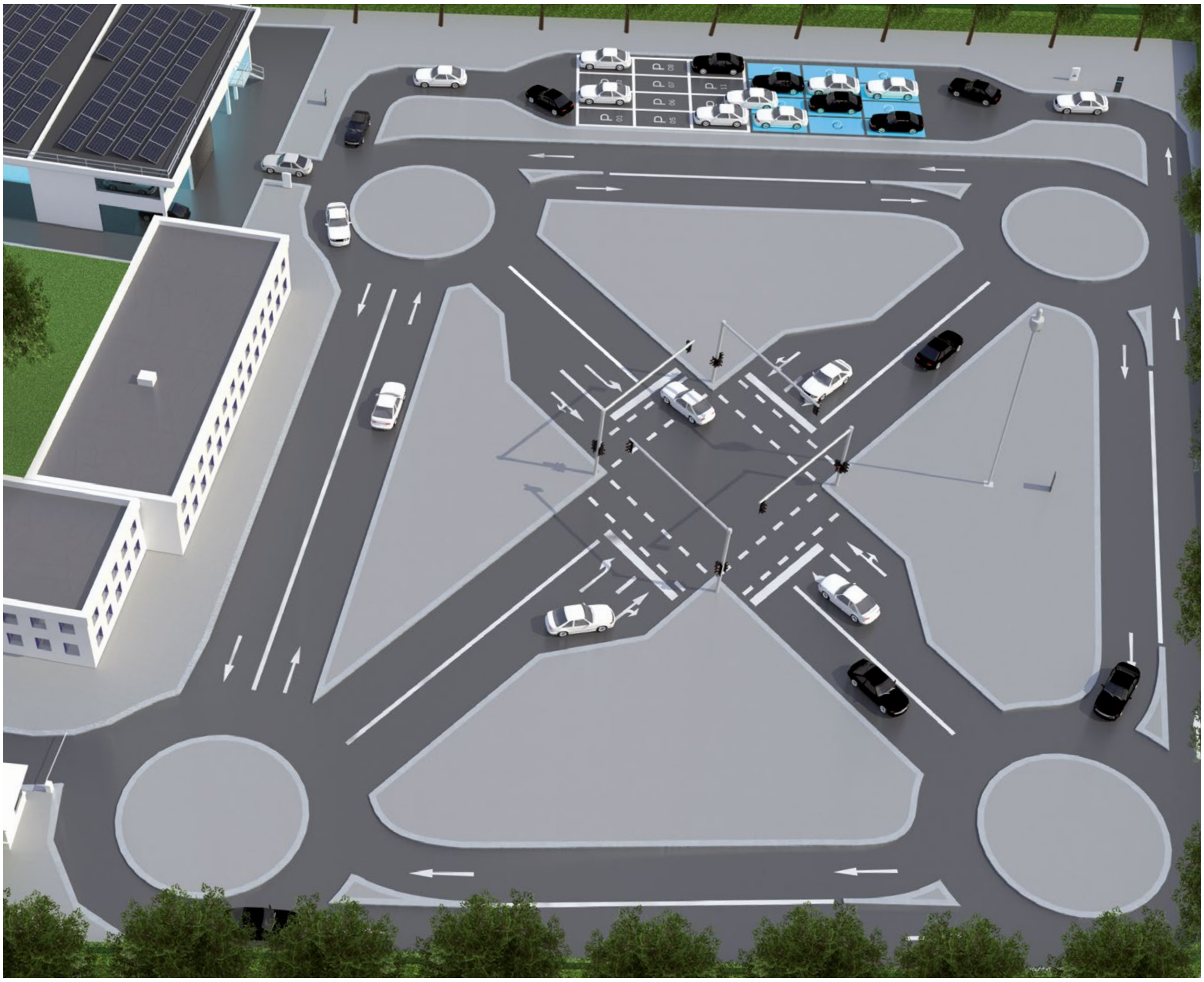
Digital Testbed

To support co-simulations and enable ex-ante preparation of real-world tests in simulations and simulators, the testbed is also available in digital form. These digital models allow for the design, testing, and validation of future testbed configurations before physical implementation, improving planning efficiency and reducing set-up time.

The development of test scenarios follows a structured workflow:

1. It begins with the creation of a new CAD layout, or the use of existing intersection plans provided by municipalities. These serve as the blueprint for road geometry and infrastructure placement.
2. A Swept Path analysis is then conducted to verify vehicle manoeuvrability and to identify potential conflicts or spatial constraints.
3. The refined layout forms the basis for generating digital maps, typically using the OpenDrive format. Tools such as RoadRunner are used to create high-fidelity, standardized representations of the road network.

OpenDrive maps are crucial for virtual testing, CAV motion planning, and simulation, providing a standardized interface that supports multiple applications and ensures comprehensive testing and validation of CAV systems.



Benefits and Use Cases

The testbed offers significant value to a wide range of stakeholders involved in the development, testing, and deployment of intelligent transportation systems:

- Automotive manufacturers benefit from a controlled, real-world environment for the pre-certification testing of automated driving functions. This reduces development risks lowers costs compared to large-scale field trials and accelerates time-to-market.
- Urban planners and public authorities can use the infrastructure to test and evaluate adaptive traffic management strategies. The insights gained support evidence-based decisions for future urban infrastructure and mobility planning.
- Academic institutions and research organisations benefit from a dedicated platform to explore topics such as human–vehicle interaction, traffic efficiency, and sustainable urban mobility under reproducible conditions.
- Regulatory bodies can leverage data and findings from testbed experiments to inform policy development and define standards and safety frameworks for the integration of connected and automated vehicles into existing traffic systems.

Conclusion and Recommendations

The development and deployment of automated and connected mobility solutions requires a rigorous validation process that integrates digital simulation with real-world testing. The Mobility Innovation Campus plays a key role in this ecosystem by offering a controlled yet highly flexible environment for testing and experimenting with next-generation transportation technologies.

Through iterative testing, data-driven insights, and cross-sector collaboration, the facility accelerates the transition to safer, more efficient and more sustainable mobility systems. To fully realize the potential of this testbed, stakeholders are encouraged to engage in collaborative projects exploring innovative applications of automated mobility:

- Industry leaders can leverage the testbed's advanced infrastructure to refine CAV performance under realistic conditions.
- Regulatory authorities gain access to validated experimental data for the development of standardized safety protocols and evidence-based policymaking.
- Research institutions benefit from a reproducible and well-instrumented environment to advance mobility science and human-technology interaction.

Looking ahead, the continued expansion of the testbed infrastructure, including additional urban features and complexity, will further broaden its applicability and support the safe integration of automated mobility solutions across diverse transportation contexts.

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