Introduction of the Experimental Twin for Real-World Testing of CAVs at the Mobility Innovation Campus

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ABSTRACT

This paper introduces a novel approach to research and development in traffic engineering through the concept of experimental twins, designed to enhance the integration and safety of connected and automated vehicles (CAVs) and vulnerable road users (VRUs) such as cyclists and pedestrians. Our methodology combines high-fidelity digital twin simulations with real-world experimental testing on a state-of-the-art testbed. This hybrid approach allows for the replication of various urban traffic scenarios with high precision, providing a controlled environment to study and validate CAVs, VRU behavior, and interactions between CAVs and VRUs.

Experimental twins recreate real-world traffic conditions within a testbed, utilizing adaptable infrastructure and advanced sensing technologies. These physical replicas of the real world enable rigorous testing of CAV systems under realistic yet controlled conditions, ensuring higher absolute validity compared to purely digital simulations. The incorporating of experimental twins in the validation process significantly enhances the predictive accuracy of safety and efficiency metrics in urban scenarios. Our presented testbed's flexible configuration supports a wide range of traffic scenarios, making it a crucial tool for validating CAV technologies. The study demonstrates that the integration of experimental twins bridges the gap between simulations and real-world applications, providing valuable insights for the development of safer and more efficient mobility solutions.

Future work will focus on refining VRU behavior models, expanding the capabilities of experimental twins, and addressing broader societal and policy implications.

This research establishes a robust framework for advancing urban traffic and facilitating the safe and effective deployment of CAVs in diverse urban environments.

Keywords: Real-World Testing, Testbed, Proving Ground, Experimental Twin, Connected Automated Vehicles (CAV), Vulnerable Road Users (VRU)

INTRODUCTION AND MOTIVATION

Since the 1950s, transport planning and engineering have predominantly focused on vehicle-centric designs [1]. Presently, a considerable proportion of public space is dedicated to motorized road traffic, including both moving and parked vehicles. This approach has led to the installation of traffic detectors at urban intersections to monitor motorized traffic flow. Consequently, cities now possess extensive data on motorized traffic patterns within urban areas. This information is utilized not only to manage intersection control but also to monitor overall traffic conditions, detect accidents, and identify traffic congestion, subsequently informing the public [2].

However, urban mobility is not limited to motorized vehicles. In recent years, there has been a notable increase in the number of cyclists and pedestrians. This goes hand in hand with an increase in public and political awareness for such modes of transportation. To address this growing demand, urban and transport planning are increasingly prioritizing these alternative modes. Consequently, urban cycling networks have been significantly expanded, and pedestrian pathways have been widened compared to several decades ago. This shift reflects a broader recognition of the need to accommodate diverse transportation modes within urban environments.

Despite this slow shift in societal, political and scientifical focus on vulnerable road users (VRU), research and models to describe VRU behavior especially in the interaction with motorized road traffic are still in its initial stages [3]. Especially with the appearance of highly automated driving functions either as an advanced driver assistance system (ADAS) or as a key cornerstone for connected and automated vehicles (CAV), the tactical and operational behavior of VRUs are playing a significant role for the safe operation of such functions in the urban context, where the presence of VRUs is very high. In contrast to the development of state-of-the-art vehicle and driver behavior models where a vast amount of data could be generated in the vehicles itself, using the ever-growing number of in-vehicle sensors, VRUs are very sparsely equipped with advanced sensors to detect their mobility behavior.

The focus on urban areas and urban traffic, which includes also narrower road space shared with other modes of traffic, especially with VRUs like cyclists, pedestrians, or e-scooter-drivers increases the safety-related need for better models to understand the behavior of such modes of transportation. Therefore, the interaction between those different modes especially at the intersection level plays a significant role in the testing and validation of new innovative mobility solutions. Intersections are critical points in urban transport networks on which different road users such as buses, trucks, cars, vehicles, pedestrians, and cyclists meet.

To calibrate and validate vehicle-based systems behavioral models of VRUs are used to detect, understand, and predict their behavior. In the development and training those models are used in simulations to understand the implications and effects on traffic safety and traffic efficiency. The validity, and therefore the representability of the reality, of such models is crucial for the reliable and safe operation. The parameters for those models are, as mentioned above, not easily measurable on the VRU-side due to the lack of sensors. Therefore, external sensors are needed to gather the required model parameters to be used in simulations and the development, calibration, and validation of further applications.

Analogous to the concept of a digital twin, which denotes a digital replica of physical entities for purposes such as simulations, we introduce the notion of an experimental twin. This experimental twin is a physical representation of the real world within an experimental testbed environment. The use of adaptable intersection layouts, variable lane markings, and moveable building components enables the recreation of real-world traffic infrastructure within this testbed. This facilitates the replication of real-world traffic scenarios for experimental purposes.

METHODOLOGY

The rapid advancement of CAV technologies on our roads necessitates rigorous testing methodologies to ensure safety, efficiency, and also the future user acceptance. Traditionally, simulations have played a pivotal role in the development and validation of CAV systems due to their cost-effectiveness and the ability to replicate a vast array of scenarios. However, the relative validity of simulations – how well they replicate specific aspects of real-world conditions – differs significantly from their absolute validity, which is the overall accuracy in representing real-world outcomes. This discrepancy underscores the importance of supplementing simulations with real-world testing.

Relative Versus Absolute Validity

While simulations provide a controlled environment to assess CAV behaviors under diverse conditions, they inherently lack the unpredictability and complexity of real-world traffic. This is where the distinction between relative and absolute validity becomes critical [4]. Relative validity pertains to the accuracy of specific parameters or scenarios within a simulation when compared to real-world data. Absolute validity, on the other hand, measures the overall fidelity of the simulation in replicating real-world outcomes. The gap between these two types of validity can lead to discrepancies in the performance and safety evaluations of CAV systems or their interactions with VRUs.

To bridge this gap, it is essential to integrate real-world experiments into the overall validation process. Real-world testing not only provides a more comprehensive assessment of CAV systems under real traffic conditions but also helps in evaluating user acceptance of connected automated driving. This approach ensures that CAVs are not only technically sound but also well-received by the public.

Introduction of Experimental Twins

One promising approach to enhance the realism and accuracy of CAV testing is the use of experiments on private testbeds. Drawing a parallel to existing methodologies in other scientific fields, we propose the concept of experiments in an experimental twin on a testbed as a tool in traffic engineering to bridge the significant validity gap between simulation and real-world implementation. These testbeds serve as a hybrid between simulation and real-world environments, enabling researchers to conduct controlled yet highly realistic experiments. By creating experimental twins – replicas of real-world environments within controlled test facilities – researchers can subject CAV systems to a wide range of scenarios that are difficult to replicate in purely digital simulations or also in the real world on public roads. This method combines the best aspects of simulation (control, repeatability, and safety) with the unpredictability and complexity of real-world driving.

Evaluation and Validation

Experimental twins facilitate the evaluation of CAV systems in near-real-world conditions while maintaining a level of control that allows for detailed analysis and iteration. As the complexity of CAV systems and the demands of urban traffic environments continue to grow, the reliance on these sophisticated testing methodologies will become increasingly vital. By augmenting simulation with robust experimental testing, researchers can achieve a higher level of absolute validity, ensuring that CAVs are ready for safe and efficient integration into real-world traffic systems.

Even though simulation models continuously improve due to an ever-growing availability of real-world data sets on traffic behavior like from drone observations [5], still, a calibration of specific traffic behavior patterns requires real-world observations in fully controlled scenarios and conditions. This approach enables researchers and developers to assess and policymakers, interest groups, and the public to experience the real impact of traffic or mobility innovations in a controlled environment before making the substantial, costly, and time-consuming transition to public space, thereby mitigating technical risks, and enhancing social acceptance through fail-safe systems.

Dedicated Private Testbeds and Multi-Stage Development Process

Therefore, in this work we propose the use of experiments on a dedicated private testbed [6,7] as a crucial step in the real environment validation of yet-to-be-implemented traffic and mobility innovations. There are various testbeds for mobility and traffic existing around the world which are focusing mostly on vehicular traffic only and mostly on either the evaluation of safety related questions or for testing vehicle driving dynamics [8,9]. On this testbed we want to focus on urban traffic including all existing modes of transportation and with the aim to assess and validate particularly questions in the field of traffic efficiency and acceptance.

The foremost objective in the development of traffic engineering applications is to ensure the safety of all road users. This is followed by the aim of enhancing traffic flow efficiency for all users. This priority is particularly crucial in urban areas, where a diverse array of road users converge, presenting complex traffic scenarios. To meet the stringent safety standards in road traffic, innovations in traffic engineering typically undergo a multi-stage development process.

In analogy to other scientific domains, we propose to include the crucial new step of experiments in this current state-of-the-art process. This is also represented in the following
Figure **1**:

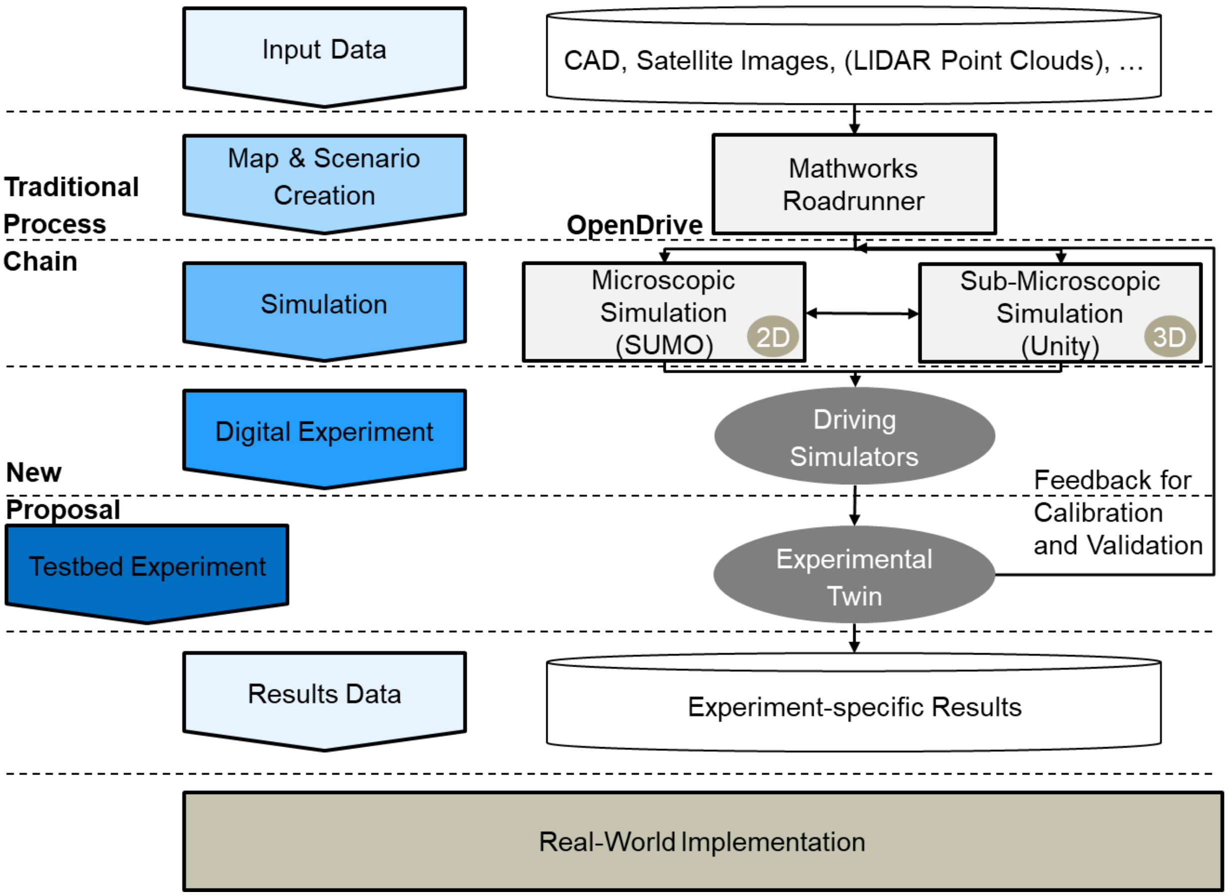

Figure 1 Flowchart showing the connection and interfaces between the different research tools.

In
Figure **1** the proposed steps for the validation of new traffic engineering innovations are represented and described in detail in the following:

1. Input Data:

Detailed data on traffic flows, accident statistics, and various traffic engineering parameters are collected and analyzed. These datasets include precise localization information from CAD models, high-resolution satellite images, and dense LiDAR point clouds. Advanced data analytics techniques are employed to build comprehensive models that provide a deeper understanding of traffic dynamics, patterns, and potential bottlenecks.

2. Map & Scenario Generation:

Tools like MathWorks and Roadrunner as well as the OpenDrive standard are utilized for generating accurate maps and traffic scenarios. Roadrunner is used for creating detailed 3D road networks in OpenDrive guaranteeing standardizing road descriptions, ensuring compatibility and integration across various simulation platforms and real-world applications.

3. Simulation:

Real-world traffic scenarios are meticulously recreated in digital simulations to study the impact of traffic engineering solutions on traffic volume, flow, and safety. Microscopic simulations in SUMO (Simulation of Urban MObility) offer a detailed two-dimensional analysis of individual vehicle movements and interactions. For more granular insights, sub-microscopic simulations in Unity provide a three-dimensional environment that captures finer details of vehicle dynamics.

4. Digital Experiment:

High-fidelity driving and mobility simulators are used to conduct digital experiments. These simulators ensure more realistic human behavior under various conditions and allow researchers to study human traffic behavior and performance as well as interactions between road users under various controlled scenarios. Data from these simulations contribute to refining and calibrating traffic models and improving the accuracy of microscopic simulations.

5. Testbed Experiments:

Prototypes of traffic engineering innovations are rigorously tested in a controlled testbed simulating real-world conditions while ensuring safety and control for the public. On dedicated testbeds the scenarios can be created with the same layouts and boundary conditions like in the simulation. We call this an “Experimental Twin”. The feedback from these tests is critical for calibrating and validating simulation models, ensuring they accurately represent real-world phenomena.

6. Results Data:

The results from these testbed experiments are meticulously recorded and analyzed by extensive sensor systems vehicle-side and infrastructure-side. This includes quantitative data on traffic flow improvements, reductions of safety-critical interactions, and other performance metrics. Qualitative feedback from the road users and observers is also considered. This comprehensive dataset helps in refining the traffic models and informs further development and testing of traffic engineering solutions.

7. Real-World Implementation:

Subsequently the transport engineering innovations are deployed in living labs, which are designated areas within real traffic environments in the public road space where new technologies and concepts are evaluated. These living labs provide a unique opportunity to evaluate the performance of innovations in actual transport systems under uncontrolled boundary conditions. Active user involvement is encouraged, allowing for real-time feedback and interaction with the new technologies, which is crucial for iterative improvement and public acceptance.

TESTBED

The testbed, which is used for the described experiments is located in the South of Munich, Germany at the IABG campus in Taufkirchen. The testbed is a joint venture of Chair of Traffic Engineering and Control at the Technical University of Munich (TUM), the IABG mbH and the Free State of Bavaria.

The testbed consists of an asphalted open testbed area with dimensions of 105 x 80 meters, a two-story parking garage and a simulation center with offices and meeting rooms. In the subsequent sub-sections and in the following

Figure **2**, the individual parts of the testbed and its equipment are described in further detail.

Compared to other testbeds, the IABG and TUM testbed is strongly characterized by its clear focus on urban mobility and complex traffic scenarios with a wide variety of different road users including especially also vulnerable road users (VRU) like pedestrians and cyclists.

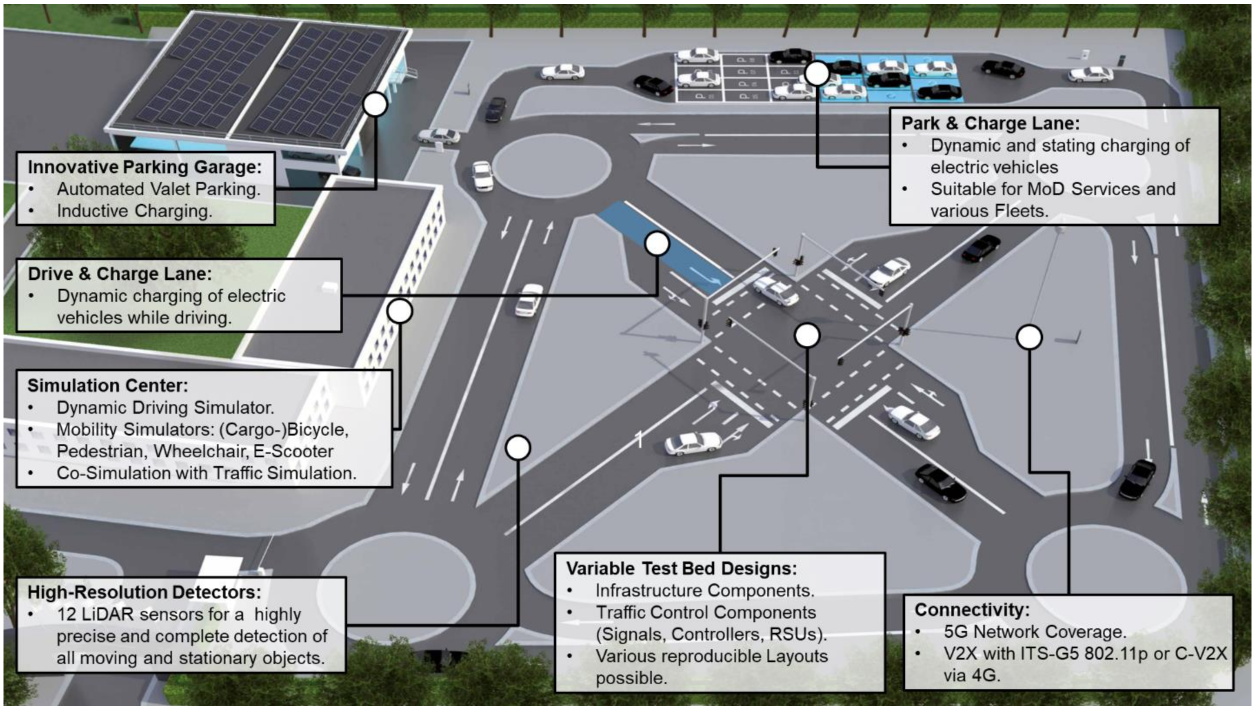

Figure 2 The testbed and its different elements.

Stationary and Mobile LiDAR Sensors

The testbed has a full and redundant sensor coverage with 12 LiDAR sensors from multiple angles to guarantee a 100 % detection rate even with multiple obstacles like houses, trees or other vehicles which might obstruct the field of view of individual sensors.

Each sensor station is equipped with two LiDAR sensors. One 360-degree long-range Ouster OS1 64 Gen2 LiDAR with a vertical field of view of 45 degrees below horizon and 64 lines with an angle speed of 10-20 Hz to cover objects in the distance and one 360-degree RoboSense bpearl blind spot LiDAR with a vertical field of view 90 degrees and 32 lines with an angle speed of 10-20 Hz to cover all objects in the direct surrounding and below the sensor location.

There is one sensor station in the middle of each of the four outer edges of the testbed, mounted at 4 meters height as well as two mobile rover stations with a telescope pole to enable a sensor height between 2,30 and 5,30 meters. Each of those six sensor stations is equipped with both a long-range and a blind spot LiDAR sensor with sensor data fusion of the LiDAR point clouds to cover the full surrounding of the sensor location. The fused point clouds of all sensor stations are used to create a classification of all objects representing traffic participants like car, truck, motorbike, bicycle, and pedestrian [10]. The data is then provided in real-time as a fused object list for the whole testbed.

To cope with the ever-growing importance of data privacy in the public space on the one hand but also the ever-growing need for data from sensors in the field of traffic, the use of LiDAR sensors is a great fit. A big advantage of using LiDAR only sensors is – aside from the precise distance information of alle detected objects – the fully data protection law compliant detection fulfilling the European Union regulation EU 2016/679 on information privacy, the GDPR (General Data Protection Regulation) [11,12].

Stationary and Dynamic Inductive Charging Lanes

The Park & Charge area on the western edge of the testbed is consisting of three parallel lanes. Two lanes are equipped each with three individual inductive charging spots and one lane forms a continuous charging lane with a length of around 17 meters.

The Drive & Charge is also a continuous 17 meters long charging lane which is located at the central part of the testbed and can therefore be used to charge vehicles while driving. It can also be part of a bus stop to inductively charge buses during the onboarding process.

All inducive charging lanes and charging spots are charging equipped vehicles with 22 kW.

Traffic Signal System

A state-of-the-art traffic signal system is also part of the testbed equipment. The traffic signal poles and heads are completely flexible and can be moved and rearranged according to the layout requirements. There are four signal heads with three lamps for vehicular traffic as well as eight signal heads with two lamps for pedestrian signals. The Yunex Silux2.VLP (Very Low Power) LED signals and come with various removable and exchangeable symbol inserts with 200 mm diameter, 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 the Sitraffic Canto as wells as the OCIT-O V2.0 protocols. Up to four partial nodes, 64 signal groups and 250 (virtual) detectors are supported, offering a various range of possible setups. To enable an easy access for research the signal controller includes an API for the integration of individual control algorithms, data connections and data provision to third party system via V2X. It is also enabled to receive and incorporate R09-Telegrams.

For the V2X communication the traffic signal system is also equipped with a hybrid Road-Side Unit (RSU), the Yunex Traffic RSU2X. The RSU2X is equipped with a dual-radio, dual-stack technology to enable the hybrid communication in the IEEE 802.111p/DSRC as well as in the C-V2X (3GPP Rel. 14/15) environment. This is guaranteed by two Toplink 5,9 GHz and one Toplink LTE 4G communication unit providing a maximum radio range of up to 2500 meters. Being able to manage up to 4000 message verifications and 130 message signature operations per second the penetration rate of connected vehicles and connected devices is therefore almost not limited. For the localization and time synchronization the RSU it is equipped with GNSS with 2.0 meters CEP position accuracy and WAAS corrections support with GPS, Galileo, Glonass as well as Beidou satellites.

To enable a state-of-the-art traffic actuated control the traffic signal system is equipped with four Yunex Traffic Sivicam CI-2 MOS (black & white) video cameras, which can be used to create virtual detection loops for eight zones per camera with a guaranteed detection range of 50 meters. Due to existing data privacy regulations the resolution is limited to 640x480 pixel.

5G Campus Network Coverage

The dedicated 5G network of the testbed consists of the two central components RAN and Core. The RAN (Radio Access Network) is made up of a BBU (Base Band Unit) and two ViCell 5G RRH (Remote Radio Heads) connected to it. This creates two 5G base stations (gNodeB), resulting in one radio cell for the open testbed and one radio cell for the interior of the parking garage. There is unrestricted mobility between the cells. The 5G radio cells are operated in the 5G campus network frequency band, i.e., band n78 (3700-3800 MHz).

Due to the open interfaces and the characteristics of a private 5G network, research and development in the direction of 5G+ and 6G technologies is also possible and planned for the existing network infrastructure. This also includes the spoofing and jamming of signals (GPS, V2X-messages, etc.) for CAVs.

Future Parking Garage

Directly connected to the testbed is the dedicated parking garage, with a dimension of approximately 25 x 30 meters. The two stories of the parking garage are connected with a 180 degrees circular ramp. Each story has an especially high ceiling of 2,95 meters for taller vehicles like automated shuttle busses or vehicles with a sensor rack on the roof. With its dimensions and layout, the parking garage provides almost all possible scenario configurations for automated valet parking (AVP) standard according to the ISO 23374-1:2023 *Intelligent transport systems – Automated valet parking systems (AVPS)* [13] and is also suitable as a testbed for cooperative parking systems [14].

Next to the parking garage there is a 25 meters long and 3,20 meters wide ramp with partly a 15 % and a 7.5 % inclination. The ramp ends at an elevated point including a vehicle pit.

The parking garage also has one parking sport with inductive charging at each level. In addition to that, there are three 22 kW conductive charging stations inside of the parking garage as well as two parking spots with a preparation for automated robotic arm charging with up to 100 kW. The power supply is party covered by the own photovoltaics plant with 53 kWp, which covers the complete roof area of the parking garage.

Power and Cable-based Network Connectivity

The whole testbed is equipped with multiple access terminals for 230 V power supply as well as Gigabit Ethernet and glass fiber connections. There are nine access points in cabinets installed surrounding the testbed area connected to a glass fiber ring and seven underground access terminals installed as in the asphalted area. Each of those access terminals is equipped with three 230 V power supply, four to eight LC Duplex glass fiber and four to eight RJ45 Ethernet.

Further Equipment

Further equipment on the testbed includes a bus stop platform which is moveable and adjustable in its dimensions. The bus stop platform is composed of 250 rectangular modules, each measuring 30 x 30 cm with a height of 14 cm. These modules can be individually installed to meet specific experimental requirements, allowing for a wide range of configurations. The platform is bordered with curb elements that distribute lateral loads from bus tires across the platform, ensuring stability and durability. Additionally, these curb elements feature a longitudinal retroreflective strip, making the platform visible both day and night. Those existing individual elements can also be used as curbstones alongside the street space. Flexible lane and pavement markings similar to construction site markings enable the creation of all diverse kinds of scenarios and layouts. In addition to ground-based elements there are also various traffic signs available to recreate different static traffic control scenarios. Artificial buildings and trees and hedges in moveable planters serve as obstacles and field of view obstructions for human drivers as well as sensors and cameras. To allow the participation of any traffic participant in V2X-based cooperative mobility, there is a retrofit V2X-unit (Dual-Mode Road Side Unit with support for DSRC/802.11p as well as C-V2X) available which is able to send and receive CAMs to be displayed on the integrated screen. The V2X unit is designed for a maximum radio coverage of 2,500 m and ensures reliable performance also for high traffic load scenarios with up to 4,000 message verifications and 130 message signature operations per second.

Directly next to the testbed there is also the simulation center and office building of the TUM Research Group on Test Fields and Simulators of the Chair of Traffic Engineering and Control with a direct view on the whole testbed. The simulation center offers various kinds of human-in-the-loop simulators like a bicycle simulator, a cargo-bike simulator, a e-scooter simulator, a wheelchair simulator, a pedestrian simulator, and a state-of-the-art driving simulator with six degrees of freedom [15]. The direct fiberglass connection between the testbed and the simulation center allows low-latency co-simulations in various applications.

Test Vehicles

The testbed also includes various vehicle types, which can be used for the experiments. Among them are for example multiple regular bicycles, four different electric cargo bikes, a wheelchair and regular (electric) vehicles. Various successful and ongoing research also enables the availability of specially equipped vehicles which can be used for research at the testbed. This includes:

- An electric bicycle rickshaw with trailer for Ride-Parcel-Pooling [16].
- A Boreal Bike fully equipped bicycle with C-V2X on-board unit, a 360-degree LiDAR sensor, surround view cameras, GNSS and other cycling behavior sensors [17].
- An e-scooter equipped with an inertial measurement unit providing the e-scooter's acceleration and deceleration profile, its orientation, and angular rates.
- A modified BMW i3 electric vehicle equipped with inductive charging hardware.
- A modified BMW iX1 electric research vehicle for AR testing.
- A connected and automated three-wheeled electric bicycle rickshaw equipped with LiDARs, Radars and cameras for automated and teleoperated driving [18].
- TUM’s automated research vehicle EDGAR [19].

Digital Testbed

To enable the co-simulation in virtual experiments as well as the ex-ante preparation of real-world tests in simulations and simulators the testbed is also provided in a digital version. Those digital versions can also be used for the planning and testing of future real-world layouts, which can then be reproduced and implemented at the testbed.

The development of testbed experiments involves a detailed workflow that begins with the creation of a new CAD plan or the availability of the plan for an existing intersection from a municipality, which provides the foundational blueprint for road layouts and infrastructure. Following this, a Swept Path Analysis is conducted to ensure vehicle maneuverability within the designed spaces, identifying and resolving potential conflicts. The refined designs then serve as the basis for further planning and the generation of detailed maps. These maps typically are created in the OpenDrive [20] format using tools like RoadRunner [21], to create a standardized and high-fidelity representation of the road network. Such OpenDrive maps are crucial for virtual testing, CAV motion planning, and simulation, providing a standardized interface that supports various applications and ensures comprehensive testing and validation of CAV systems.

CONCLUSIONS

This paper highlights the critical need for advancing our current traditional validation of traffic engineering innovations based on traffic simulations. Controlled real-world experiments are crucial and our presented approach fills the gap between theoretical simulations and the final real-world application of new and innovative mobility solutions. Our study proposes the innovative concept of "experimental twins" as a pivotal bridge between simulations and real-world testing. Experimental twins, which replicate real-world environments within controlled testbeds, offer a hybrid approach that combines the controlled, repeatable nature of simulations with the unpredictability and complexity of real-world scenarios. We therefore advocate for the expanded utilization of testbeds, akin to the one presented, to recreate urban scenarios and use cases.

The multi-stage development process outlined in this paper, from data input to real-world implementation, underscores the importance of integrating rigorous real-world experiments into the validation process of traffic engineering solutions. By leveraging advanced sensor technology, such as stationary and mobile LiDAR sensors, to be able to detect everything within the controlled environment, we can gather precise data essential for calibrating and validating VRU behavior and interaction models with CAVs.

Also, it is imperative that experimental research and subsequent real-world implementations prioritize the comprehensive and inclusive representation of diverse road users.

OUTLOOK AND FUTURE WORK

The increasing integration of CAVs in our mobility system creates a significant transition in our urban mobility, characterized by enhanced safety, efficiency, and inclusivity.

The shift towards accommodating Vulnerable Road Users (VRUs) such as cyclists and pedestrians marks a significant departure from the vehicle-centric paradigms of the past. As we continue to refine the methodologies and technologies discussed in this paper, several topics for future work and development present themselves.

An important next step involves improving the accuracy and comprehensiveness of existing VRU behavior models. Given the limited availability of sensor-equipped VRUs, our concept of an experimental twin provides an innovative method to gather data on pedestrian, cyclist, and e-scooter behavior in controlled and reproducible experiments. Future research should explore further development of machine learning algorithms to analyze VRU behaviors and to further enhance the reliability of simulation models.

The concept of the experimental twin has demonstrated significant potential in bridging the gap between digital simulations and real-world scenarios. Future work should focus on refining these experimental setups, ensuring they can replicate increasingly complex urban environments. Collaborations with municipalities and urban planners will be essential to obtain real-world intersection layouts and traffic patterns, which can then be recreated within the testbed. Moreover, continuous improvements in sensor technology and data fusion techniques will enhance the fidelity of these experimental twins, providing more accurate and actionable insights.

The testbed's infrastructure will continue to evolve, incorporating new technologies and expanding its scope to cover a wider range of scenarios. This includes integrating additional VRU types like wheelchair users or other mobility-impaired road users and developing modular infrastructure elements that can be rapidly reconfigured to simulate various urban environments. Enhancing the testbed’s digital twin with high-resolution, real-time data will enable more sophisticated offline simulations but also enable a seamless integration and real-time co-simulation or co-operation of traffic simulation, mobility simulators and testbed experiments. The testbed will also explore the integration of emerging communication technologies, such as 6G and direct cellular connections between devices, to support advanced V2X applications.

The introduction of new transport technologies and models necessitates a parallel focus on societal acceptance and policy adaptation. Future work should include extensive user studies and public engagement initiatives to foster the acceptance of CAV integration strategies. Policymakers must be involved in the development process to ensure that regulations evolve in tandem with technological advancements, facilitating smooth and safe implementation.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: conception and design: M. Margreiter; methodology: M. Ilic, A. Joshi; implementation: M. Margreiter, M. Ilic, A. Joshi; draft manuscript preparation: M. Margreiter. All authors reviewed the results and approved the final version of the manuscript.

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