Autonomous Vehicle for Industry 5.0: Digital Twin for System Safety Validation

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Abstract: Autonomy and digitalization are megatrends in today's world and influence our everyday lives on many levels. The same applies to industry, whereas the manufacturing and engineering industry is heavily under digitalization, also known as Industry 4.0. Now the next step is to focus on where human-centric and sustainable resilient processes are considered a priority. This is an Industry 5.0 paradigm, where humans and robots must work together, with social aspects and increased safety in mind. From the product development and engineering point of view, realistic system simulations and digital counterparts are beneficial to ensure proper complex system development and interactions between robots and humans. In this research, we investigate the methodology to design and implement a comprehensive digital twin of an Autonomous Vehicle (AV) interacting in the context of Industry 5.0 and modern industrial environments. We propose a step-by-step digital twin creation methodology for industrial environments where the AV shuttle bus is intended to serve as a mobility service for the workforce connected to industrial processes. In this research, the main focus is a safety assessment and simulations of an AV interaction in the environment and humans. However, the digital twin, once created, can be used for many other simulations and different purposes.

1 INTRODUCTION

The process from Industry 1.0 to 5.0 represents the evolution of manufacturing and production, driven by technological advancements and changing societal needs. In Industry 1.0, humans have seen the introduction of mechanization, steam engines, and water power, generating a transition from manual labor to mechanized production. From Industry 2.0, electricity and assembly lines powered the introduction of mass production techniques, thus fostering work on standardization and large-scale production. The main strength in this stage was the enhanced productivity at a reduced cost. In the third revolution, in the late 20th century, we have seen the introduction of automation, computing machines, and electronics. This also generated the digitalization of manufacturing processes, the introduction of robotics, and initial IT systems to automate simple mechanical tasks. Here, the industry benefited from greater precision, efficiency, and flexibility. Workers became more educated and performed less risky tasks, thus improving safety.

The fourth industrial revolution, still happening these days, is characterized by the introduction of cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), big data, and cloud computing. Industries are becoming smarter, and machines are more interconnected, the focus goes on data in terms of quantity and speed in data exchange and fostering initial automated decision-making.

The principles at the core of Industry 5.0 lie in the enhancement of human-machine collaboration and customization of production without forgetting about sustainability and ethical AI. In simple words, the concept of Industry 5.0 is to integrate advanced technology having human-centric goals (Alves et al., 2023). The focus shifts to the integration of human creativity and decision-making with advanced technologies like AI and robotics to create more customized and sustainable production.

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Building upon the principles of Industry 5.0, the integration of human-centric, sustainable, and resilient processes into mobility systems is becoming a cornerstone for future innovation. Advanced technologies are pivotal in this transition, enabling the development of adaptive, efficient, and safe solutions for industrial and mobility ecosystems. In the context of AVs, these principles are critical to designing systems that harmoniously interact with humans while addressing sustainability goals. The incorporation of circular economy practices, enhanced collaboration between human workers and intelligent systems, and robust resilience strategies ensures the scalability and reliability of these innovations. This multidimensional approach fosters not only technological advancement but also addresses societal and environmental challenges, aligning industrial progress with broader human and ecological needs. Several EU Horizon projects are actively addressing these challenges e.g. SURE 5.0 - Supporting the SMEs Sustainability and Resilience Transition towards Industry 5.0 in the Mobility, Transport and Automotive, Aerospace and Electronics European Ecosystems, focusing on supporting SMEs in adopting advanced technologies and integrating Industry 5.0 principles into their operations.

The question is now: *"how AVs and smart transportation systems fit into the concept of Industry 5.0?"* From a technological and societal perspective, driverless vehicles embody the core principles of Industry 5.0, i.e. human-machine collaboration, customization of production, sustainability, the human-centric goal in technological development, and ethical AI. Driverless vehicles represent an example of an advanced collaboration between AI, robotics, and human input. Fully AVs must be designed to coexist with road users, requiring advanced human-machine interaction capabilities, such as intuitive communication and adaptive behaviors in the emerging concept known as *language of driving* (Kalda et al., 2022). Furthermore, such automated vehicles are embedded in a more complex system of intelligent mobility, thus

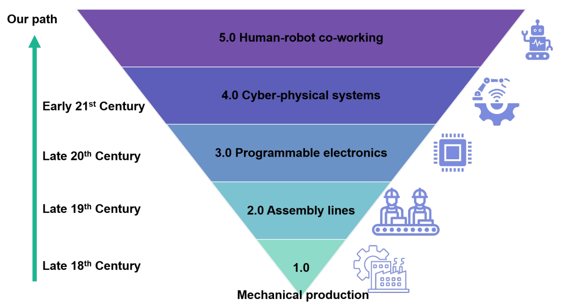

Figure 1: Conceptual depiction of the path from mechanical production to Industry 5.0.

embracing different modes of transportation and on-demand services into more integrated mobility as a service concept. This is a clear example of customization in the production of services. The new mobility systems are also designed in consideration of high efficiency, electrification, and reduced environmental pollution, thus integrating the sustainability concept of Industry 5.0.

2 INTEGRATED AND SECURE MOBILITY AS A SERVICE APPROACH

Mobility as a Service (MaaS) is a concept focused on offering on-demand services with optimized resources. In this framework, centrally orchestrated AVs play a crucial role in addressing mobility demands for specific cases and situations (Hensher et al., 2020). However, for MaaS to be effectively implemented, AV orchestration cannot function as a standalone component of the mobility solution, particularly in public or semi-public transportation contexts. Instead, AVs and on-demand transport services must be integrated into a comprehensive transport management system considering all available transportation options (Slamnik-Kriještorac et al., 2023).

For instance, alongside traditional public transport solutions such as buses and trains, MaaS should accommodate alternative modes of transportation like public e-scooters, ride-sharing, and more. Additionally, various services, directly and indirectly related to transportation, must be considered. Directly related services include ticketing, route planning, seat booking, and similar functions. Indirect services like monitoring, statistical data collection, future route planning, and other emerging functionalities should also seamlessly interface with transportation services.

In the context of Industry 5.0, it is essential to integrate MaaS systems with industrial processes and workforce management procedures to provide seamless and energy-efficient services. This necessitates secure communication between all sub-systems, particularly to protect against cyberattacks (Roberts et al., 2023).

A MaaS solution based on the open-source Estonian X-Road secure data exchange framework, initially developed for governmental data exchange was designed and implemented (Robles et al., 2019), (Paide et al., 2018). This framework was adapted to a MaaS transportation management system and implemented in a prototype solution. The concept was tested in practical pilot cases involving autonomous

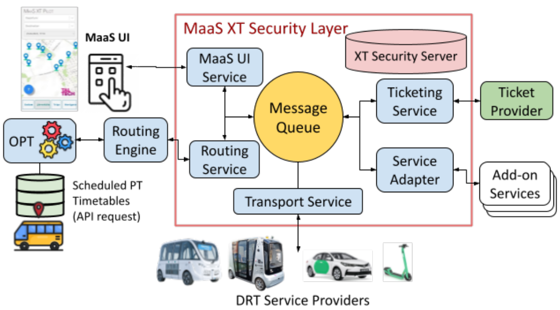

Figure 2: The architecture of the proposed MaaS XT system is designed to seamlessly integrate multiple mobility services into a secure and scalable ecosystem.

minibuses in locations such as Rae and the Port of Tallinn. Additional cybersecurity experiments were conducted on the solution, as detailed in related publications (Roberts et al., 2021). Our research demonstrates the potential of integrating secure, efficient, and flexible transportation management systems to address the growing complexity of mobility demands in modern urban and industrial environments.

The proposed MaaS XT system (Kalda et al., 2024) is a lightweight middleware framework, illustrated in Fig. 2. The system includes several interconnected modules within the Mass XT Security Layer, ensuring robust communication and interaction between service layers. Core components such as the XT Security Server, Ticketing Service, and Service Adapter enable essential functionalities, including secure data exchange, ticketing management, and integrating external add-on services. The Message Queue facilitates reliable and asynchronous communication between modules, ensuring seamless operations. It includes a UI Service for user interfaces and a Routing Service for route optimization, connecting users to various transport solutions. The platform integrates AVs, public transport, and last-mile options such as e-scooters. The Routing Engine and Transport Service components work together to address mobility demands dynamically. A key characteristic of the proposed concept is its open-source nature and openly documented interface descriptions. This openness facilitates the integration of additional functional modules, such as those required for Industry 5.0-specific industrial interfacing with the general MaaS ecosystem.

Add-on services can be seamlessly integrated through the Service Adapter, which employs a standardized specification for unified message exchange structures. This enables consistent and reliable communication between the MaaS XT system and supplementary modules.

In the context of Industry 5.0, the add-on service is envisioned as a system that connects available transport services, including last-mile AVs, to industrial processes. The proposed concept links an AV shuttle fleet with factory operations, enabling the scheduling and planning of routes, as well as efficient fleet management. A fleet of AV shuttles is orchestrated through a cloud-based fleet management solution, which is interconnected with manufacturing processes. This system predicts and dynamically manages demand-based AV shuttle routing according to workforce movement needs within the factory premises, such as transportation between different production units in the factory area.

This approach demonstrates the potential of the MaaS XT system to seamlessly integrate mobility solutions with industrial processes, thereby enhancing operational efficiency and supporting the principles of Industry 5.0

3 METHODOLOGY FOR CREATING DIGITAL TWINS IN INDUSTRY 5.0

3.1 Realistic Environment Creation

Creating realistic environments is pivotal in validating AVs for Industry 5.0, where human-centric and sustainable systems are paramount. Digital twin technology plays a crucial role in replicating real-world scenarios with high fidelity, enabling precise validation processes (Hu et al., 2024). Digital twinning enables us to simulate diverse environments like urban streets, industrial sites, and campuses. Game engines like Unity and Unreal allow the generation of complex environments and scenarios, including varying weather conditions, traffic density, and pedestrian interactions, which are essential for testing the robustness of AV decision-making algorithms(Chance et al., 2022) (Michalík et al., 2021). These simulations replicate static elements, such as road layouts and signage, and dynamic elements, such as vehicle movement and human behavior, ensuring comprehensive validation.

Virtual environment creation for AV validation can be achieved through two main approaches. The

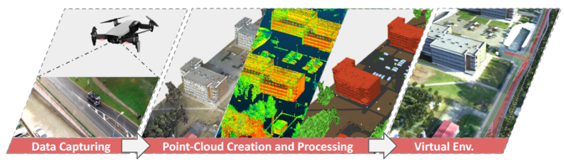

Figure 3: Building a virtual environment by aerial imaging and processing to obtain a 3D virtual terrain.

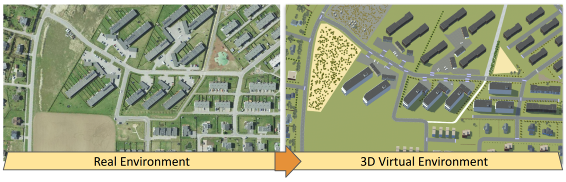

Figure 4: Large-scale residential area converted to a virtual environment usable for high-fidelity AV simulation terrain.

first involves processing aerial imagery with georeferenced data to automatically generate 3D terrains suitable for simulation (see Fig. 3). This method (Malayjerdi et al., 2020) efficiently replicates large-scale environments, including topographical and infrastructural details. While this approach offers automation and scalability, the resulting environments may lack the refined appearance for high-fidelity simulations.

The second approach utilizes pre-made urban features and vegetation to replicate real-world elements more precisely and visually appealingly (see Fig. 4). This method allows for greater control over the environment's aesthetic and functional details but requires more manual work. However, modern tools like RoadRunner simplify this process significantly, enabling users to design detailed virtual environments and export them seamlessly into game-engine-based high-fidelity simulators, enhancing the realism and utility of AV validation scenarios (Pikner et al., 2024).

3.2 Shuttle Modelling

Within the virtual environment engine, vehicles are modeled with varying levels of detail to serve different simulation purposes. A basic cuboid 3D mesh model is used to calculate collisions and define the vehicle's physical boundaries. For sensor simulations, such as LiDAR or radar, a more intricate 3D model is designed to support raycasting and ensure accurate detection interactions. Finally, the most detailed model focuses on the vehicle's appearance, capturing its external design for visual realism. These three models are integrated into the simulation software to collectively define the vehicle's physical, sensory, and visual properties, enabling comprehensive and realistic testing. Fig. 5 shows these three models for the iseAuto shuttle (Sell et al., 2024).

3.3 Simulation Concept

After the virtual environment and the desired vehicle model are prepared, the next step is the evaluation process, which involves three main stages as shown in Fig. 6: scenario generation, simulation execution, and result analysis.

Scenario generation: This is the initial stage where realistic test cases are designed to replicate various operational design domains (ODDs). These scenarios consider diverse factors, including road geometries, environmental conditions, traffic patterns, and pedestrian interactions. By creating functional, logical, and concrete scenarios, the system can address both standard and edge-case situations that AVs may encounter.

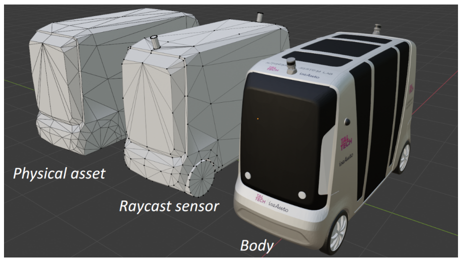

Figure 5: Three different models for a vehicle to be configured inside the simulation engine. Physical, Sensory, and visual mesh are the three mesh models needed for the vehicle model-building process.

Simulation execution: The second stage can utilize a range of low- (Medrano-Berumen et al., 2020) to high-fidelity simulators (Dosovitskiy et al., 2017). Based on this choice, the software-in-the-loop (SiL) (Umang et al., 2024) or hardware-in-the-loop (HiL) method can be configured accordingly. SiL simulations test the software stack, including perception, decision-making, and control algorithms, within a fully virtual environment. This allows for rapid iteration and debugging. In contrast, HiL simulations incorporate physical hardware, such as controllers and sensors, into the virtual setup. This hybrid approach ensures that hardware and software interact seamlessly under real-time conditions, providing a more holistic system evaluation (Sarhadi and Yousefpour, 2015).

Result analysis: The final stage involves assessing the performance and safety of the AV based on simulation outcomes. Metrics such as collision rates, trajectory adherence, response times, and other performance metrics are evaluated to identify potential weaknesses or areas for improvement. Advanced an-

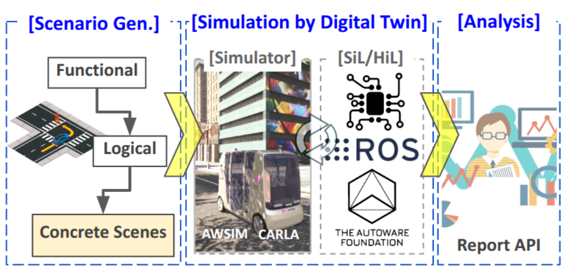

Figure 6: The validation process for AVs: scenario generation, simulation execution, and result analysis.

alytics and visualization tools are often employed to gain deeper insights into system behavior, enabling targeted refinements. These three stages form a robust framework for validating and optimizing AV systems in diverse and complex scenarios.

4 VALIDATION

In the validation framework for AVs, two distinct levels of validation are essential: high-level validation and low-level validation(Pikner et al., 2024; Malayjerdi et al., 2021).

High-level validation focuses on testing the core autonomous algorithms that operate at the software level of the vehicle. These include critical modules such as localization, detection, and planning. Localization ensures the vehicle accurately determines its position in the environment, detection identifies obstacles and interprets sensory inputs, and planning determines safe and efficient routes for navigation. This level of validation is typically conducted using SiL simulations, which provide a virtual environment for testing these algorithms without requiring physical hardware. By simulating various operational design domains (ODDs), high-level validation ensures that the software can perform reliably under diverse and challenging conditions.

Low-level validation, on the other hand, addresses the vehicle's control systems that manage hardware-specific tasks such as driving, steering, and braking. These systems operate through a Controller Area Network (CAN) that facilitates communication between the vehicle's low-level components. Validation at this level involves ensuring that the drive controllers, steering actuators, and other hardware elements function correctly and respond appropriately to commands from the high-level system. Low-level validation can be conducted entirely in simulation, replicating the physical controllers virtually, or by integrating the physical hardware into the simulation framework using HiL setups. This integration bridges the gap between the digital and physical domains, enabling comprehensive testing of software and hardware systems in unison.

Together, high-level and low-level validation form a robust methodology for assessing AV systems' safety, reliability, and performance. This two-tiered approach ensures that the vehicle operates effectively in real-world conditions by addressing both the software and hardware aspects. A Separate case study has been conducted and covered in (Pikner et al., 2022; Sell et al., 2022).

5 INDUSTRIAL USE CASE OF TRANSPORTATION AS A SERVICE

Transport as a Service (TaaS) represents a transformative shift in mobility, moving away from traditional vehicle ownership toward a seamless, on-demand, and subscription-based transportation model. By leveraging advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and data analytics, TaaS platforms enable users to plan, book, and pay for transportation services through digital interfaces, creating a more efficient, affordable, and sustainable ecosystem. MaaS and TaaS might seem similar on a first glance they differ in their scope, focus, and operational approach. While MaaS focuses on integrating and streamlining access to multiple modes of transportation, TaaS emphasizes providing a single, efficient transport service as an alternative to ownership. Both are components of the broader shift toward shared, efficient, and sustainable mobility solutions.

This model aligns with global trends emphasizing shared economies, digital transformation, and environmental responsibility. It is a key enabler of smart cities and modern lifestyles, offering solutions for commuters, tourists, and businesses seeking efficient logistics.

The Volvo Autonomous Solution (V.A.S) at Volvo Group is at the forefront of TaaS innovation, redefining mobility and logistics with a focus on safety, sustainability, and efficiency (Pisarov and Mester, 2021). Volvo's approach extends beyond autonomous trucks or machinery to encompass a fully integrated autonomous transport ecosystem tailored to customer needs (Volvo Autonomous Solutions, 2025).

Key features of Volvo's TaaS solutions include:

- *Advanced Autonomous Transport Systems*: Operating in quarries, mines, and highways, Volvo's systems utilize a "virtual driver," a system developed in-house or with partners like Aurora. These systems manage dynamic driving tasks in predefined environments.
- *High-Integrity AVs*: Purpose-built or adapted for autonomous operations, these vehicles are equipped with robust systems ensuring safety and reliability.
- *Comprehensive Fleet Management*: offering end-to-end control over operations, integrating seamlessly with existing Transportation Management System (TMS), Fleet Management System (FMS), or Enterprise Resource Planning (ERP) systems for optimal performance (Rensfeldt and Kniele, 2024).

Developing a TaaS solution requires consideration of several key areas, including standards, efficiency, and the integration of digital twin technology. Volvo's TaaS framework exemplifies the principles of Industry 5.0, focusing on human-centric, sustainable, and resilient systems. Unlike Industry 4.0, which emphasizes IoT, AI, and automation, Industry 5.0 prioritizes collaboration between advanced technologies and human operators. Volvo's solutions complement human

Figure 7: Developing a Digital Twin for TaaS in V.A.S.

capabilities by enhancing safety and efficiency in hazardous environments like quarries or mines highlighting its human-centric design principle. Autonomous systems handle repetitive tasks, allowing human operators to focus on higher-value activities. By integrating electric and AVs, optimizing transport flows, and minimizing resource wastage, Volvo's TaaS solutions contribute to greener supply chains and reduced environmental impact. These efforts align with global sustainability goals. Simultaneously, Volvo Autonomous Solutions (V.A.S.) has established an internal simulation platform to conduct hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing, utilizing digital twins of sites and vehicles/machines. This approach reduces lead times for software development and verification while optimizing the use of physical resources, including machines, personnel, and test facilities. The V.A.S foster innovation and customization, while its tailored solutions address the unique needs of each client, ensuring optimal performance and adaptability across industries (Fig. 7).

Volvo's TaaS system architecture (Fig. 8) consists of five primary subsystems:

- *Site Control and monitoring*: Centralized management and supervision of the fleet, support systems, and safety protocols.
- *Driver*: In-house systems that execute site control instructions and plan movements.
- *Autonomy-Enabled Machine/Vehicle*: Vehicles equipped with advanced autonomous capabilities.
- *Safety*: Emergency stops, barriers, and integrated safety protocols.
- *Infrastructure*: Supporting systems, including connectivity, GNSS, loading equipment, and charging stations.

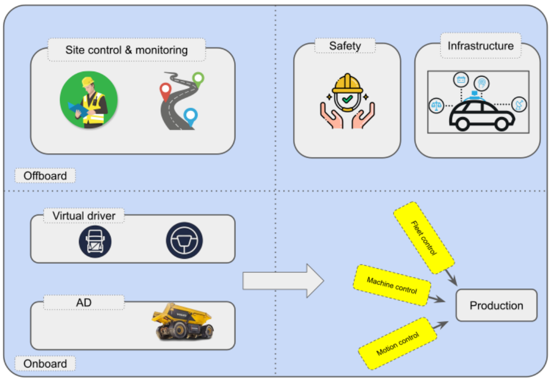

Figure 8: V.A.S TaaS System high-level Architecture with five subsystems.

By embedding Industry 5.0 principles into its TaaS framework, Volvo Group is driving innovation, reducing environmental impact, and enhancing industrial resilience. Its human-centric, sustainable approach is paving the way for a future where technology and ingenuity converge to revolutionize transportation.

5.1 Experimental Pilots

To bridge the gap between theoretical modeling and practical application, the proposed digital twin framework was validated through real-world pilot studies involving AV shuttles and autonomous freight transport operations. These pilot deployments provided valuable data to enhance the accuracy of digital twin simulations, ensuring that the methodology remains grounded in practical, real-world conditions. The collected data enabled refinements in environmental modeling, sensor fusion, and the interaction between autonomous systems and human-operated infrastructure. This section presents two experimental use cases: one focusing on MaaS in urban mobility and another exploring TaaS in logistics and industrial automation.

5.1.1 MaaS Integration

The AV shuttle experiment was conducted in two distinct locations, focusing on testing the interaction between the AV system and its surrounding infrastructure within the MaaS XT platform. The Tallinn Sadama pilot (see Fig. 9), situated in a highly dynamic urban setting, assessed system compatibility and data exchange within a larger digital ecosystem. Meanwhile, in the Rae suburban area, an AV shuttle operated within a predefined service area, collecting diverse environmental and operational data to support

Figure 9: Rae pilot with iseAuto AV shuttle (top) and Tallinna Sadam pilot with Navya EVO AV shuttle (bottom).

Figure 10: Autonomous Operations for DHL Supply Chain.

real-time mobility solutions. The open-data platform created during this pilot study served as a continuous feedback loop, improving the digital twin's predictive modeling capabilities.

By incorporating real-world AV sensor data, the digital twin was enhanced to simulate dynamic road conditions, pedestrian presence, and vehicle interactions more accurately. The integration of this pilot data strengthened the validation process by ensuring that the digital twin could simulate and analyze safety-critical scenarios in MaaS ecosystems. The approach aligns with Industry 5.0 principles by creating a human-centric, resilient, and data-driven mobility framework that enhances adaptive transport planning and decision-making.

5.1.2 TaaS for Industrial Logistics

Beyond urban mobility, the digital twin framework was validated in TaaS applications, particularly in autonomous freight transportation and industrial logistics. The V.A.S. and DHL Supply Chain project exemplifies the implementation of autonomous trucking in logistics networks, improving efficiency and reducing operational costs (Fig. 10). This experiment provided insights into integrating autonomous freight operations within the digital twin, enabling predictive modeling for route optimization, vehicle maintenance forecasting, and operational safety assessments.

Additionally, autonomous transport solutions in the mining industry were explored as another TaaS application. The Boliden mining project leveraged autonomous truck operations to enhance safety and efficiency in mining logistics, adapting infrastructure for autonomous haulage systems. Digital twin models utilized real-world mining transport data, improving terrain modeling, vehicle path optimization, and hazard detection in extreme environments.

Both experiments illustrate the scalability of digital twin methodologies across different industrial domains. By integrating real-world operational data, this research demonstrates the practical applicability of digital twins in optimizing AV ecosystems for future smart cities and industrial automation frameworks.

6 CONCLUSIONS

This paper explores the concept of Industry 5.0 in relation to automated driving and transportation, highlighting advanced collaboration between humans and robots. As robots and automated systems transition from constrained industrial environments to open, shared spaces, emphasis must be placed on ensuring seamless coexistence between humans and robots. The paper presents an integrated approach to leveraging automated driving within the MaaS ecosystem and underscores its applicability through an industrially relevant use case.

While the proposed approach shows significant potential in integrating automated driving within the MaaS ecosystem, certain limitations need to be addressed. These include challenges in ensuring safety and trust in mixed human-robot environments, scalability of solutions across different urban settings, and the adaptation of automated systems to diverse user needs and behaviors. Additionally, the reliance on robust communication infrastructures and data privacy concerns present hurdles for widespread adoption.

To mitigate these challenges, extending validation and verification activities plays a critical role in addressing safety and reliability concerns. However, such efforts demand significant resources and a collaborative commitment across stakeholders, including academia, industry, and regulatory bodies. Furthermore, extensive real-world testing and validation across varied scenarios can provide valuable insights to refine the framework and expand its industrial applications

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