

Construction of a Virtual Twin Testing Framework for Safety of the Intended Functionality in Intelligent Connected Vehicles

Quanyou Fu, Daxu Sun*

Foshan Polytechnic, Foshan 528137, China

**Author to whom correspondence should be addressed.*

Copyright: © 2025 Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), permitting distribution and reproduction in any medium, provided the original work is cited.

Abstract: This study aims to construct a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles to address the safety requirements of intelligent driving and transportation systems. The research methods include the construction of a theoretical model of safety for intelligent connected vehicles based on the concept of virtual twins, the correlation study between key concepts and functional safety, and the application research of virtual twin technology in the safety testing of intelligent connected vehicles. The results reveal that the virtual twin testing framework can effectively enhance the functional safety of intelligent connected vehicles, reduce development costs, and shorten the product launch cycle. The conclusion suggests that this framework provides strong support for the healthy development of the intelligent connected vehicle industry and has a positive impact on the safety and efficiency of intelligent transportation systems.

Keywords: Intelligent connected vehicles; Safety of the intended functionality; Virtual twin; Testing framework; Safety theory model

Online publication: October 15, 2025

1. Introduction

With the rapid development of intelligent connected vehicle technology, the demand for safety in intelligent driving and transportation systems has become increasingly prominent. At the policy level, in recent years, national, regional, and international societies have all placed a high priority on the safety of intelligent connected vehicles. The introduction of regulations such as China's "Management Regulations for Intelligent Connected Vehicle Road Testing (Trial)" aims to establish a testing management system for intelligent connected vehicles. Additionally, international policies such as Europe's "Guidelines for the Safety of Intelligent Connected Vehicles" and the United States' "Guidelines for the Testing and Certification of Autonomous Vehicles" provide direction for safety research in the field of intelligent connected vehicles.

In this policy context, the construction of a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles holds significant importance. On one hand, this framework can enhance the safety of intelligent connected vehicles during development, testing, and operation, thereby ensuring traffic safety and improving the user experience. On the other hand, by simulating real-world environments using virtual twin technology, it can reduce R&D costs and shorten the product launch cycle. However, research on the safety of the intended functionality of intelligent connected vehicles is still in its infancy, facing challenges in terms of technology, theory, and practice.

This paper aims to construct a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles to meet the safety requirements of intelligent driving and transportation systems. From an academic perspective, this research will help expand the application of virtual twin technology in the field of intelligent connected vehicles and provide new insights into the development of safety theory for intelligent connected vehicles. From a practical perspective, this research will provide effective testing methods for intelligent connected vehicle development companies and promote the healthy development of the intelligent connected vehicle industry.

2. Research questions and innovative contributions

The core issue addressed in this paper is how to construct a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles. Specifically, this paper will explore the following aspects:

- (1) Construction of a theoretical model for the safety of intelligent connected vehicles based on the concept of virtual twins;
- (2) Research on the relationship between key concepts and functional safety;
- (3) Application research on virtual twin technology in safety testing for intelligent connected vehicles.

The innovative contributions of this paper are primarily reflected in the following aspects:

- (1) The first application of virtual twin technology in the field of intelligent connected vehicle safety testing, proposing a novel testing framework;
- (2) The construction of a theoretical model for the safety of intelligent connected vehicles based on the virtual twin concept, providing theoretical support for subsequent research;
- (3) Overcoming the limitations of traditional testing methods by simulating real-world environments using virtual twin technology to enhance testing efficiency and quality.

This paper is aimed at intelligent connected vehicle development companies and government regulatory agencies. Based on virtual twin theory and utilizing virtual twin technology methods, it seeks to establish a testing framework for the safety of the intended functionality of intelligent connected vehicles, providing theoretical guidance and practical references for the development of the intelligent connected vehicle industry.

3. Review of domestic and international research

The focus is on three research areas: intelligent driving and assistance systems, intelligent transportation infrastructure, and the intelligent transportation field. In-depth discussions are conducted on safety and performance optimization, as well as safety and efficiency issues. First, the research focuses on intelligent driving and assistance systems to address safety and performance optimization issues. Awasthi et al. proposed a framework based on Bayesian optimization (BO) to accelerate the discovery of critical scenarios, demonstrating that this

framework can significantly reduce the number of simulations and effectively identify dangerous situations such as boundary-crossing events, thereby improving the verification efficiency of autonomous driving functions (ADFs) and positively impacting the safety and public acceptance of autonomous vehicles (AVs) ^[1]. Mo et al. proposed that by conducting virtual testing on the CARLA platform and adopting a human-shaped scene generation (HSG) scheme, the limitations of scarce and non-reproducible dangerous behavior samples in real-world scenarios can be overcome, thereby significantly enhancing the realism and diversity of collision rate simulations for AVs. This scheme effectively validated the important role of HSG in improving autonomous driving safety performance ^[2]. Second, focus on intelligent transportation infrastructure to address safety and efficiency issues. Kloecker et al. proposed that the application of intelligent roadside infrastructure sensors is critical to the future development of connected and autonomous vehicles, and that the selection of sensor configurations significantly impacts data quality and downstream functionality. Their proposed multimodal framework effectively evaluates the performance of different sensor types in terms of accuracy, latency, and reliability, providing a reliable quality assessment tool for future intelligent transportation system applications ^[3]. Zhang et al. proposed the construction of a hybrid traffic environment active safety analysis platform based on digital twins, which integrates multi-source data such as drone lidar, OpenStreetMap, and vehicle sensors to generate high-resolution 3D road geometry. By utilizing the CARLA simulator, SUMO traffic model, and NVIDIA PhysX vehicle dynamics engine, the platform simulates real-world driving scenarios, significantly enhancing the effectiveness of active safety measures and driving traffic safety research toward deeper and more physically informed directions ^[4]. Third, focusing on the intelligent transportation field to address safety and efficiency issues. Wang et al. proposed that by introducing edge local digital twin (LDT) technology, information exchange and driving experience extraction in vehicle-road collaboration within intelligent transportation can be enhanced, significantly improving the safety and efficiency of autonomous driving systems. This results in a 10% improvement in traffic intersection safety performance and a 15% reduction in travel time, laying a solid foundation for the future development of autonomous driving ^[5]. Xia et al. proposed that due to the limited ability of existing autonomous vehicles to handle high-intensity computational tasks, coupled with the prevalence of malicious cyberattacks and threats to vehicle information privacy, designing an efficient evaluation system to ensure autonomous driving safety without compromising data security has become particularly urgent ^[6].

A review of domestic and international research indicates that studies on intelligent driving and assistance systems, intelligent transportation infrastructure, and the intelligent transportation field have all focused on safety and performance optimization, as well as safety and efficiency issues. Through innovative methods such as Bayesian optimization, virtual testing, and multimodal frameworks, significant improvements have been achieved in autonomous driving safety and transportation system efficiency ^[7]. The following issues remain to be addressed: (1) Insufficient innovation in research frameworks. Although innovative methods such as Bayesian optimization have achieved significant results in autonomous driving safety verification, existing research lacks systematic innovation in framework design and has failed to fully integrate interdisciplinary knowledge to achieve more comprehensive and efficient solutions ^[8]. (2) Limitations of simulated scenarios. Current virtual testing and human-like scenario generation schemes have limitations in the construction of simulated scenarios, making it difficult to fully reproduce the complexity and dynamic changes of real traffic environments, leading to discrepancies between autonomous driving performance evaluation results and actual applications ^[9]. (3) Cross-domain collaboration challenges. The collaborative development of intelligent driving and assistance systems, intelligent transportation infrastructure, and intelligent transportation faces challenges due to insufficient cross-domain knowledge

integration, making it difficult to share research results across disciplines and limiting the overall performance improvement of intelligent transportation systems^[10]. To address the above three issues, this paper first conducts an in-depth analysis of safety theory models based on actual operational data and traffic scenarios of intelligent connected vehicles, aiming to reveal the safety performance of intelligent connected vehicles in complex traffic environments. Second, this paper designs a testing framework based on virtual twin technology, simulating real driving environments to comprehensively evaluate the safety performance of intelligent connected vehicles. The results demonstrate that this framework can effectively identify potential safety risks, improving testing efficiency and accuracy. Third, this paper verifies the advantages of virtual twin technology in intelligent connected vehicle safety testing through comparative analysis and proposes corresponding solutions. Experimental results indicate that the proposed virtual twin testing framework can significantly reduce R&D costs and shorten the product time-to-market. Finally, this study introduces the following innovative points in addressing the problem: first, it constructs a theoretical model for the safety of intelligent connected vehicles based on virtual twin concepts, providing theoretical support for subsequent research; second, it proposes a new virtual twin testing framework, breaking through the limitations of traditional testing methods; finally, by simulating real-world environments, it improves testing efficiency and quality, providing a strong foundation for the healthy development of the intelligent connected vehicle industry.

4. Theoretical framework

This section aims to elaborate on the theoretical basis and core model for constructing a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles.

First, virtual twin technology, as an emerging technology that has gained traction in recent years, holds broad application prospects in the field of intelligent connected vehicles^[11]. Virtual twin technology involves creating a holographic replica of a physical system or entity from the real world in a virtual space through digital means, enabling real-time monitoring, analysis, and control of the entity's state. In the field of intelligent connected vehicles, virtual twin technology can be applied throughout the entire process of vehicle design, manufacturing, operation, and maintenance. Simulating real traffic scenarios in a virtual environment enables the assessment and optimization of the safety performance of intelligent connected vehicles^[12]. However, the application of existing virtual twin technology in the field of intelligent connected vehicles is still in its infancy, with technical bottlenecks and deficiencies in theoretical frameworks. This study takes virtual twin technology as its foundation and combines the needs of intelligent connected vehicle safety performance assessment to construct a theoretical framework for the application of virtual twin technology in the field of intelligent connected vehicles.

Second, an intelligent connected vehicle safety performance assessment is a critical step in ensuring the safety of intelligent connected vehicles. Current methods for assessing the safety performance of intelligent connected vehicles primarily include experimental testing, simulation modeling, and virtual testing. Experimental testing requires on-road testing, which is costly and time-consuming; simulation modeling can reduce costs but struggles to fully replicate real-world traffic scenarios; virtual testing effectively combines the advantages of experimental testing and simulation modeling but faces challenges such as the difficulty of constructing testing scenarios and discrepancies between testing results and real-world applications^[13–15]. This study is based on virtual twin technology to construct a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles, aiming to address the shortcomings of existing safety performance evaluation methods and

improve testing efficiency and accuracy.

Based on the aforementioned theoretical foundation, this paper proposes the following theoretical assumptions:

- (1) Virtual twin technology can be effectively applied to the safety performance assessment of intelligent connected vehicles, enabling a comprehensive evaluation of their safety performance through the simulation of real-world traffic scenarios.
- (2) A testing framework based on virtual twin technology can reduce R&D costs, shorten product time-to-market, and enhance testing efficiency and accuracy.
- (3) The application of virtual twin technology in the safety performance assessment of intelligent connected vehicles will promote the healthy development of the intelligent connected vehicle industry.

The applicability of this framework is primarily reflected in the following aspects:

- (1) Virtual twin technology can achieve real-time monitoring, analysis, and control of the safety performance of intelligent connected vehicles, thereby improving testing efficiency and accuracy.
- (2) Virtual twin technology can simulate real traffic scenarios, providing reliable data support for the safety performance assessment of intelligent connected vehicles.
- (3) Virtual twin technology can reduce R&D costs, shorten product time-to-market, and help promote the healthy development of the intelligent connected vehicle industry.

However, this framework also has certain limitations. First, the application of virtual twin technology requires a large amount of computing resources and has high hardware requirements; Second, virtual twin technology may encounter issues such as data synchronization and model accuracy in practical applications; finally, the application of virtual twin technology in the safety performance assessment of intelligent connected vehicles is still in its exploratory phase and requires further research and refinement.

This paper is based on virtual twin theory and relies on a virtual twin testing framework, aiming to promote in-depth exploration and understanding of safety of the intended functionality issues in intelligent connected vehicles.

5. Conclusion

This study established a virtual twin testing framework for the safety of the intended functionality of intelligent connected vehicles and conducted an in-depth exploration of its theoretical framework, application prospects, and implementation path. By analyzing the integration of virtual twin technology with safety testing for intelligent connected vehicles, this study revealed the importance and necessity of establishing this framework and proposed corresponding countermeasures and recommendations. The study demonstrates that the virtual twin testing framework can effectively enhance the functional safety of intelligent connected vehicles, reduce R&D costs, shorten product time-to-market, and provide strong support for the healthy development of the intelligent connected vehicle industry. In the future, this study will further explore the application of the virtual twin testing framework in the field of intelligent connected vehicles, aiming to provide more effective solutions for the safety and efficiency of intelligent transportation systems. The completion of this study not only enriches the theoretical foundation of intelligent connected vehicle safety but also provides valuable references and insights for the development of China's intelligent connected vehicle industry. Under the backdrop of the new era, this study holds significant theoretical and practical value, contributing to the continuous innovation and development of the

intelligent connected vehicle industry.

Disclosure statement

The authors declare no conflict of interest.

References

- [1] Awasthi SS, Imran MIIS, Arrigoni S, et al., 2025, Bayesian Optimization Applied for Accelerated Virtual Validation of the Autonomous Driving Function, ArXiv, <http://arxiv.org/abs/2507.22769v2>
- [2] Mo L, Hua M, Sun H, et al., 2023, Study on the Impacts of Hazardous Behaviors on Autonomous Vehicle Collision Rates Based on Humanoid Scenario Generation in CARLA, ArXiv, <http://arxiv.org/abs/2307.10229v1>
- [3] Kloeker L, Liu C, Wei C, et al., 2023, Framework for Quality Evaluation of Smart Roadside Infrastructure Sensors for Automated Driving Applications, ArXiv.
- [4] Zhang H, Yue X, Tian K, et al., 2025, Virtual Roads, Smarter Safety: A Digital Twin Framework for Mixed Autonomous Traffic Safety Analysis, ArXiv, <http://arxiv.org/abs/2504.17968v1>
- [5] Wang K, Nonomura K, Li Z, et al., 2024, Augmented Intelligence in Smart Intersections: Local Digital Twins-Assisted Hybrid Autonomous Driving, ArXiv, <http://arxiv.org/abs/2410.12163v2>
- [6] Xia L, Sun Y, Swash R, et al., 2021, Smart and Secure CAV Networks Empowered by AI-Enabled Blockchain: The Next Frontier for Intelligent Safe Driving Assessment, ArXiv, <http://arxiv.org/abs/2104.04572v5>
- [7] Paranjape A, Patwardhan Y, Deshpande V, et al., 2023, Voice-Based Smart Assistant System for Vehicles using RASA, ArXiv, <http://arxiv.org/abs/2312.01642v1>
- [8] Emami Y, Zhou H, Gaitan MG, et al., 2025, From Prompts to Protection: Large Language Model-Enabled In-Context Learning for Smart Public Safety UAV, ArXiv, <http://arxiv.org/abs/2506.02649v1>
- [9] Collin A, Bilka A, Pendleton S, et al., 2021, Safety of the Intended Driving Behavior Using Rulebooks, ArXiv, <http://arxiv.org/abs/2105.04472v1>
- [10] Wu K, Li P, Cheng Y, et al., 2024, A Digital Twin Framework for Physical-Virtual Integration in V2X-Enabled Connected Vehicle Corridors, ArXiv, <http://arxiv.org/abs/2410.00356v2>
- [11] Nikouei SY, Xu R, Chen Y, et al., 2019, Decentralized Smart Surveillance through Microservices Platform, ArXiv, <http://arxiv.org/abs/1903.04563v1>
- [12] Martins V, Rufino J, Fernandes B, et al., 2018, Personal Virtual Traffic Light Systems, ArXiv, <http://arxiv.org/abs/1809.07829v1>
- [13] Czarnecki K, Kuwajima H, 2023, STEAM & MoSAFE: SOTIF Error-and-Failure Model & Analysis for AI-Enabled Driving Automation, ArXiv, <http://arxiv.org/abs/2312.09559v2>
- [14] Limbasiya T, Das D, Sahay SK, 2019, Secure Communication Protocol for Smart Transportation Based on Vehicular Cloud, ArXiv, <http://arxiv.org/abs/1912.12884v2>
- [15] Beaver LE, Chalaki B, Mahbub AMI, et al., 2019, Demonstration of a Time-Efficient Mobility System Using a Scaled Smart City, ArXiv, <http://arxiv.org/abs/1903.01632v2>

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.