Embedded Intelligence and Cyber-Physical Systems for Advanced Autonomous Vehicle Control

Prof. Marco A. De Santis
Department of Computer Science, University of Bologna, Italy

Dr. Lucia Romano
Department of Computer, Control, and Management Engineering, Sapienza University of Rome, Italy

V0LUME03 ISSUE01 (2024)
Published Date: 04 January 2024 // Page no.: - 01-08

ABSTRACT

Advances in autonomous vehicle (AV) technology increasingly rely on the seamless fusion of embedded intelligence and cyber-physical systems (CPS) to achieve reliable perception, decision-making, and actuation in real time. Embedded intelligence places machine-learning inference, sensor fusion, and safety monitoring directly on resource-constrained controllers at the vehicle edge, reducing end-to-end latency and improving resilience to connectivity disruptions. Meanwhile, CPS frameworks orchestrate tight feedback loops among heterogeneous sensors, embedded processors, vehicular networks, and cloud or edge infrastructure, enabling scalable coordination across fleets and dynamic environments. This paper surveys recent progress in integrating these domains, highlighting (i) neuromorphic and hardware-accelerated AI for low-power, high-throughput onboard inference; (ii) middleware and digital-twin architectures that close the loop between physical vehicle dynamics and cyber models; (iii) adaptive, learning-based control strategies that account for uncertainty and support fail-operational behavior; and (iv) security mechanisms that maintain integrity across the sensing-computation-control pipeline. We synthesize open research challenges—including real-time verification of AI controllers, cross-layer cybersecurity, and standardized co-simulation frameworks—and outline future directions such as federated learning, explainable autonomy, and safety-assured reinforcement learning. By illuminating the synergistic potential of embedded intelligence and CPS, this work charts a path toward AV platforms that are more responsive, trustworthy, and scalable.

Keywords: - Autonomous Vehicles, Embedded Intelligence, Cyber-Physical Systems, Real-Time Control, Sensor Fusion, Machine Learning, Edge Computing, Vehicle-to-Everything (V2X), Adaptive Control, Functional Safety.

1. INTRODUCTION

The advent of autonomous vehicles (AVs) marks a transformative era in transportation, promising enhanced safety, efficiency, and accessibility in smart cities and intelligent transportation systems (ITS) [1, 10, 16]. At the core of this revolution lies the sophisticated interplay of Cyber-Physical Systems (CPS) and embedded technology. CPS refers to systems that integrate computational and physical components, interacting in a feedback loop where physical processes affect computations and vice-versa [11]. In the context of AVs, these systems encompass a multitude of sensors, processors, communication networks, and actuators that collectively enable autonomous operation [17, 21]. Embedded technology, on the other hand, provides the foundational hardware and software platforms – such as Electronic Control Units (ECUs) and real-time operating systems – upon which these CPS are built and executed [43].

The seamless integration of these two domains is paramount for robust and reliable autonomous driving. AVs demand real-time data processing, precise control actions, and resilient security measures, all facilitated by high-performance embedded systems within a complex CPS framework [24]. This article explores how the convergence of CPS principles and advanced embedded technologies is instrumental in controlling autonomous vehicle driving, addressing the intricate challenges and unlocking the vast potential of this emerging field. We delve into the methodologies, observed results, and broader implications of this integration, culminating in a discussion of future directions and persistent challenges.

METHODS

The control of autonomous vehicle driving through the integration of CPS and embedded technology involves a multi-layered architecture, where various components work in concert to achieve intelligent navigation and decision-making. This section outlines the key methodological aspects and technologies employed.

1. Architectural Foundation: Cyber-Physical Systems in AVs

Autonomous vehicles are inherently complex CPS, comprising interconnected computational elements and physical processes [11, 24]. The architecture typically involves layers for perception, decision-making, and actuation.

- **Sensors for Environmental Perception:** AVs rely heavily on a diverse suite of sensors to perceive their surroundings [21]. This includes LiDAR, cameras, radar, and ultrasonic sensors [21]. Advanced perception algorithms, often leveraging deep learning and machine learning, process data from these sensors for object detection, segmentation, and tracking [14, 20, 26, 31, 39, 48]. For instance, joint scene flow estimation and moving object segmentation on rotational LIDAR data enhance environmental understanding [13].
- **Communication Networks:** Vehicle-to-everything (V2X) communication, including Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V), is a critical component for information sharing and cooperative control [34, 35, 36, 37, 40]. Technologies like 5G and the Internet of Vehicles (IoV) provide the necessary high-bandwidth, low-latency communication for real-time data exchange, enabling advanced functionalities like intelligent traffic flow control [15, 27, 46, 50]. This communication is crucial for overcoming occlusions and sharing perception task-oriented information [49].
- **Centralized and Distributed Control:** Control mechanisms can range from centralized ECUs to distributed safety mechanisms utilizing middleware and hypervisors for enhanced reliability and redundancy [4, 43]. Real-time control is paramount for responsive and safe operation [15, 29, 51].

2. Embedded Technology for Real-time Control

Embedded systems are the computational backbone of AVs, providing the processing power and real-time capabilities required for autonomous functions.

- **Electronic Control Units (ECUs) and Domain Controllers:** Modern AVs feature numerous ECUs dedicated to specific functions (e.g., engine control, braking, steering) [43]. The trend is moving towards domain controllers that integrate multiple functions, reducing complexity and enhancing communication [43]. These units often employ real-time operating systems (RTOS) to guarantee timely execution of critical tasks.
- **Middleware and Software Architectures:** Middleware facilitates communication and data exchange between different software components and hardware modules within the vehicle [4]. This includes robust frameworks for managing sensor data, control algorithms, and human-machine interaction.
- **High-Performance Computing Platforms:** Autonomous driving requires significant computational power for complex algorithms like sensor fusion, path planning, and decision-making [19]. Embedded systems for AVs are equipped with powerful processors, GPUs, and specialized AI accelerators to handle these demands efficiently.
- **Integration with AI and Machine Learning:** Machine learning, particularly deep learning, is deeply embedded within AV control systems for tasks such as object recognition, prediction of other road users' behavior, and end-to-end driving policies [18, 41, 45]. Hybrid modeling techniques, like AGRU with a dual-attention mechanism, are used for vehicle lateral dynamics control under limited data [12]. Optimal consensus control for multi-agent systems with time delays also leverages data-based approaches with prioritized experience replay [25].

3. Key Operational Aspects

The integrated CPS and embedded technologies enable several critical operational aspects of autonomous driving.

- **Localization and Mapping:** Accurate self-localization is fundamental. Technologies like GNSS (Global Navigation Satellite System) with triple-frequency signals and various sensor fusion techniques (e.g., LiDAR-inertial odometry) contribute to precise positioning, even in challenging urban environments [19, 44, 47].
- **Path Planning and Motion Control:** After perceiving the environment and localizing the vehicle, sophisticated algorithms generate safe and efficient trajectories [32]. This involves real-time adjustment of speed, steering, and braking. Advanced control theories, including fuzzy control and fixed-time safe tracking control, are being developed to enhance performance and stability [22, 33, 47]. For heavy trucks, adaptive memory event triggered output feedback finite-time lane keeping control with roll prevention is crucial [15].
- **Cybersecurity and Safety Mechanisms:** Given the safety-critical nature of AVs, cybersecurity is integral to the CPS design [11, 24]. Embedded security modules, secure communication protocols, and threat analysis frameworks are crucial to protect against adversarial attacks on sensors, communication, and control systems [2, 11, 16, 28,

30, 42]. Distributed safety mechanisms further enhance overall system dependability [4].

RESULTS

The extensive integration of cyber-physical systems and embedding technology has yielded significant advancements in the capabilities and performance of autonomous vehicles. These results manifest across various critical domains of autonomous driving.

1. Enhanced Perception and Environmental Understanding

The synergy between diverse sensors and embedded processing units has dramatically improved the vehicle's ability to perceive its environment.

- **Multi-Sensor Fusion:** Advanced sensor fusion techniques, often powered by deep learning models running on embedded processors, lead to more robust and accurate environmental models [19, 20]. This allows for precise object detection, classification, and tracking even in complex and dynamic urban scenarios [31, 39, 48]. For example, the joint scene flow estimation and moving object segmentation from rotational LiDAR data significantly improves environmental perception [13].
- **Improved Localization:** The integration of GNSS, inertial measurement units (IMUs), and visual odometry, processed by embedded systems, provides highly accurate and resilient localization, critical for precise navigation in varied environments, including urban areas [44, 47]. Positioning calibration mechanisms for connected autonomous vehicles further enhance accuracy [29].
- **Real-time Perception under Challenging Conditions:** Embedded systems enable real-time processing of vast amounts of sensor data, allowing AVs to react instantaneously to changing road conditions, traffic, and unexpected events [15]. Research is ongoing to improve perception under extreme weather conditions [42].

2. Sophisticated Decision-Making and Motion Control

The embedded intelligence within the CPS framework enables highly sophisticated decision-making and precise motion control.

- **Adaptive and Robust Control:** Advanced control algorithms, including non-linear fractional-order type-3 fuzzy control, have been successfully implemented on embedded platforms to enhance path-tracking performance and stability [33]. Fixed-time safe tracking control for uncertain high-order non-linear systems further improves robust control capabilities [22].
- **Intelligent Trajectory Planning:** AVs can generate optimal and safe trajectories in real-time, considering traffic dynamics, obstacles, and vehicle capabilities [32, 51]. This includes advanced lane-keeping control with roll prevention for heavy trucks [15] and integrated deep reinforcement learning frameworks for high-speed cruising performance [28].
- **Human-like Control Maneuvers:** Developments in robotic manipulation, such as friction-driven strategies for agile steering wheel manipulation, demonstrate the embedded systems' capacity to execute complex, human-like control actions [9].
- **Improved Traffic Flow and Efficiency:** Cooperative control strategies enabled by V2X communication, processed by embedded systems, can stabilize freeway mixed traffic, improve throughput, and optimize traffic flow [38, 52]. Real-time bus waiting time estimation systems based on multi-source data further exemplify efficiency gains [35].

3. Enhanced Safety and Security Posture

The emphasis on CPS security and safety-by-design principles in embedded systems has led to more resilient autonomous platforms.

- **Cyber-Physical Security:** The architectural integration of security measures, from secure vehicular communication protocols to reconfigurable ECU architectures, has been shown to mitigate various cyber threats to AVs [2, 11, 24, 42, 43]. This includes cross-layer authentication based on physical-layer signatures for secure vehicular communication [45].
- **Fault Tolerance and Dependability:** Embedded systems with redundant components and fail-safe algorithms for exteroceptive sensors contribute significantly to the overall dependability of autonomous vehicles, ensuring continued safe operation even in the event of component failures [4, 44].
- **Risk Assessment and Mitigation:** Scenario-based threat analysis and risk assessment for over-the-air updates demonstrate proactive approaches to maintaining safety and security throughout the vehicle's lifecycle [26].

Overall, the results indicate that the deep integration of CPS and embedded technology is not merely an incremental improvement but a fundamental enabler for the advanced functionalities and safety critical operations of autonomous vehicles.

DISCUSSION

The integration of Cyber-Physical Systems (CPS) with embedded technology for controlling autonomous vehicle driving represents a significant leap forward in automotive engineering and intelligent transportation. The results demonstrate that this synergistic approach enhances perception, refines decision-making, and strengthens the overall safety and security of AVs. However, this complex integration also introduces a unique set of challenges that warrant ongoing research and development.

1. Significance of Integrated Systems

The reported results underscore the criticality of CPS and embedded technology working in unison. The ability to process vast amounts of sensor data in real-time, make complex decisions, and execute precise control commands is directly attributable to the high-performance embedded computing platforms and the robust, interconnected nature of the CPS architecture. This integration moves AVs beyond mere automation towards genuine autonomy, where vehicles can perceive, understand, and interact with dynamic environments much like human drivers [1].

The improvements in perception, particularly through multi-sensor fusion [19, 20] and real-time scene analysis [13], allow AVs to build a more comprehensive and accurate model of their surroundings, which is foundational for safe navigation. Similarly, advanced control algorithms, executed by embedded systems, enable smoother, more efficient, and safer vehicle movements, from lane-keeping [15] to agile steering [9] and high-speed cruising [28]. The focus on cybersecurity within this integrated framework is paramount, as the vehicle's increasing connectivity and reliance on software make it vulnerable to attacks that could have catastrophic safety implications [2, 11, 24]. Solutions like cross-layer authentication [45] and secure ECU architectures [43] are vital in this regard.

2. Persistent Challenges and Future Directions

Despite the progress, several challenges remain.

- **Security and Robustness:** While advancements in cybersecurity for AVs have been made [11, 24], the attack surface continues to grow with increasing connectivity (V2X) [2, 40]. Ensuring absolute robustness against sophisticated adversarial attacks on perception [16] and control systems remains a major hurdle. Future work must focus on more resilient, self-healing CPS architectures and advanced intrusion detection systems [18].
- **Real-time Performance and Resource Management:** Autonomous driving demands extremely low latency and high computational throughput. Optimizing resource management in vehicular edge computing to balance demand and communication overhead for federated learning tasks in IoV is a current area of research [27, 50]. Future embedded systems need to push the boundaries of real-time processing capabilities, potentially leveraging novel computing paradigms.
- **Data Management and AI Model Development:** The immense volume of data generated by AVs presents challenges in storage, processing, and transfer [27]. Developing efficient data-driven AI models that can learn from limited data or adapt to novel situations (few-shot identification) [3] is crucial. This includes empowering spatial knowledge graphs for mobile traffic prediction [23] and hybrid modeling approaches for vehicle dynamics [12, 53].
- **Validation and Verification:** Proving the safety and reliability of complex, AI-driven CPS in AVs is an enormous task. Comprehensive testing, simulation (e.g., TORCS [47]), and formal verification methods are essential. Scenario-based threat analysis and risk assessment for over-the-air updates is a step in this direction [26].
- **Human-Machine Interaction (HMI) and User Acceptance:** As automation levels increase, understanding drivers' perception and trust in autonomous systems is vital [37]. Research on augmented recognition of distracted driving states [44] and subjective driving risk prediction [39] contributes to safer and more intuitive HMI.
- **Legal and Ethical Frameworks:** The rapid technological advancement outpaces the development of legal and ethical frameworks for liability, data privacy, and decision-making in unforeseen circumstances. This requires ongoing dialogue among policymakers, engineers, and ethicists.
- **Interoperability and Standardization:** Ensuring seamless interoperability between different manufacturers' AVs and between vehicles and infrastructure requires robust standardization efforts in communication protocols and data formats [4, 10].
- **Advanced Control and Optimization:** Future research will continue to refine control strategies,

including neural network prescribed-time observer-based output-feedback control for uncertain non-linear systems [30], and ship formation and route optimization using improved PSO and DP algorithms [48], which can be adapted to AV platooning and traffic management.

3. Comparative Analysis

Compared to earlier approaches focusing solely on isolated vehicle control systems, the integrated CPS and embedded technology paradigm offers a holistic solution [17]. Earlier research on intelligent vehicle network routing [34, 35, 36] laid the groundwork for today's V2X capabilities. The current focus on machine learning and deep learning within vehicular networks [46], coupled with advanced sensor fusion [20], represents a significant evolution from traditional control theory applications in vehicles. The emphasis on security as an inherent part of the CPS design, rather than an afterthought, is also a crucial distinction [11, 24].

CONCLUSION

The successful realization of fully autonomous vehicles hinges upon the intricate integration of Cyber-Physical Systems and advanced embedded technologies. This article has highlighted how this convergence enables sophisticated perception, intelligent decision-making, and precise motion control, leading to enhanced safety, efficiency, and overall performance in autonomous driving. While significant progress has been made in areas such as multi-sensor fusion, adaptive control, and cyber-physical security, persistent challenges related to robustness against adversarial attacks, real-time performance optimization, and comprehensive validation remain. Future research must continue to push the boundaries of AI, communication, and control theory within these integrated frameworks to usher in a new era of truly autonomous and safe transportation.

REFERENCES

1. Aldakkhelallah A, Simic M. 2021. Autonomous vehicles in intelligent transportation systems.
2. Ali ES, Hasan MK, Hassan R, Saeed RA, Hassan MB, Islam S, Nafi NS, Bevinakoppa S. 2021. Machine learning technologies for secure vehicular communication in internet of vehicles: recent advances and applications. Security and Communication Networks 2021(1):8868355
3. An X-K, Du L, Jiang F, Zhang Y-J, Deng Z-C, Kurths J. 2024. A few-shot identification method for stochastic dynamical systems based on residual multipeaks adaptive sampling. Chaos: An Interdisciplinary Journal of Nonlinear Science 34(7):62101
4. Bijlsma T, Buriachevskyi A, Frigerio A, Fu Y, Goossens K, Örs AO, van der Perk PJ, Terechko A, Vermeulen B. 2020. A distributed safety mechanism using middleware and hypervisors for autonomous vehicles.
5. Cai Z, Zhu X, Gergondet P, Chen X, Yu Z. 2023. A friction-driven strategy for agile steering wheel manipulation by humanoid robots. Cyborg and Bionic Systems 4(2):64
6. Campisi T, Severino A, Al-Rashid MA, Pau G. 2021. The development of the smart cities in the connected and autonomous vehicles (CAVs) era: from mobility patterns to scaling in cities. Infrastructures 6(7):100
7. Chattopadhyay A, Lam K-Y. 2017. Security of autonomous vehicle as a cyber-physical system.
8. Chattopadhyay A, Lam K-Y, Tavva Y. 2020. Autonomous vehicle: security by design. IEEE Transactions on Intelligent Transportation Systems 22(11):7015-7029
9. Chen X, Cui J, Liu Y, Zhang X, Sun J, Ai R, Gu W, Xu J, Lu H. 2024b. Joint scene flow estimation and moving object segmentation on rotational LIDAR data. IEEE Transactions on Intelligent Transportation Systems 25(11):17733-17743
10. Chen J, Yu C, Wang Y, Zhou Z, Liu Z. 2024a. Hybrid modeling for vehicle lateral dynamics via AGRU with a dual-attention mechanism under limited data. Control Engineering Practice 151(2):106015
11. Cheng Q, Chen W, Sun R, Wang J, Weng D. 2024. RANSAC-based instantaneous real-time kinematic positioning with GNSS triple-frequency signals in urban areas. Journal of Geodesy 98(4):24
12. Damaj IW, Serhal DK, Hamandi LA, Zantout RN, Mouftah HT. 2021. Connected and autonomous electric vehicles: quality of experience survey and taxonomy. Vehicular Communications 28(16):100312
13. Deng Y, Zhang T, Lou G, Zheng X, Jin J, Han Q-L. 2021. Deep learning-based autonomous driving systems: a survey of attacks and defenses. IEEE Transactions on Industrial Informatics 17(12):7897-7912
14. Ding F, Zhu K, Liu J, Peng C, Wang Y, Lu J. 2024b. Adaptive memory event triggered output feedback finite-time lane keeping control for autonomous heavy truck with roll prevention. IEEE Transactions on Fuzzy Systems 32(12):6607-6621
15. Ding C, Zhu L, Shen L, Li Z, Li Y, Liang Q. 2024a. The intelligent traffic flow control system based on 6G and optimized genetic algorithm. IEEE Transactions on Intelligent Transportation Systems 1-14

16. DiPalma C, Wang N, Sato T, Chen QA. 2021. Security of camera-based perception for autonomous driving under adversarial attack.

17. Duan X, Jiang H, Tian D, Zou T, Zhou J, Cao Y. 2021. V2I based environment perception for autonomous vehicles at intersections. China Communications 18(7):1-12

18. Eskandarian A, Wu C, Sun C. 2019. Research advances and challenges of autonomous and connected ground vehicles. IEEE Transactions on Intelligent Transportation Systems 22(2):683-711

19. Fayyad J, Jaradat MA, Gruyer D, Najjaran H. 2020. Deep learning sensor fusion for autonomous vehicle perception and localization: a review. Sensors 20(15):4220

20. Fu Y, Dong M, Zhou L, Li C, Yu FR, Cheng N. 2024. A distributed incentive mechanism to balance demand and communication overhead for multiple federated learning tasks in IoV. IEEE Internet of Things Journal 12(8):10479-10492

21. Gazis A, Ioannou E, Katsiri E. 2019. Examining the sensors that enable self-driving vehicles. IEEE Potentials 39(1):46-51

22. Gong J, Liu Y, Li T, Chai H, Wang X, Feng J, Deng C, Jin D, Li Y. 2023. Empowering spatial knowledge graph for mobile traffic prediction.

23. Guo C, Hu J, Hao J, Celikovsky S, Hu X. 2023. Fixed-time safe tracking control of uncertain high-order nonlinear pure-feedback systems via unified transformation functions. ArXiv

24. Guo L, Yang B, Ye J, Chen H, Li F, Song W, Du L, Guan L. 2020. Systematic assessment of cyber-physical security of energy management system for connected and automated electric vehicles. IEEE Transactions on Industrial Informatics 17(5):3335-3347

25. Hu J, Jiang H, Liu D, Xiao Z, Zhang Q, Min G, Liu J. 2023. Real-time contactless eye blink detection using UWB radar. IEEE Transactions on Mobile Computing 23(6):6606-6619

26. Ji L, Lin Z, Zhang C, Yang S, Li J, Li H. 2024. Data-based optimal consensus control for multiagent systems with time delays: using prioritized experience replay. IEEE Transactions on Systems, Man, and Cybernetics: Systems 54(5):3244-3256

27. Ju X, Jiang Y, Jing L, Liu P. 2023. Quantized predefined-time control for heavy-lift launch vehicles under actuator faults and rate gyro malfunctions. ISA Transactions 138(2):133-150

28. Khatun M, Glass M, Jung R. 2021. An approach of scenario-based threat analysis and risk assessment over-the-air updates for an autonomous vehicle.

29. Li T, Alhilal A, Zhang A, Hoque MA, Chatzopoulos D, Xiao Z, Li Y, Hui P. 2019. Driving big data: a first look at driving behavior via a large-scale private car dataset.

30. Li S, Chen J, Peng W, Shi X, Bu W. 2023a. A vehicle detection method based on disparity segmentation. Multimedia Tools and Applications 82(13):19643-19655

31. Li Z, Hu J, Leng B, Xiong L, Fu Z. 2023b. An integrated of decision making and motion planning framework for enhanced oscillation-free capability. IEEE Transactions on Intelligent Transportation Systems 25(6):5718-5732

32. Liang J, Yang K, Tan C, Wang J, Yin G. 2024. Enhancing high-speed cruising performance of autonomous vehicles through integrated deep reinforcement learning framework. IEEE Transactions on Intelligent Transportation Systems 26(1):835-848

33. Ling Y, Chu X, Lu Z, Wang L, Wen X. 2020. PCM: a positioning calibration mechanism for connected autonomous vehicles. IEEE Access 8:95046-95056

34. Luo J, Wang G, Li G, Pesce G. 2022. Transport infrastructure connectivity and conflict resolution: a machine learning analysis. Neural Computing and Applications 34(9):6585-6601

35. Lv J, Ju X, Wang C. 2025. Neural network prescribed-time observer-based output-feedback control for uncertain pure-feedback nonlinear systems. Expert Systems with Applications 264(5):125813

36. Mohammadzadeh A, Taghavifar H, Zhang C, Alattas KA, Liu J, Vu MT. 2024. A non-linear fractional-order type-3 fuzzy control for enhanced path-tracking performance of autonomous cars. IET Control Theory & Applications 18(1):40-54

37. Noh S, An K, Han W. 2015. Toward highly automated driving by vehicle-to-infrastructure communications.

38. Novakazi F, Johansson M, Strömberg H, Karlsson M. 2021. Levels of what? Investigating drivers' understanding of different levels of automation in vehicles. Journal of Cognitive Engineering and Decision Making 15(2–3):116-132

39. Peng X, Song S, Zhang X, Dong M, Ota K. 2024. Task offloading for IoAV under extreme weather conditions using dynamic price driven double broad reinforcement learning. IEEE Internet of Things Journal 11(10):17021-17033

40. Poudel B, Munir A. 2018. Design and evaluation of a reconfigurable ECU architecture for secure and dependable automotive CPS. IEEE Transactions on Dependable and Secure Computing 18(1):235-252

41. Qi G, Liu R, Guan W, Huang A. 2024. Augmented recognition of distracted driving state based on electrophysiological analysis of brain network. Cyborg and Bionic Systems 5(2):130

42. Rasheed I, Hu F, Hong Y-K, Balasubramanian B. 2020. Intelligent vehicle network routing with adaptive 3D beam alignment for mmWave 5G-based v2X communications. IEEE Transactions on Intelligent Transportation Systems 22(5):2706-2718

43. Rong Y, Xu Z, Liu J, Liu H, Ding J, Liu X, Luo W, Zhang C, Gao J. 2022. Du-Bus: a realtime bus waiting time estimation system based on multi-source data. IEEE Transactions on Intelligent Transportation Systems 23(12):24524-24539

44. Sabaliauskaite G, Cui J, Liew LS, Zhou F. 2018. Integrated safety and cybersecurity risk analysis of cooperative intelligent transport systems.

45. Sharath MN, Mehran B. 2021. A literature review of performance metrics of automated driving systems for on-road vehicles. Frontiers in Future Transportation 2:759125

46. Shin D, Park K-M, Park M. 2020. Development of fail-safe algorithm for exteroceptive sensors of autonomous vehicles. Electronics 9(11):1774

47. Song D, Zhao J, Zhu B, Han J, Jia S. 2024. Subjective driving risk prediction based on spatiotemporal distribution features of human driver's cognitive risk. IEEE Transactions on Intelligent Transportation Systems 25(11):16687-16703

48. Sun G, Song L, Yu H, Chang V, Du X, Guizani M. 2018a. V2V routing in a VANET based on the autoregressive integrated moving average model. IEEE Transactions on Vehicular Technology 68(1):908-922

49. Sun G, Zhang Y, Liao D, Yu H, Du X, Guizani M. 2018b. Bus-trajectory-based street-centric routing for message delivery in urban vehicular ad hoc networks. IEEE Transactions on Vehicular Technology 67(8):7550-7563

50. Sun G, Zhang Y, Yu H, Du X, Guizani M. 2019. Intersection fog-based distributed routing for V2V communication in urban vehicular ad hoc networks. IEEE Transactions on Intelligent Transportation Systems 21(6):2409-2426

51. Tang F, Mao B, Kato N, Gui G. 2021. Comprehensive survey on machine learning in vehicular network: technology, applications and challenges. IEEE Communications Surveys & Tutorials 23(3):2027-2057

52. Vasudev H, Deshpande V, Das D, Das SK. 2020. A lightweight mutual authentication protocol for V2V communication in internet of vehicles. IEEE Transactions on Vehicular Technology 69(6):6709-6709

53. Wang Q, Chen J, Song Y, Li X, Xu W. 2024b. Fusing visual quantified features for heterogeneous traffic flow prediction. Promet-Traffic&Transportation 36(6):1068-1077

54. Wang Y, Sun R, Cheng Q, Ochieng WY. 2024c. Measurement quality control aided multisensor system for improved vehicle navigation in urban areas. IEEE Transactions on Industrial Electronics 71(6):6407-6417

55. Wang F, Xin X, Lei Z, Zhang Q, Yao H, Wang X, Tian Q, Tian F. 2024a. Transformer-based spatio-temporal traffic prediction for access and metro networks. Journal of Lightwave Technology 42(15):5204-5213

56. Wymann B, Espié E, Guionneau C, Dimitrakakis C, Coulom R, Sumner A. 2000. TORCS, the open racing car simulator. Software. 4(6):2

57. Xiao B, Guo J, He Z. 2021. Real-time object detection algorithm of autonomous vehicles based on improved YOLOV5S.

58. Xiao J, Ren Y, Du J, Zhao Y, Kumari S, Alenazi MJ, Yu H. 2024. CALRA: practical conditional anonymous and leakage-resilient authentication scheme for vehicular crowdsensing communication. IEEE Transactions on Intelligent Transportation Systems 99:1-13

59. Xiao Z, Shu J, Jiang H, Min G, Chen H, Han Z. 2023. Overcoming occlusions: perception task-oriented information sharing in connected and autonomous vehicles. IEEE Network 37(4):224-229

60. Xu P, Lan D, Yang H, Zhang S, Kim H, Shin I. 2025. Ship formation and route optimization design based on improved PSO and DP algorithm. IEEE Access 13:15529-15546

61. Yang J, Yang K, Xiao Z, Jiang H, Xu S, Dustdar S. 2023. Improving commute experience for private car users via blockchain-enabled multitask learning. IEEE Internet of Things Journal 10(24):21656-21669

62. Yao Y, Shu F, Cheng X, Liu H, Miao P, Wu L. 2023. Automotive radar optimization design in a spectrally crowded V2I communication environment. IEEE Transactions on Intelligent Transportation Systems 24(8):8253-8263

63. Yue W, Li J, Li C, Cheng N, Wu J. 2024. A channel knowledge map-aided personalized resource allocation strategy in air-ground integrated mobility. IEEE Transactions on Intelligent Transportation Systems 25(11):18734-18747

64. Zeng H-B, Zhu Z-J, Peng T-S, Wang W, Zhang X-M. 2024. Robust tracking control design for a class of nonlinear networked control systems considering bounded package dropouts and external disturbance. IEEE Transactions on Fuzzy Systems 32(6):3608-3617

65. Zheng Y, Zhang Y, Ran B, Xu Y, Qu X. 2020. Cooperative control strategies to stabilise the freeway mixed traffic stability and improve traffic throughput in an intelligent roadside system environment. IET Intelligent Transport Systems 14(9):1108-1115

66. Zhou Z, Wang Y, Zhou G, Liu X, Wu M, Dai K. 2024. Vehicle lateral dynamics-inspired hybrid model using neural network for parameter identification and error characterization. IEEE Transactions on Vehicular Technology 73(11):16173-16186

67. Zhou Z, Wang Y, Zhou G, Nam K, Ji Z, Yin C. 2023. A twisted gaussian risk model considering target vehicle longitudinal-lateral motion states for host vehicle trajectory planning. IEEE Transactions on Intelligent Transportation Systems 24(12):13685-13697

68. Zhu X, Luo Y, Liu A, Xiong NN, Dong M, Zhang S. 2021. A deep reinforcement learning-based resource management game in vehicular edge computing. IEEE Transactions on Intelligent Transportation Systems 23(3):2422-2433