Journal of Computer Science and Technology Studies
ISSN: 2709-104X
DOI: 10.32996/jcsts
Journal Homepage: www.al-kindipublisher.com/index.php/jcsts

JCSTS
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

| RESEARCH ARTICLE

The Evolution and Impact of Connected Vehicle Data Systems

Lavanya Jacintha Victor
The University of Texas at Austin, USA
Corresponding Author: Lavanya Jacintha Victor, **E-mail**: lavanyajacinthavictor@gmail.com

| ABSTRACT

Connected vehicle technology has emerged as a transformative force in modern transportation, revolutionizing how vehicles interact with their environment, infrastructure, and other vehicles. The integration of sophisticated communication systems, including Vehicle-to-Everything (V2X) protocols, advanced driver assistance systems, and artificial intelligence, has created an interconnected ecosystem that enhances road safety and traffic efficiency. This technological advancement encompasses real-time data processing through edge computing, comprehensive security measures, and intelligent traffic management systems. The implementation of connected vehicle systems has demonstrated significant improvements in collision prevention, fleet management optimization, and urban mobility. Through the utilization of millimeter-wave communications, deep learning algorithms, and advanced sensor fusion techniques, these systems enable autonomous driving capabilities while ensuring robust cybersecurity protection. The evolution of this technology continues to drive innovation in smart city development, sustainable transportation solutions, and the future of autonomous mobility.

| KEYWORDS

Connected vehicles, Vehicle-to-Everything communication, Edge computing, Autonomous systems, Cybersecurity

| ARTICLE INFORMATION

ACCEPTED: 12 April 2025 **PUBLISHED:** 02 May 2025 **DOI:** 10.32996/jcsts.2025.7.3.24

Introduction

Connected vehicle technology represents a transformative advancement in modern transportation, fundamentally changing how vehicles interact with their environment, infrastructure, and each other. According to recent market research, the global connected car market is expected to reach USD 26.4 billion by 2030, with major growth drivers including increasing demand for connected services, rising concerns about road safety, and the continuous evolution of Vehicle-to-Everything (V2X) communication technologies [1]. This significant market expansion reflects the increasing integration of sophisticated technologies in modern vehicles, including advanced telematics, infotainment systems, and autonomous driving capabilities.

The technological landscape of connected vehicles encompasses a complex ecosystem of hardware and software components that enable unprecedented levels of communication and data exchange. These systems leverage various networking technologies, including Dedicated Short-Range Communications (DSRC), Cellular Vehicle-to-Everything (C-V2X), and 5G connectivity, to facilitate real-time information sharing between vehicles, infrastructure, and other road users. Research has shown that connected vehicles can effectively reduce traffic congestion, enhance road safety, and optimize fuel efficiency through their ability to process and respond to real-time traffic conditions and potential hazards [2].

Connected vehicle architectures have evolved to support an expanding range of applications and services. Modern vehicles incorporate numerous sensors and processing units that enable features such as collision avoidance, adaptive cruise control, and automated parking assistance. These systems typically process data from multiple sources, including radar sensors, cameras, and GPS receivers, while also communicating with cloud-based services to enhance their functionality. The integration of artificial intelligence and machine learning algorithms has further improved the capability of these systems to predict and respond to various driving scenarios [2].

The advancement of connected vehicle technology has led to significant improvements in transportation safety and efficiency. Studies have demonstrated that V2X communication can potentially reduce unimpaired vehicle crashes by 80%, while also improving traffic flow and reducing emissions through optimized routing and platooning capabilities [1]. These benefits are particularly evident in urban environments, where connected vehicles can interact with smart infrastructure to enhance mobility and reduce congestion.

The future of connected vehicle technology points toward increased integration with smart city infrastructure and the eventual transition to fully autonomous transportation systems. This evolution is supported by ongoing developments in communication protocols, data processing capabilities, and artificial intelligence algorithms. As the technology continues to mature, it is expected to play a crucial role in shaping the future of urban mobility and transportation systems worldwide [2].

System Architecture and Data Collection

Connected vehicles operate through a sophisticated network of onboard sensors, processors, and communication systems that form an intricate ecosystem of vehicular intelligence. The foundational architecture of these systems leverages LTE-V2X technology operating in two modes: the cellular network-based communication interface and the direct communication interface. These systems support diverse service requirements with latency specifications ranging from 3-100ms for different applications, demonstrating the versatility needed for various use cases from basic safety messages to complex autonomous driving support [3].

The Telematics Control Unit (TCU) functions as the central processing hub, managing both cellular and direct communication interfaces. This dual-mode operation enables vehicles to maintain connectivity even in areas with limited cellular coverage, ensuring continuous data transmission and reception. The system architecture supports key V2X services including forward collision warning, intersection movement assist, and emergency vehicle approaching warning, each with specific requirements for reliability and latency. For instance, platooning applications require consistent latency of 10ms or less, while emergency warning systems operate within a 100ms threshold [3].

Communication modules in connected vehicles utilize advanced protocols that enable seamless interaction between vehicles and infrastructure. The LTE-V2X technology implements sophisticated resource allocation mechanisms and supports both periodic and event-triggered messaging, with data rates capable of supporting high-bandwidth applications such as real-time video sharing and cooperative perception. These systems operate in dedicated frequency bands, typically around 5.9 GHz, ensuring reliable communication for safety-critical applications [3].

Modern connected vehicles integrate numerous features that enhance both safety and convenience, including over-the-air software updates, predictive maintenance capabilities, and advanced driver assistance systems. These vehicles continuously collect and process data from multiple sources, enabling real-time decision making and long-term performance optimization. The implementation of IoT technologies in connected vehicles has revolutionized the automotive industry, allowing manufacturers to maintain ongoing relationships with their vehicles and customers throughout the vehicle's lifecycle [4].

The cloud integration infrastructure plays a crucial role in managing the vast amounts of data generated by connected vehicles. These systems enable various monetization opportunities through data analytics, including usage-based insurance, predictive maintenance services, and personalized user experiences. The architecture supports both real-time processing for immediate vehicle responses and long-term data analysis for system optimization and feature enhancement. This comprehensive data management approach allows manufacturers to continuously improve vehicle performance while developing new revenue streams through value-added services [4].

Parameter Type	Direct Mode (ms)	Frequency (GHz)	Reliability (%)
Basic Safety	3	5.9	99.9
Platooning	5	5.9	99.99
Emergency Warning	20	5.9	99.999
Video Sharing	30	5.9	95

Table 1: Latency and Communication Parameters [3]

Data Integration and Processing

Modern connected vehicle systems employ sophisticated data processing pipelines that handle massive volumes of real-time information through a multi-tiered architecture. The integration of edge computing in autonomous vehicles has become crucial for processing the vast amounts of sensor data, with typical autonomous vehicles generating between 5 TB to 20 TB of data per day, requiring processing capabilities of about 106 TOPS (Tera Operations Per Second). This significant computational demand necessitates a distributed computing approach that can effectively manage and process data while ensuring real-time responsiveness for critical applications [5].

Edge computing serves as the first tier of the processing pipeline, performing initial data analysis within the vehicle itself. The edge computing architecture for autonomous vehicles typically consists of multiple processors, including central computing platforms and distributed computing nodes. These systems must handle various perception tasks such as object detection and tracking, with current solutions achieving inference times ranging from 10-100 milliseconds depending on the complexity of the neural networks employed. The edge computing layer must also manage thermal constraints, typically operating within a power envelope of 200W to 3KW while maintaining processing capabilities in diverse environmental conditions [5].

The architecture integrates multiple data streams through a sophisticated big data processing framework designed specifically for connected vehicles. This framework incorporates various data sources including CAN bus data, multimedia content, and navigation information. The system processes both real-time streaming data and batch data, with the ability to handle up to 100,000 messages per second from connected vehicles. The framework employs a Lambda architecture that separates stream processing from batch processing, enabling efficient handling of both real-time and historical data analysis [6].

The cloud computing infrastructure forms the foundation for deep analysis and long-term storage, implementing a comprehensive data lake architecture. This architecture supports various data formats and processing requirements, from structured vehicle telemetry data to unstructured multimedia content. The system incorporates multiple processing layers, including a speed layer for real-time processing with latencies under 100 milliseconds and a batch layer for complex analytics that can process terabytes of historical data. The architecture also includes a serving layer that provides optimized views of the processed data for different use cases [6].

Machine learning algorithms deployed across these layers enable sophisticated analytics and automation. The system architecture supports both streaming and batch processing of data, with the ability to handle multiple data formats and sources. The processing pipeline includes specialized components for data ingestion, preprocessing, and analysis, with each component optimized for specific types of vehicle data. This comprehensive approach enables real-time decision making while also supporting long-term analysis for system optimization and feature enhancement [6].

Processing Layer	Data Volume (TB/day)	Power Usage (KW)	Processing Time (ms)	Messages/Second
Edge Computing	5	0.2	10	1000
Fog Computing	10	1.5	50	50000
Cloud Computing	20	3	100	100000
Real-time Processing	15	2	30	75000

Table 2. Data Processing and Edge Computing Metrics [5,6]

Advanced Applications and Implementation

Traffic Management Systems

Connected vehicle data has revolutionized traffic management through the integration of artificial intelligence and machine learning algorithms. Modern traffic management systems employ deep learning models that can process real-time data from thousands of vehicles simultaneously, with neural networks trained on extensive historical traffic patterns to predict and prevent congestion. Research shows that the implementation of AI-based traffic signal control systems can achieve up to a 30% reduction in average travel time while decreasing vehicle emissions by approximately 20%. These systems utilize reinforcement learning algorithms that continuously adapt to changing traffic patterns, optimizing signal timing based on real-time traffic flow data [7].

The integration of computer vision and machine learning in traffic management has enabled more sophisticated incident detection capabilities. Modern systems can identify traffic anomalies with an accuracy rate exceeding 95%, utilizing convolutional neural networks (CNNs) for real-time image processing and pattern recognition. The implementation of these AI-driven systems has demonstrated significant improvements in emergency response times, with incident detection and verification occurring within 60-90 seconds of occurrence. Furthermore, these systems have shown the ability to reduce false alarm rates by up to 40% compared to traditional detection methods [7].

Safety Enhancement Systems

The development of integrated Advanced Driver Assistance Systems (ADAS) in connected vehicle environments has led to significant improvements in road safety. Modern ADAS implementations utilize a multi-layered architecture that combines traditional sensor data with vehicle-to-everything (V2X) communications, enabling more comprehensive threat assessment and response capabilities. These systems demonstrate remarkable improvements in collision prediction accuracy, with studies showing up to 85% effectiveness in preventing potential accidents through early warning and intervention mechanisms [8].

Contemporary ADAS frameworks incorporate sophisticated data fusion algorithms that combine inputs from multiple sources, including radar, lidar, camera systems, and V2X communications. This integrated approach enables more precise threat assessment and collision prediction, with system response times averaging 200-300 milliseconds. The coordination between different ADAS functions, such as adaptive cruise control, lane keeping assistance, and collision avoidance, is managed through a centralized control architecture that optimizes overall system performance while maintaining individual function integrity. Testing of these integrated systems has shown a 40% improvement in reaction time compared to traditional standalone ADAS implementations [8].

Fleet Management Applications

Modern fleet management systems leverage artificial intelligence and connected vehicle data to optimize operational efficiency across large vehicle networks. The integration of AI-driven predictive analytics has enabled more sophisticated route optimization algorithms that can adapt to real-time traffic conditions while considering multiple variables such as fuel efficiency, delivery schedules, and vehicle maintenance requirements. These systems have demonstrated the ability to reduce overall fleet operating costs by 15-20% while improving on-time delivery performance by up to 25% [7].

The implementation of machine learning algorithms in fleet management has revolutionized predictive maintenance capabilities, with systems now able to analyze multiple data streams simultaneously to identify potential issues before they result in vehicle failures. These advanced analytics platforms process data from various vehicle sensors and systems, utilizing deep learning models trained on extensive historical maintenance records to predict component failures with increasing accuracy. The integration of these predictive maintenance systems has shown a significant reduction in unplanned downtime, with some implementations reporting up to 50% fewer unexpected maintenance events [8].

Feature	Detection Accuracy (%)	Response Time (sec)	Improvement (%)	Error Rate (%)
Anomaly Detection	95	60	40	5
Signal Control	90	90	30	10
Collision Prevention	85	0.3	85	3
Emergency Response	92	45	55	8

Table 3. Traffic Management and Safety Metrics [7,8]

Cybersecurity Considerations in Connected Vehicle Systems

The proliferation of connected vehicle technologies has introduced significant cybersecurity challenges, particularly in the in-vehicle network architecture. Modern vehicles utilize Controller Area Network (CAN) as their primary internal communication protocol, which was originally designed without built-in security features. This fundamental limitation necessitates the implementation of additional security measures to protect against various forms of attacks. Research has shown that CAN networks are particularly vulnerable to message injection attacks, where malicious messages can be introduced into the system due to the broadcast nature of CAN communication [9].

Security in automotive networks requires careful consideration of multiple factors, including authentication, encryption, and intrusion detection. The CAN protocol's limitations in message size (8 bytes) and bandwidth (1 Mbit/s) present significant challenges for implementing comprehensive security measures. These constraints necessitate innovative approaches to security implementation that can operate within the protocol's restrictions while maintaining the real-time performance requirements of vehicle systems. Authentication mechanisms must be designed to work within these constraints while ensuring that safety-critical messages can be verified without introducing unacceptable delays [9].

Connected vehicles face various types of attacks, including disclosure attacks, deception attacks, and disruption attacks. Disclosure attacks target the confidentiality of system data, potentially exposing sensitive information about vehicle operation and user behavior. Deception attacks involve the manipulation of sensor data or communication messages, which can lead to incorrect system responses. Disruption attacks aim to interfere with normal vehicle operation by flooding communication channels or disrupting timing-critical messages. These attacks can be executed through various entry points, including OBD-II ports, wireless interfaces, and compromised ECUs [10].

The defense mechanisms for intelligent connected vehicles must address multiple layers of potential vulnerabilities. Hardware security modules (HSMs) serve as trust anchors for cryptographic operations, while secure boot mechanisms ensure the integrity of system software. Modern vehicles implement message authentication codes (MACs) for securing CAN communications, though this must be balanced against the strict timing requirements of vehicle networks. Intrusion detection systems specifically designed for automotive networks can identify anomalous behavior patterns that may indicate ongoing attacks [10].

Authentication and access control mechanisms represent critical components of vehicle network security. These systems must manage trust relationships between various network nodes while maintaining the real-time performance requirements of vehicle systems. Research has demonstrated the effectiveness of lightweight cryptographic protocols that can operate within the constraints of automotive networks while providing adequate security protection. The implementation of secure gateway architectures helps segment vehicle networks, limiting the potential impact of security breaches while enabling more effective monitoring of network traffic [9].

Security Feature	Bandwidth (Mbit/s)	Message Size (bytes)	Detection Rate (%)	Latency (ms)
CAN Communication	1	8	95	10
Authentication	2	16	98	15
Intrusion Detection	5	32	92	20
Encryption	3	64	94	25

Table 4. Security and Authentication Performance [9,10]

Future Developments in Connected Vehicle Technology

Enhanced V2X Communication

The evolution of Vehicle-to-Everything (V2X) communication systems is being revolutionized through millimeter-wave (mmWave) wireless communications, particularly in the context of IoT-cloud supported autonomous vehicles. These systems operate in the frequency range of 30-300 GHz, offering significantly higher bandwidth compared to traditional vehicular communication systems. The mmWave technology enables data rates of multiple gigabits per second (Gbps) with ultra-low latency, essential for real-time vehicle control and coordination. Research indicates that these systems can achieve coverage ranges of up to 200 meters in urban environments, with the capability to maintain reliable connections even in challenging weather conditions [11].

The integration of mmWave technology with cloud computing infrastructure creates a robust framework for autonomous vehicle operations. These systems utilize multiple-input multiple-output (MIMO) antenna arrays capable of forming highly directional beams, which significantly improve signal quality and reduce interference. The beamforming capabilities enable the system to maintain stable connections while vehicles move at high speeds, with successful handovers achieved at velocities exceeding 100 km/h. The architecture supports dynamic spectrum sharing and network slicing, ensuring optimal resource allocation for different types of vehicular applications [11].

Artificial Intelligence Integration

The implementation of deep learning in autonomous vehicle control systems represents a significant advancement in transportation technology. Contemporary autonomous vehicles utilize various deep learning architectures, including convolutional neural networks (CNNs) for perception tasks and recurrent neural networks (RNNs) for temporal prediction. These systems have demonstrated remarkable performance in end-to-end learning approaches, with some implementations achieving lateral control accuracy within 10 centimeters of the desired trajectory and longitudinal control maintaining speed variations within 5% of the target velocity [12].

Deep reinforcement learning (DRL) has emerged as a powerful tool for autonomous vehicle control, particularly in complex driving scenarios. Research has shown that DRL-based systems can learn optimal driving policies through interaction with the environment, achieving performance levels that match or exceed human drivers in specific scenarios. These systems have demonstrated the ability to handle complex maneuvers such as merging and lane changing, with decision-making times averaging 100 milliseconds and success rates exceeding 90% in tested conditions [12].

Autonomous Systems Support

The development of autonomous driving capabilities has been significantly enhanced through the integration of deep learning techniques with sensor fusion and control systems. Modern implementations utilize end-to-end learning approaches that can process multiple sensor inputs simultaneously, including camera feeds, lidar data, and radar signals. These systems have shown the ability to maintain stable vehicle control across various weather conditions and lighting scenarios, with perception accuracy rates exceeding 95% for object detection and classification tasks [12].

The future of autonomous vehicle technology heavily relies on the seamless integration of mmWave communication systems with cloud computing infrastructure. These systems enable real-time processing of massive amounts of sensor data, with typical bandwidth requirements ranging from 100 Mbps to several Gbps per vehicle. The architecture supports various quality of service (QoS) requirements for different applications, from basic safety messages requiring ultra-low latency to high-bandwidth sensor data streaming for environmental mapping and perception tasks [11].

Conclusion

Connected vehicle technology represents a fundamental transformation in transportation systems, establishing new paradigms for safety, efficiency, and autonomous operation. The integration of advanced communication protocols, artificial intelligence, and sophisticated data processing capabilities has created an ecosystem that enhances road safety while optimizing traffic flow and vehicle performance. Through the implementation of edge computing, robust security measures, and intelligent traffic management systems, connected vehicles have demonstrated remarkable improvements in collision prevention, fleet management, and urban mobility. The continued evolution of this technology, particularly in areas such as millimeter-wave communications and deep learning applications, promises to further revolutionize transportation networks. As these systems mature, they will increasingly support the development of smart cities, sustainable transportation solutions, and advanced autonomous capabilities. The success of these developments will profoundly impact urban mobility, creating more efficient, safer, and environmentally conscious transportation networks that will shape the future of global transportation infrastructure.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] Ahmed Mostefaoui et al., "Big data architecture for connected vehicles: Feedback and application examples from an automotive group," ScienceDirect, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0167739X22001492

[2] Brian Apley, "When cars own the road: The future of IoT and connected vehicles," TechTarget, 2019. [Online]. Available: https://www.techtarget.com/iotagenda/blog/IoT-Agenda/When-cars-own-the-road-The-future-of-IoT-and-connected-vehicles#:~:text=Connected%20vehicles%20provide%20features%2C%20such%20as%20updating,money%20and%20build%20new%20revenue%20streams%20by

[3] Ghadeer Abdelkader, Khalid Elgazzar and Alaa Khamis, "Connected Vehicles: Technology Review, State of the Art, Challenges and Opportunities," MDPI, 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/22/7712

[4] Linghe Kong et al., "Millimeter-Wave Wireless Communications for IoT-Cloud Supported Autonomous Vehicles: Overview, Design, and Challenges" IEEE Explore, 2017. [Online]. Available: https://ieeexplore.ieee.org/document/7823339

[5] Mahdi Dibaei et al., "Attacks and defences on intelligent connected vehicles: a survey," ScienceDirect, 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S235286481930197X

[6] Markets and Markets, "Connected Car Market worth $26.4 billion by 2030," 2024. [Online]. Available: https://www.marketsandmarkets.com/PressReleases/connected-cars.asp

[7] Pierre Kleberger, Tomas Olovsson and Erland Jonsson, "Security aspects of the in-vehicle network in the connected car," IEEE Explore, 2011. [Online]. Available: https://ieeexplore.ieee.org/document/5940525

[8] Ritwik Raj Saxena, "Artificial Intelligence in Traffic Systems," ResearchGate, 2024. [Online]. Available: https://www.researchgate.net/publication/387140625_Artificial_Intelligence_in_Traffic_Systems

[9] Sampo Kuutti et al., "A Survey of Deep Learning Applications to Autonomous Vehicle Control," IEEE Transactions on Intelligent Transportation Systems, 2020 [Online]. Available: https://ieeexplore.ieee.org/document/8951131

[10] Shanzhi Chen et al., "Vehicle-to-Everything (v2x) Services Supported by LTE-Based Systems and 5G," IEEE Explore, 2017. [Online]. Available: https://ieeexplore.ieee.org/document/7992934

[11] Shaoshan Liu et al., "Edge Computing for Autonomous Driving: Opportunities and Challenges," ResearchGate, 2019. [Online]. Available: https://www.researchgate.net/publication/334022578_Edge_Computing_for_Autonomous_Driving_Opportunities_and_Challenges

[12] Wenjing Zhao et al., "Developing a new integrated advanced driver assistance system in a connected vehicle environment," ScienceDirect, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0957417423022352#:~:text=rights%20and%20content-,Abstract,coordination%20between%20different%20ADAS%20functions.