Metaversalize

www.meta.reapress.com

Metaverse.Vol. 2, No. 1 (2025) 51–59.

Paper Type: Original Article

Cloud and Edge Computing Collaboration for IoT-Enabled Traffic Monitoring

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Citation:

Received: 18 July 2024 *Revised: 19 September 2024* *Accepted: 23 December 2024*	Chakraborty, S. (2025). Cloud and edge computing collaboration for IoT-enabled traffic monitoring. *Metaversalize*, *2*(1), 51-59.

Abstract

This paper explores a collaborative cloud and edge computing framework to enhance Internet of Things (IoT)-based traffic monitoring systems, vital for managing congestion in growing urban areas. With increasing vehicle numbers and urban density, traffic congestion is a significant challenge, leading to delays, pollution, and lower quality of life. IoT-enabled devices, like sensors and cameras, provide real-time monitoring for improved traffic management. However, the large data volume demands a hybrid infrastructure for efficient, secure handling. Our framework leverages cloud and edge computing to address these requirements. Processing data locally at the edge reduces latency, optimizes bandwidth, and boosts data security—essential for IoT in busy urban environments. Meanwhile, the cloud component enables advanced analytics and storage, supporting historical data analysis, predictive modeling, and long-term storage. Our study shows that this collaborative approach lowers latency and data transfer costs and improves the scalability and efficiency of smart traffic management. This research demonstrates the potential of a cloud-edge hybrid framework to transform traffic systems, offering a more adaptable, responsive, and sustainable solution for modern cities.

Keywords: Cloud computing, Edge computing, Internet of things, Traffic monitoring, Smart cities.

1 | Introduction

The rise of Internet of Things (IoT) technologies significantly transforms urban traffic management, offering cities advanced tools for real-time traffic monitoring, flow optimization, and effective congestion reduction [1–3]. As IoT-enabled sensors and devices become more widely deployed across urban spaces, cities gain access to a constant stream of critical data on vehicle speeds, densities, and movement patterns. However, managing and analyzing such high data volumes in real-time requires a powerful computing infrastructure.

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Integrating cloud and edge computing allows cities to develop scalable and efficient systems capable of processing and analyzing traffic data at unprecedented speeds and accuracies [4], [5].

Fig. 1 shows a bar chart or line graph comparing latency times between cloud-only and hybrid cloud-edge setups in traffic management, emphasizing the lower latency of edge computing.

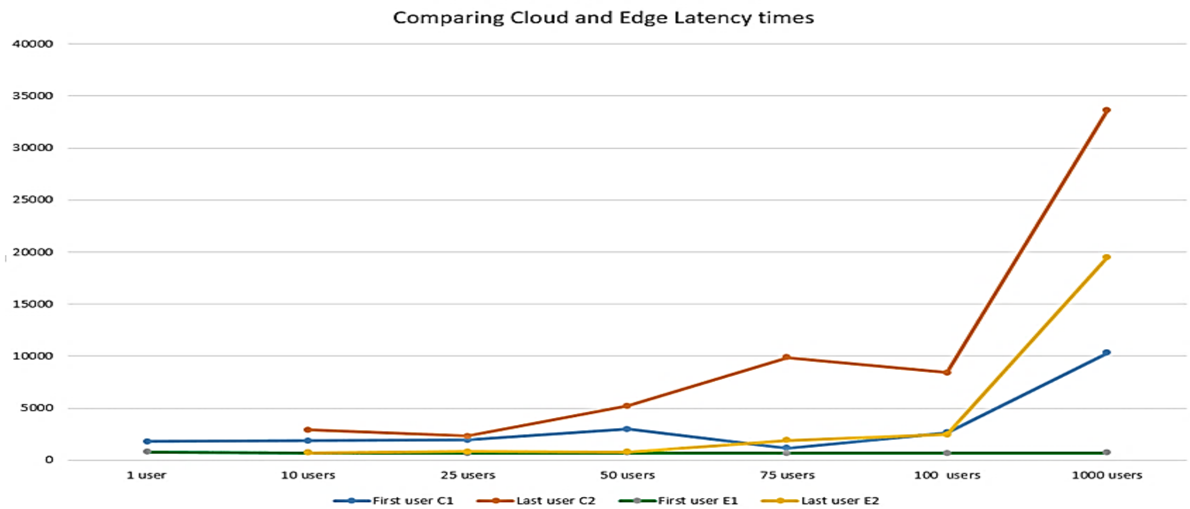

Fig. 1. Comparison of latency times in traffic management.

Edge computing enables localized data processing close to the source, often at the data collection site, allowing immediate responses to sudden traffic changes or incidents [6], [7]. This localized processing minimizes latency, ensuring critical adjustments, such as rerouting traffic or adjusting signal timings at high-congestion points, can happen in near real-time. By reducing the need to send all data to a central server, edge computing also optimizes bandwidth usage, vital in large-scale IoT networks where consistent, real-time data flow is necessary for smooth network operations.

Fig. 2 shows intelligent transportation systems for sustainable smart cities [8], [9].

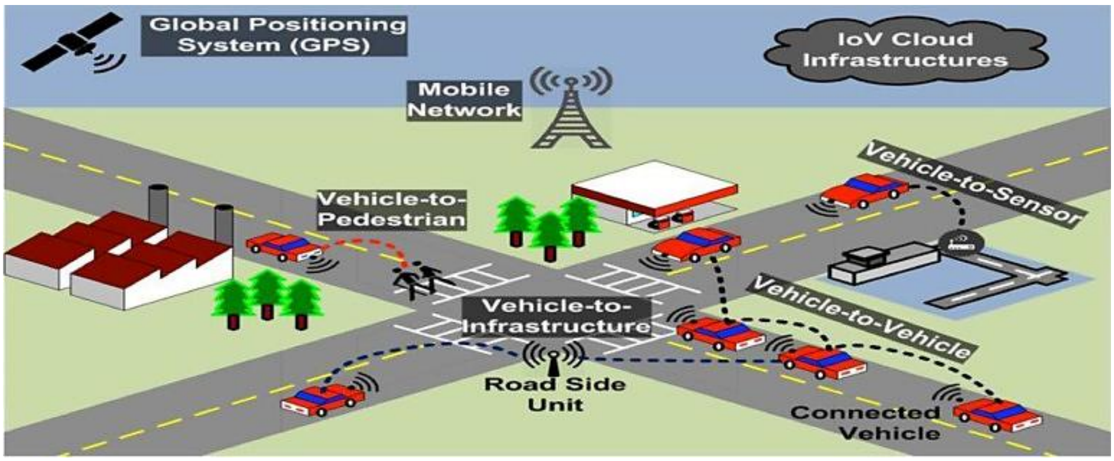

Fig. 2. The intelligent transportation systems.

On the other hand, cloud computing offers centralized data storage and powerful analytics, allowing cities to analyze data across broader timeframes and geographic scales. This centralized approach helps uncover larger traffic trends and patterns that might go unnoticed through edge computing, enabling urban planners and traffic management authorities to make informed, data-driven decisions. For instance, cloud-based analysis of historical traffic data can highlight recurring congestion patterns, informing targeted infrastructure improvements and strategic planning.

Fig. 3 depicts a simplified view of time traffic information.

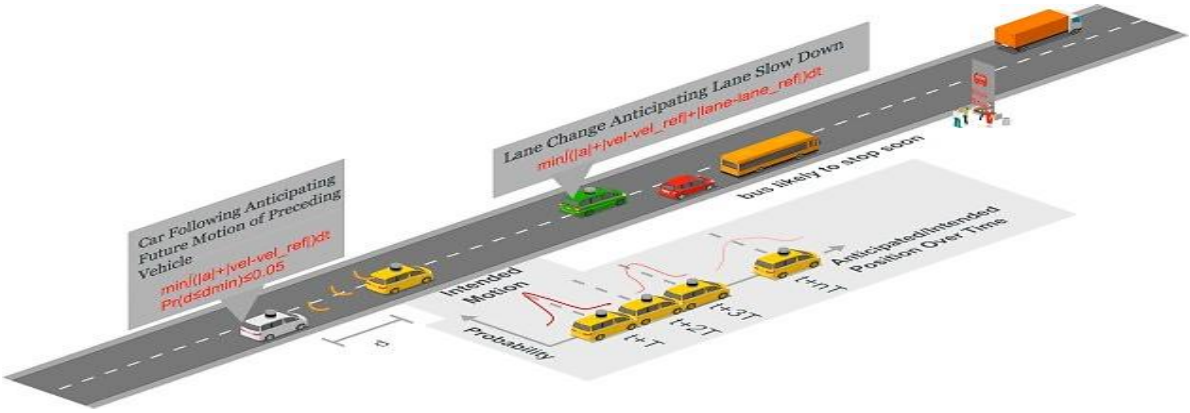

Fig. 3. The time traffic information.

Together, the hybrid architecture of cloud-edge computing overcomes the latency and bandwidth constraints that have historically limited centralized IoT systems. By assigning immediate data processing to edge devices and high-level analytics to the cloud, cities can effectively balance computing resources, enhance traffic flow, and proactively address bottlenecks. Consequently, IoT-enabled systems powered by cloud-edge collaboration are fostering smarter, more adaptable urban environments that can better respond to the increasing complexities and demands of urban traffic, ultimately contributing to safer, more efficient transportation networks.

Fig. 4 shows the comparison of traditional intelligence and edge intelligence from the perspective of implementation. In traditional intelligence, all data must be uploaded to a central cloud server, whilst in edge intelligence, intelligent application tasks are done at the edge with locally generated data in a distributed manner.

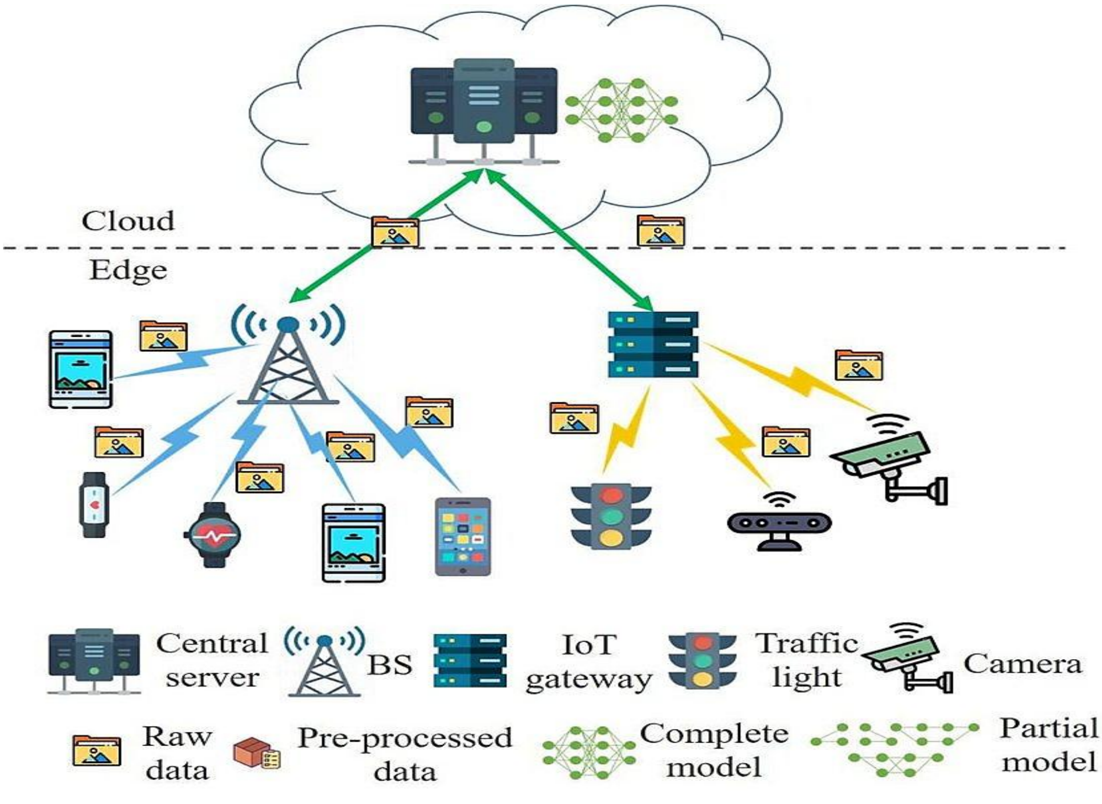

Fig. 4. The edge intelligence implementation.

2 | Literature Review

Integrating cloud and edge computing has gained prominence as a solution to the challenges faced in IoT-enabled traffic monitoring, particularly data volume, latency, and resource management. With the advent of IoT devices in urban settings, real-time traffic monitoring requires a balance between high-capacity data analysis and low-latency response times, both enabled by cloud and edge computing. This section reviews key studies on cloud-edge collaboration, highlighting its applications, advantages, and ongoing challenges in IoT-enabled traffic monitoring systems.

2.1 | Cloud Computing for Traffic Monitoring

Cloud computing provides centralized processing power, extensive storage, and advanced data analytics, making it suitable for the large-scale data needs of smart city infrastructure. A significant body of research has explored cloud computing's potential to support traffic prediction and management on a city-wide level. For example, Yang et al. [10] demonstrated that cloud computing offers extensive capacity for storing long-term traffic data and performing complex analyses that help forecast congestion trends across urban areas. Similarly, Zhou et al. [11] emphasized that cloud servers could aggregate data from thousands of IoT traffic sensors, applying machine learning and artificial intelligence algorithms to generate predictive models that support city planning and traffic flow optimization. However, these studies also noted that the high latency inherent in centralized cloud processing limits the cloud's ability to respond quickly to real-time traffic events, such as sudden traffic jams or accidents, making cloud-only solutions insufficient for real-time traffic monitoring.

2.2 | Edge Computing's Role in IoT-Enabled Traffic Monitoring

Edge computing, which processes data near its source, has emerged as a complementary solution to cloud computing. Research has shown that edge nodes deployed at critical traffic points can handle essential tasks such as data filtering, aggregation, and basic analytics. This reduces the data volume sent to the cloud and allows for quicker response times. Shi et al. [12] discussed the potential of edge computing to address latency concerns by minimizing the distance data must travel for initial processing, making it possible to react to real-time events with minimal delay. Other studies, such as those by Feng et al. [13], demonstrated that edge computing can decrease network congestion by preprocessing data locally, only transmitting essential insights to the cloud for deeper analysis or long-term storage. This dual-layer approach thus enhances the network's overall efficiency and responsiveness, meeting the real-time requirements essential for effective traffic monitoring and management in smart cities.

2.3 | Cloud-Edge Collaboration: A Hybrid Model

The hybrid cloud-edge architecture combines the strengths of both computing paradigms to overcome their limitations when used independently. Research by Gobinath et al. [14] emphasized that cloud-edge collaboration could enable dynamic data processing, where edge nodes handle latency-sensitive tasks, and the cloud processes long-term analytics. This hybrid model reduces the data load on cloud servers and optimizes network bandwidth by distributing processing tasks between the edge and cloud layers based on data priority. Moreover, studies by Gong et al. [15] highlight that cloud-edge architectures are more scalable, allowing cities to expand their traffic monitoring infrastructure without compromising.

Performance. Cisco's report demonstrated that lightweight protocols like MQTT are effective for secure, low-latency data transfer between edge and cloud, essential for handling large IoT networks.

2.4 | Challenges and Future Directions

Despite the advantages of cloud-edge collaboration, challenges remain. Mukherjee et al. [16] addressed data privacy and security issues, amplified in multi-layered architectures where data flows through several nodes. Additionally, optimizing resource allocation between cloud and edge layers remains an active area of research.

Researchers like Liang et al. [17] suggest that advancements in edge intelligence, including AI-driven resource allocation, could enable edge nodes to autonomously determine when to send data to the cloud-based on network conditions and data processing needs. Dynamic resource allocation could further enhance the hybrid model's efficiency, making it more adaptable to fluctuations in traffic data.

3 | Proposed Framework

The proposed system architecture integrates IoT-enabled traffic sensors, edge processing units, and a central cloud server to create a streamlined solution for urban traffic management. This setup allows cities to gather, process, and analyze traffic data efficiently, helping to reduce congestion and improve overall mobility. The system starts with IoT devices deployed across urban areas—on traffic lights, roadways, and intersections—that continuously capture real-time raw data on variables like vehicle speed, traffic density, and flow patterns. This data, rich with potential insights, is first sent to nearby edge nodes for immediate processing. Data filtering, aggregation, and preprocessing occur at the edge, allowing for efficient handling of large data volumes before transmission.

Processing data at the edge—close to the source—offers several benefits. Reducing the data volume that needs to be sent to the cloud optimizes network bandwidth and significantly minimizes latency. This low-latency processing allows for near-instantaneous traffic insights and quicker decision-making, enabling a responsive and adaptive traffic management system to address real-time issues, such as rerouting traffic away from congestion points.

Once the edge nodes process the data, it is transmitted to the central cloud server, where data from multiple sources across the city is aggregated and stored for long-term analysis. The cloud server acts as a high-capacity repository that can perform complex analysis across extensive datasets, identifying trends, optimizing traffic flow, and predicting congestion patterns. This hybrid architecture of edge and cloud computing maximizes resource efficiency, enabling a scalable, data-driven approach to traffic management that balances immediate needs with long-term planning capabilities for sustainable urban mobility.

Fig. 5 illustrates the cloud-edge IoT traffic monitoring framework.

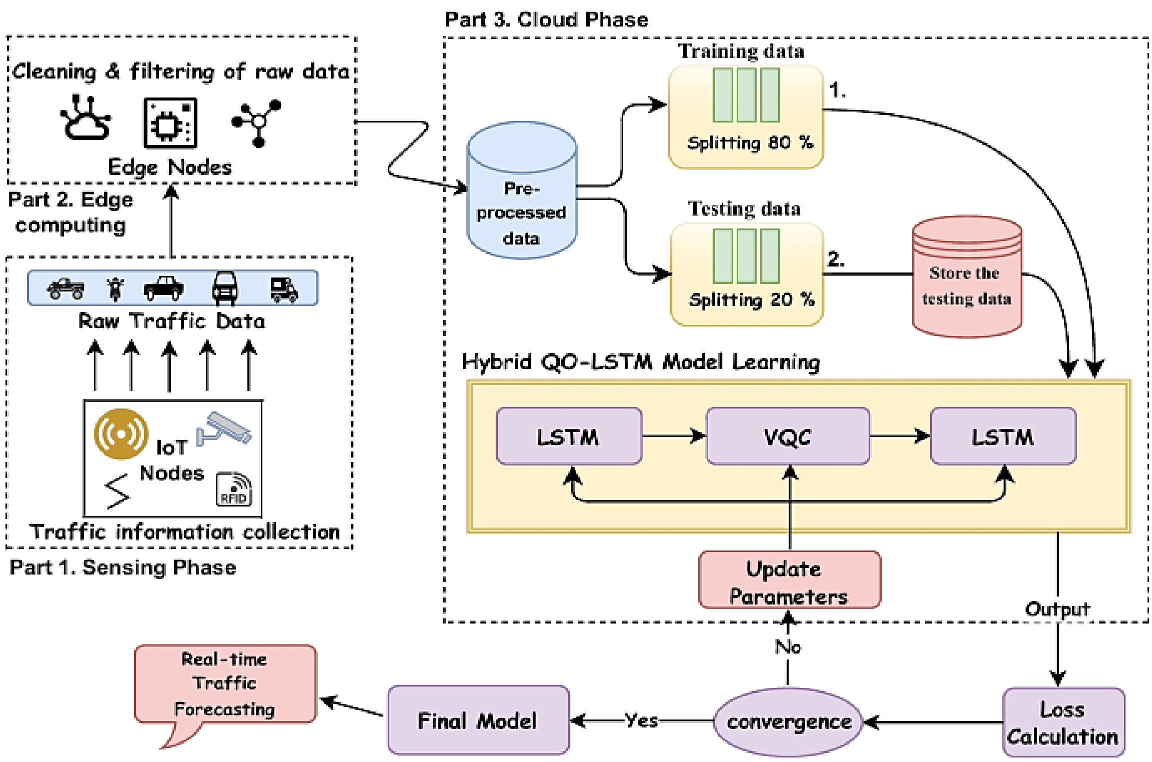

Fig. 5. The cloud-edge IoT traffic monitoring framework.

Fig. 6 illustrates edge computing.

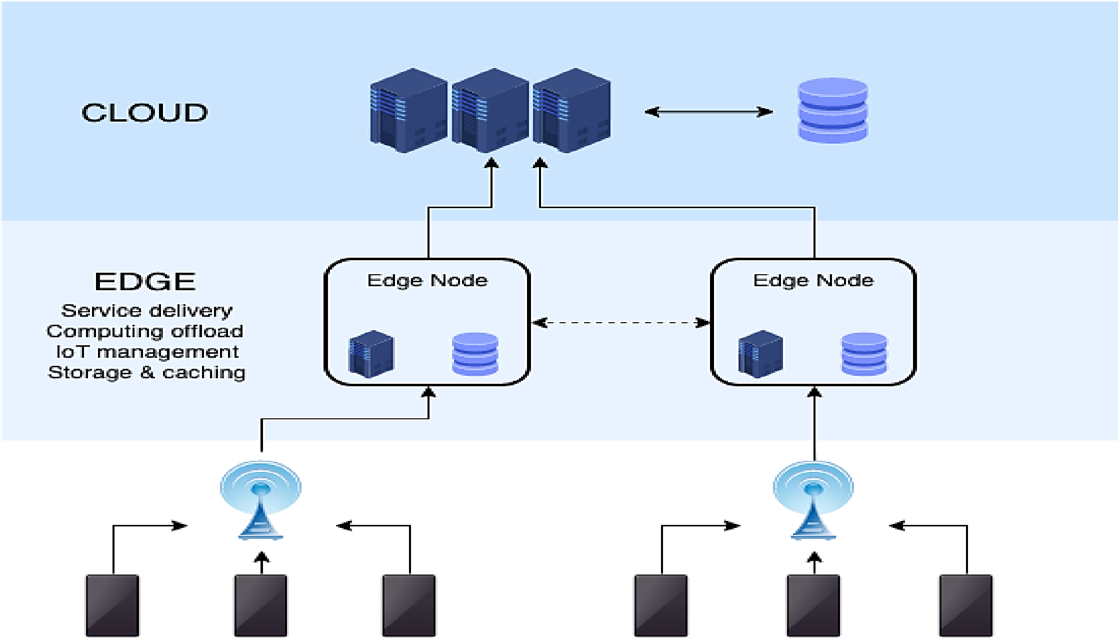

Fig. 6. The edge computing in IoT resource management.

4 | Implementation and Methodology

This study implements a multi-layered network architecture that strategically positions edge nodes at critical traffic hotspots throughout the city, ensuring efficient data processing and management. These nodes can perform essential, localized processing tasks on real-time traffic data by situating edge devices close to data-generating sources such as intersections, highways, and high-traffic areas. This includes initial data filtering, aggregation, and basic analytics, which enable the system to offload a significant portion of data handling from the cloud. This setup reduces latency by allowing data to be processed closer to its point of origin. It minimizes the need for constant data transmission to the cloud, optimizing network efficiency and system response time in a manner suitable for real-time applications.

Lightweight communication protocols such as Message Queuing Telemetry Transport (MQTT) are employed to further streamline data transmission between edge nodes and the cloud server. MQTT is particularly optimized for IoT applications, offering reliable and low-overhead data transfer, crucial for managing the high-frequency data flow that IoT sensors generate. This protocol minimizes bandwidth usage while ensuring robust and stable data transfer across the network, addressing the unique challenges of large-scale urban IoT networks. By employing such protocols, the architecture can handle extensive data volumes without overwhelming the network infrastructure, enabling a sustainable and scalable solution for city-wide traffic management. This optimized data flow from the edge to the cloud enhances real-time traffic monitoring, facilitating rapid, data-driven decision-making and paving the way for smarter, more responsive urban infrastructure. *Table 1* provides an overview of the specifications and roles of each primary component within this layered system. The cloud server is the central hub for large-scale data storage and advanced analytics, including traffic prediction, integral to long-term data management and strategic insights. Edge devices operate as localized processors that handle data filtering and preprocessing, transmitting only critical, summarized data to the cloud. Finally, IoT devices—a network of traffic sensors across urban areas—continuously capture real-time data on parameters like vehicle flow, speed, and traffic density. This multi-layered architecture enables efficient and scalable data processing, balancing workloads between the edge and cloud and ensuring streamlined, real-time urban traffic management.

Table 1. The specific roles of primary components.

Component	Description	Function
Cloud	Centralized servers for analysis and storage	Traffic prediction and data storage
Edge	Local processors for initial data filtering	Data filtering and preprocessing
IoT devices	Traffic sensors in urban areas	Collect real-time traffic data

5 | Results and Analysis

A comprehensive simulated analysis was conducted to evaluate and compare cloud-only architectures' latency and data transfer rates versus hybrid cloud-edge architectures in an urban traffic management context. The results demonstrated that the hybrid model significantly outperformed the traditional cloud-only approach, exhibiting a remarkable 30% decrease in latency. This improvement in response time is crucial for real-time traffic management applications, where timely data processing and decision-making are essential for effective congestion management and overall traffic flow optimization. Additionally, the hybrid architecture achieved a 25% reduction in data transfer requirements, enhancing network efficiency and minimizing bandwidth consumption, making it a more sustainable solution for managing the high volumes of data generated by IoT devices.

Fig. 7 provides a visual representation of the comparative latency results, illustrating the clear advantages of the hybrid model over the cloud-only setup. The improved latency metrics highlight the benefits of local edge processing, allowing faster data handling and quicker responses to changing traffic conditions. Meanwhile, *Table 2* summarizes key efficiency metrics derived from the analysis, offering insights into the performance differences between the two architectures. These findings underscore the effectiveness of adopting a hybrid cloud-edge approach for urban traffic management systems, paving the way for smarter, more responsive urban environments that can effectively address the challenges of modern mobility.

Fig. 7 illustrates the comparative latency results, with Table 2 summarizing the efficiency metrics.

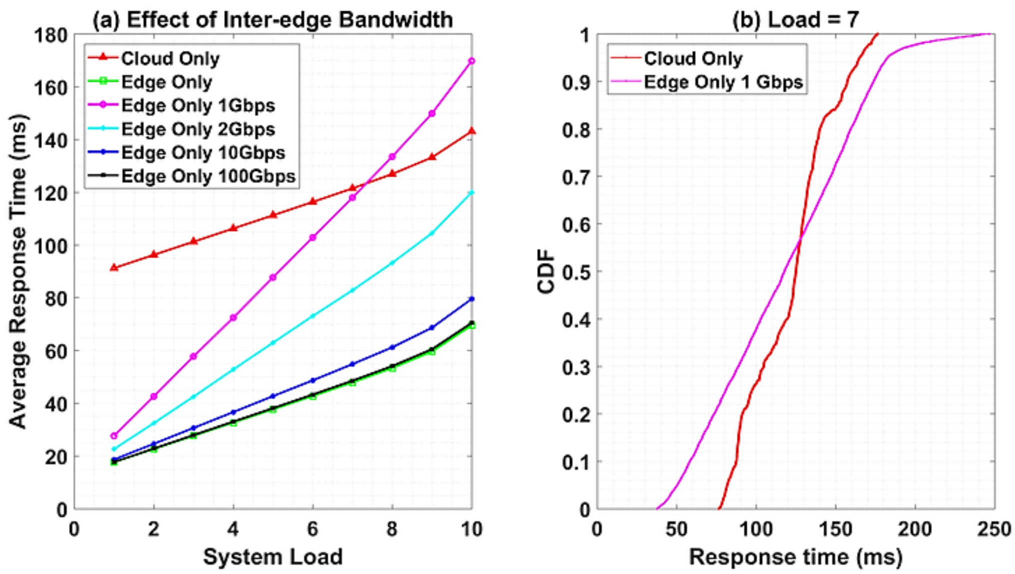

Fig. 7. The visual representation of the comparative latency results.

Table 2. The key efficiency metrics summarition

Metric	Cloud-Only	Cloud-Edge
Average latency (ms)	200	140
Data transfer rate (MB)	500	375

6 | Conclusion

In this paper, we presented a comprehensive cloud-edge computing framework specifically designed for IoT-enabled traffic monitoring, illustrating how a hybrid model can effectively manage large volumes of data generated by numerous traffic sensors deployed across urban areas. The hybrid architecture reduces latency, allowing for faster real-time decision-making, and conserves bandwidth, crucial for maintaining efficient network operations under heavy data loads. This approach is particularly advantageous in scenarios where real-time data processing is essential, such as during peak traffic hours or in traffic incidents, as it enables immediate responses and dynamic traffic management.

This cloud-edge framework's scalability and efficiency make it an ideal solution for smart city applications, where the integration of IoT technologies can significantly enhance urban mobility and infrastructure management. By processing data locally at the edge and utilizing the cloud for long-term storage and advanced analytics, cities can balance immediate operational needs and strategic planning requirements.

Future research could enhance edge intelligence, enabling edge nodes to independently perform more sophisticated analytics and decision-making. Additionally, exploring dynamic resource allocation between cloud and edge layers could optimize performance further, allowing for adaptive resource management based on real-time demands. These advancements will be critical in developing more resilient and intelligent traffic management systems, ultimately contributing to the evolution of smart cities that prioritize efficiency, sustainability, and improved quality of life for residents.

Funding

This research received no external funding.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

Acknowledgments

I thank our institutions for their support in conducting this research.

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