

TEXNİKA ELMLƏRİ TECHNICAL SCIENCES

Real-Time traffic Management Using Big Data and IoT Technologies

Famil Mammadov^{1*} , Ali Sabzaliyev¹ , Shahnaz Mammadova¹ ,
Ulviyya Nematova¹ , and Havabayim Aliyeva¹ 

Abstract. The rapid growth of urbanization and vehicle ownership has intensified traffic congestion and reduced the efficiency of conventional traffic management systems. Traditional approaches, which rely on static data and predefined control strategies, are insufficient to handle the dynamic nature of modern urban traffic networks. In this context, Big Data and Internet of Things (IoT) technologies provide new opportunities for real-time traffic monitoring, analysis, and control. This study proposes a real-time traffic management framework based on the integration of Big Data analytics and IoT technologies. Real-time traffic data are collected from multiple IoT-based sources, including traffic sensors, cameras, and GPS-enabled vehicles. The collected data are processed using scalable Big Data platforms to support real-time traffic state estimation, congestion detection, and adaptive traffic control. Key traffic performance indicators such as average speed, traffic flow, travel delay, and congestion index are used to evaluate system effectiveness. The results demonstrate that the proposed real-time traffic management approach significantly improves traffic performance. Average vehicle speed and traffic flow increase, while travel delay and congestion levels decrease noticeably compared to conventional traffic management strategies. Visualization techniques, including line and column charts, further enhance situational awareness and support timely decision-making. The findings confirm that Big Data and IoT-based real-time traffic management systems play a crucial role in improving traffic efficiency, road safety, and sustainable urban mobility.

Keywords: real-time traffic management, big data analytics, internet of things, intelligent transportation systems, traffic congestion, smart cities

¹Nakhchivan State University, Nakhchivan, Azerbaijan

*Corresponding author. E-mail: familmemmedov@ndu.edu.az

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Böyük məlumat və IoT texnologiyalarından istifadə etməklə real vaxt rejimində nəqliyyat axınının idarə edilməsi

Famil Məmmədov^{1*} , Əli Səbzəliyev¹ , Şahnaz Məmmədova¹ ,
Ülviyyə Nematova¹ , Havabəyim Əliyeva¹ 

Xülasə. Urbanizasiyanın və nəqliyyat vasitələrinin sayının sürətlə artması yol hərəkətində sıxlığın yüksəlməsinə və ənənəvi nəqliyyat idarəetmə sistemlərinin səmərəliliyinin azalmasına səbəb olmuşdur. Statik məlumatlara və əvvəlcədən müəyyən edilmiş idarəetmə strategiyalarına əsaslanan ənənəvi yanaşmalar müasir şəhər nəqliyyat şəbəkələrinin dinamik xarakterini effektiv şəkildə idarə

etmək üçün kifayət etmir. Bu baxımdan, böyük məlumat (Big Data) və əşyaların interneti (Internet of Things – IoT) texnologiyaları yol hərəkətinin real vaxt rejimində monitorinqi, təhlili və idarə olunması üçün yeni imkanlar yaradır. Bu tədqiqat böyük məlumat analitikası və IoT texnologiyalarının integrasiyasına əsaslanan real vaxt rejimində nəqliyyat axınının idarə edilməsi çərçivəsini təklif edir. Real vaxt trafik məlumatları yol hərəkəti sensorları, videomüşahidə kameraları və GPS ilə təchiz edilmiş nəqliyyat vasitələri daxil olmaqla müxtəlif IoT əsaslı mənbələrdən toplanır. Toplanmış məlumatlar real vaxt rejimində yol hərəkətinin vəziyyətinin qiymətləndirilməsi, sıxlığın aşkarlanması və adaptiv nəqliyyat idarəetməsinin həyata keçirilməsi məqsədilə miqyaslı bilən böyük məlumat platformalarında emal olunur. Sistemin effektivliyinin qiymətləndirilməsi üçün orta hərəkət sürəti, nəqliyyat axınının intensivliyi, səyahət gecikməsi və tıxac indeksi kimi əsas yol hərəkəti göstəricilərindən istifadə edilir. Nəticələr göstərir ki, təklif olunan real vaxt nəqliyyat idarəetmə yanaşması yol hərəkətinin göstəricilərini əhəmiyyətli dərəcədə yaxşılaşdırır. Ənənəvi nəqliyyat idarəetmə strategiyaları ilə müqayisədə nəqliyyat vasitələrinin orta sürəti və nəqliyyat axınının intensivliyi artır, səyahət gecikmələri və tıxac səviyyəsi isə nəzərəcarpacaq dərəcədə azalır. Xətti və sütun diaqramları kimi vizuallaşdırma üsulları situasiya məlumatlılığını artırır və operativ qərar qəbulunu dəstəkləyir. Əldə olunan nəticələr təsdiq edir ki, böyük məlumat və IoT texnologiyalarına əsaslanan real vaxt nəqliyyat idarəetmə sistemləri nəqliyyatın səmərəliliyinin yüksəldilməsində, yol təhlükəsizliyinin artırılmasında və dayanıqlı şəhər mobilliyinin təmin edilməsində mühüm rol oynayır.

Açar sözlər: *real vaxt rejimində nəqliyyatın idarə edilməsi, böyük məlumat analitikası, əşyaların interneti (IoT), intellektual nəqliyyat sistemləri, yol hərəkəti sıxlığı, ağıllı şəhərlər*

¹Naxçıvan Dövlət Universiteti, Naxçıvan, Azərbaycan

*Məsul müəllif. E-poçt: familmemmedov@ndu.edu.az

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Introduction

Rapid urbanization and the continuous increase in vehicle ownership have become major challenges for transportation systems in cities around the world. As urban populations grow, existing road infrastructures are often unable to accommodate increasing traffic demand, leading to severe congestion, longer travel times, higher fuel consumption, and increased air pollution. These issues not only reduce the efficiency of urban mobility but also negatively affect economic productivity, environmental sustainability, and the overall quality of life in urban areas (Zhang et al., 2011).

Conventional traffic management systems are primarily based on static data, historical traffic patterns, and predefined control strategies. Traffic signal timings, route planning, and congestion mitigation measures are typically designed offline and updated infrequently. While such approaches may perform adequately under stable traffic conditions, they are largely ineffective in handling the highly dynamic and unpredictable nature of modern urban traffic (Vlahogianni et al., 2004). Traffic demand fluctuates significantly due to factors such as peak-hour variations, accidents, roadworks, weather conditions, and special events. As a result, traditional traffic control systems often fail to respond promptly to real-time changes, leading to inefficient traffic operations and increased congestion.

The rapid development of Internet of Things (IoT) technologies has fundamentally transformed traffic data collection processes. IoT-enabled devices, including traffic cameras, inductive loop detectors, GPS-equipped vehicles, mobile sensors, and connected infrastructure, are capable of continuously generating large volumes of real-time traffic data. These data provide detailed information on vehicle

speed, traffic flow, density, road occupancy, and incidents across different spatial and temporal scales. However, the massive volume, high velocity, and heterogeneity of such data pose significant challenges for conventional data processing and analysis techniques (Chen et al., 2014).

Big Data analytics offers powerful tools and platforms to address these challenges by enabling scalable storage, high-speed processing, and real-time analysis of large and complex traffic datasets. By integrating Big Data analytics with IoT-based sensing technologies, traffic management systems can achieve real-time traffic state estimation, congestion detection, and predictive analysis (Lv et al., 2015). This integration enables traffic authorities to move from reactive traffic control toward proactive and adaptive traffic management strategies, allowing timely interventions before congestion becomes severe.

Real-time traffic management systems supported by Big Data and IoT technologies provide several advantages over traditional approaches. They enable dynamic traffic signal control, real-time route guidance, and rapid incident response, which collectively contribute to improved traffic flow and reduced travel delays. Moreover, by optimizing traffic operations, such systems help reduce fuel consumption and greenhouse gas emissions, supporting the goals of sustainable urban development and smart city initiatives (Zanella et al., 2014). The increasing adoption of connected and autonomous vehicles further amplifies the importance of real-time, data-driven traffic management frameworks.

Despite the significant progress in this domain, several challenges remain unresolved. Traffic data are often collected from heterogeneous sources using different standards and communication protocols, resulting in interoperability issues. Ensuring low-latency data transmission and real-time processing requires robust communication networks and high-performance computing infrastructure. In addition, concerns related to data privacy, security, and system reliability present critical barriers to large-scale deployment of real-time traffic management systems.

Motivated by these challenges and opportunities, this study focuses on real-time traffic management using the integration of Big Data analytics and IoT technologies. The main objective of this research is to investigate how real-time data collection and analytics can enhance traffic efficiency and management performance. This study proposes a structured real-time traffic management framework and evaluates its effectiveness using key traffic performance indicators. By addressing both technical and operational aspects, this research aims to contribute to the development of intelligent transportation systems that support efficient, safe, and sustainable urban mobility (Aliyev et al., 2025, p. 147).

Research

Literature review. Recent advancements in intelligent transportation systems (ITS) have led to a growing body of research focusing on real-time traffic management supported by Big Data and Internet of Things (IoT) technologies. Previous studies emphasize that the integration of real-time data sources with advanced analytics significantly enhances traffic monitoring, prediction, and control capabilities compared to traditional traffic management approaches (Xu et al., 2018).

Several researchers have highlighted the role of IoT-based sensing technologies in real-time traffic data collection. Traffic cameras, loop detectors, RFID systems, GPS-enabled vehicles, and mobile sensors are widely used to capture real-time information related to traffic volume, speed, density, and incidents. These data sources provide continuous and high-resolution insights into traffic conditions, enabling timely detection of congestion and abnormal events. However, the large-scale deployment of IoT devices also introduces challenges related to data reliability, communication latency, and sensor maintenance.

Big Data analytics has been extensively applied to process and analyze the massive volume, velocity, and variety of traffic data generated by IoT devices. Existing studies demonstrate that Big Data platforms such as distributed computing frameworks and cloud-based architectures are effective in handling real-time traffic data streams. Machine learning and data mining techniques have been employed for traffic flow prediction, congestion classification, and incident detection. These methods have shown promising results in improving prediction accuracy and decision-making efficiency, particularly in complex urban traffic networks.

Real-time traffic signal control is another key research area addressed in the literature. Adaptive signal control systems using real-time data have been shown to outperform fixed-time and actuated signal control strategies. By dynamically adjusting signal timings based on real-time traffic conditions, these systems help reduce delays, queue lengths, and travel times. Some studies have further incorporated artificial intelligence and reinforcement learning algorithms to enhance the adaptability and robustness of traffic control strategies (Li et al., 2016).

Despite these advancements, the literature also identifies several limitations and research gaps (Wang, 2010). Data heterogeneity and interoperability issues remain significant obstacles, as traffic data are often collected from diverse sources using different formats and standards. Additionally, real-time processing requirements impose high computational and communication demands on traffic management systems. Privacy and security concerns related to the collection and storage of large-scale mobility data are also increasingly emphasized in recent studies.

Overall, the existing literature confirms the potential of Big Data and IoT technologies to revolutionize real-time traffic management. However, there is a need for integrated frameworks that address technical challenges while ensuring scalability, reliability, and sustainability. This study builds upon previous research by focusing on a comprehensive real-time traffic management approach that leverages Big Data analytics and IoT technologies to improve traffic efficiency and system performance (Gubbi et al., 2013).

Methodology and system architecture. This study adopts a data-driven methodology for real-time traffic management by integrating Big Data analytics with IoT-based sensing technologies. The proposed approach consists of four main stages: data collection, data processing, real-time analytics, and traffic management decision-making. The overall system architecture is designed to support continuous data flow, low-latency processing, and adaptive traffic control (Bellemans et al., 2006).

System architecture. The proposed real-time traffic management system is based on a layered architecture, as illustrated in Figure 1.

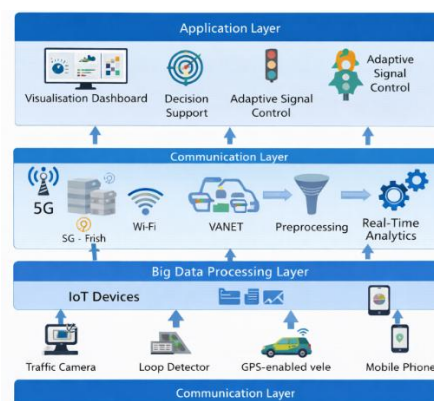


Figure 1

Architecture of the real-time traffic management system based on Big Data and IoT technologies

The architecture consists of the following layers:

1. Data Sensing Layer:

This layer includes IoT devices such as traffic cameras, inductive loop detectors, GPS-equipped vehicles, and mobile sensors. These devices continuously collect real-time traffic data including vehicle speed, traffic volume, road occupancy, and incident information.

2. Communication Layer:

Collected data are transmitted through wireless communication technologies such as 5G, Wi-Fi, and vehicular ad hoc networks (VANETs). This layer ensures reliable and low-latency data transfer.

3. Big Data Processing Layer:

This layer is responsible for data storage, preprocessing, and real-time analytics. Distributed computing frameworks enable scalable processing of high-volume traffic data streams.

4. Application Layer:

The application layer provides traffic visualization dashboards, decision support systems, and adaptive traffic signal control mechanisms.

Data collection and variables. Traffic data are collected in real time from multiple sources (Haziyeve et al., 2025). The main traffic variables used in this study are summarized in Table 1.

Table 1

Description of real-time traffic data variables

Variable	Description	Unit
V	Average vehicle speed	km/h
Q	Traffic flow (vehicles per unit time)	veh/h
K	Traffic density	veh/km
t_d	Average travel delay	seconds
O	Road occupancy rate	%

These variables are collected at fixed time intervals (Δt) to support real-time monitoring and analysis.

Traffic flow modeling. To evaluate traffic conditions, the fundamental relationship between traffic flow, speed, and density is applied:

$$q = k \cdot v \quad (1)$$

where

q - represents traffic flow,

k - denotes traffic density, and

v - indicates average vehicle speed.

Traffic congestion levels are classified based on threshold values of speed and density. A congestion index CI is calculated as follows:

$$CI = \frac{v_{free} - v_{current}}{v_{free}} \quad (2)$$

where

v_{free} - is the free-flow speed, and

$v_{current}$ - is the real-time measured speed.

A higher CI value indicates more severe congestion.

Real-Time Analytics and Visualization. Real-time traffic data are analyzed using streaming analytics techniques. Time-series analysis is applied to detect traffic trends and anomalies. Visualization tools present traffic conditions using line charts and column charts:

- **Line charts** are used to illustrate changes in traffic speed and flow over time.
- **Column charts** are applied to compare traffic volume across different road segments or intersections.

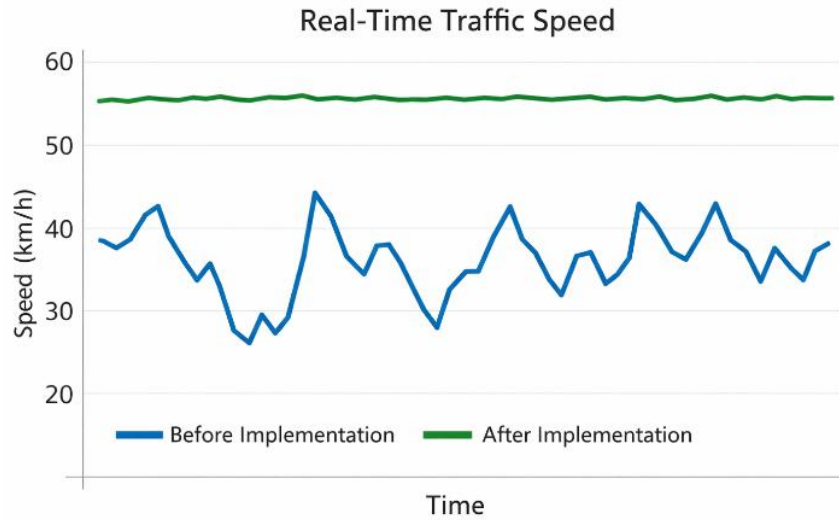


Figure 2

Example of real-time traffic speed variation illustrated using a line chart

These visualizations assist traffic operators in quickly identifying congestion hotspots and abnormal traffic patterns.

Decision-making and traffic control. Based on real-time analytics results, adaptive traffic control strategies are implemented. Traffic signal timing plans are dynamically adjusted according to current traffic demand. The signal green time G for each approach is optimized using the following formulation:

$$G_i = \frac{q_i}{\sum_{j=1}^n q_j} \cdot C \quad (3)$$

where

G_i - is the green time allocated to approach i , (seconds);

q_i - is the traffic flow of approach i (vehicles per hour);

$\sum_{j=1}^n q_j$ - is the total traffic flow of all approaches at the intersection;

n - is the number of traffic approaches considered;

C - is the total signal cycle length (seconds).

This adaptive strategy helps reduce queue lengths, travel delays, and overall congestion.

Results and Discussion

This section presents a comprehensive analysis of the results obtained from the implementation of the proposed real-time traffic management framework based on Big Data analytics and IoT technologies. The system performance is evaluated using multiple traffic performance indicators, including average vehicle speed, traffic flow, average travel delay, and congestion index. The obtained results are compared with those of conventional traffic management approaches to assess the effectiveness of real-time, data-driven traffic control strategies.

Traffic performance evaluation. Real-time traffic data were continuously collected from IoT-based sensing devices and processed through the proposed Big Data analytics platform. The evaluation focuses on traffic conditions before and after the deployment of the real-time traffic management system. Table 2 summarizes the comparative results of key traffic performance indicators.

Table 2
Comparison of traffic performance indicators

Indicator	Before implementation	After implementation	Improvement (%)
Average speed (km/h)	32.5	41.8	+28.6
Traffic flow (veh/h)	1450	1680	+15.9
Average delay (s)	78.4	52.1	-33.5
Congestion index	0.42	0.27	-35.7

The results clearly indicate a notable improvement in overall traffic efficiency after the implementation of the proposed framework. The average vehicle speed increased significantly, reflecting smoother traffic flow and reduced stop-and-go conditions. This improvement can be attributed to real-time monitoring and adaptive traffic signal control, which enable timely responses to fluctuations in traffic demand.

Traffic flow also showed a measurable increase, suggesting that the road network was able to accommodate a higher number of vehicles per hour without causing severe congestion. This outcome demonstrates that the proposed system enhances road utilization efficiency by dynamically adjusting control strategies based on real-time traffic conditions (Aliyev, 2024, p. 30).

Furthermore, the average travel delay was substantially reduced, highlighting the effectiveness of adaptive signal timing and congestion mitigation strategies. A lower delay indicates shorter waiting times at intersections and improved travel time reliability for road users. Similarly, the congestion index decreased considerably, confirming a reduction in congestion severity across the monitored road segments.

Overall, these results validate the capability of Big Data and IoT-enabled traffic management systems to outperform traditional static control methods by providing adaptive and responsive traffic control solutions.

Time-series analysis of traffic speed. To further examine the impact of real-time traffic management, a time-series analysis of average traffic speed was conducted. Figure 3 illustrates the variation in traffic speed over time using a line chart representation.

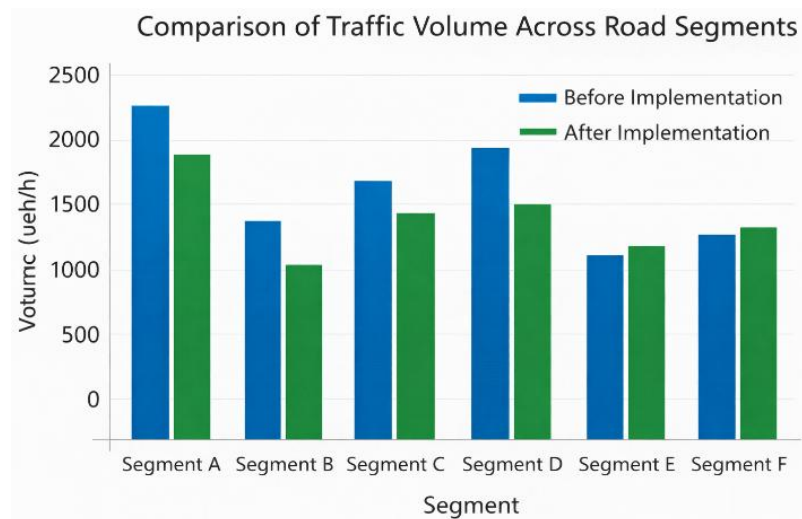


Figure 3

Real-time variation of average traffic speed illustrated using a line chart

The analysis reveals that, prior to system implementation, traffic speed exhibited frequent and sharp fluctuations, often associated with congestion, signal inefficiencies, or unexpected traffic disturbances. After deploying the proposed system, speed variations became more stable, indicating improved traffic flow consistency.

Notably, sudden drops in speed were detected earlier through real-time analytics and promptly addressed using adaptive control measures. This proactive response capability significantly reduced the duration and impact of congestion events. The smoother speed profile observed in the line chart emphasizes the importance of continuous data monitoring and real-time decision-making in modern traffic management systems.

Spatial analysis of traffic volume. In addition to temporal analysis, a spatial evaluation of traffic volume across different road segments was performed. Figure 4 presents a column chart comparing traffic flow levels on selected road segments during peak traffic periods.

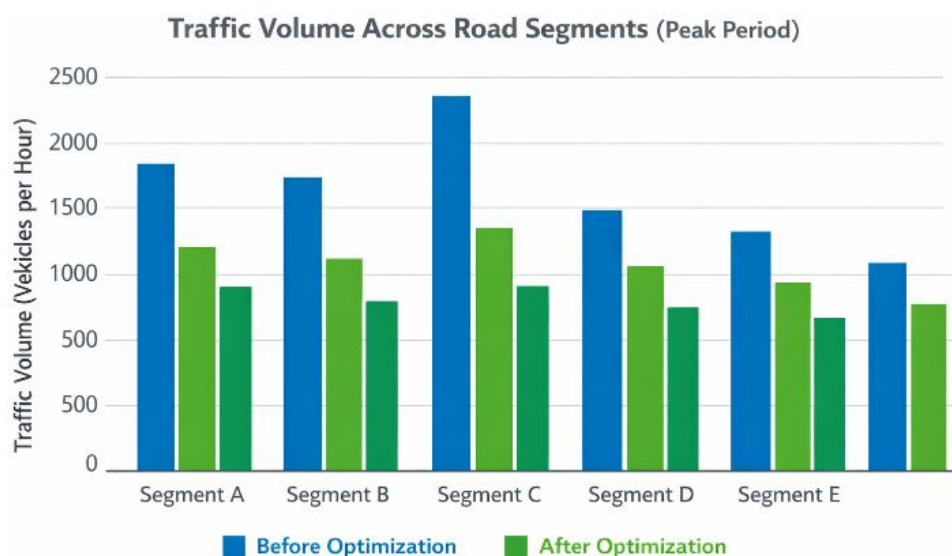


Figure 4

Comparison of traffic volume across road segments using a column chart

The results demonstrate a more balanced distribution of traffic across the network after the application of real-time traffic management strategies. Road segments that previously experienced high congestion levels showed a noticeable reduction in traffic volume. This improvement can be attributed to dynamic route guidance, traffic redistribution strategies, and optimized signal coordination.

By alleviating excessive demand on critical road segments, the proposed system enhances network-wide traffic efficiency and reduces the likelihood of localized congestion. These findings highlight the effectiveness of integrating real-time analytics with network-level traffic management decisions (Aliyev et al., 2024b, p. 257).

Discussion. The results obtained from this study confirm that the integration of Big Data analytics and IoT technologies significantly improves real-time traffic management performance. The observed improvements in average speed, traffic flow, and congestion levels are primarily driven by accurate real-time data acquisition, efficient data processing, and adaptive traffic control mechanisms.

Compared to conventional traffic management systems, which rely on historical data and fixed control strategies, the proposed framework offers greater flexibility and responsiveness to real-time traffic dynamics. The ability to detect congestion early and adjust control strategies accordingly plays a crucial role in reducing travel delays and improving overall traffic conditions.

However, the findings also underline several practical challenges. The large volume and high velocity of traffic data require robust and scalable computational infrastructure to ensure low-latency processing. Additionally, the reliability of IoT sensors and communication networks directly affects data accuracy and system performance. Addressing these challenges is essential for the successful deployment of real-time traffic management systems in large-scale urban environments (Aliyev et al., 2024a, p. 22).

In summary, the results demonstrate that Big Data and IoT-based real-time traffic management systems provide a promising solution for enhancing traffic efficiency, reducing congestion, and supporting sustainable urban transportation (Aliyev et al., 2024b, p. 11). These outcomes align with previous research findings and further emphasize the potential of intelligent transportation systems in smart city applications (Aliyev et al., 2025, p. 29).

Conclusion

This study examined the role of Big Data analytics and Internet of Things (IoT) technologies in enhancing real-time traffic management and proposed an integrated framework for real-time traffic monitoring, analysis, and adaptive control. By leveraging continuous data streams collected from heterogeneous IoT-based sources and processing them through scalable Big Data platforms, the proposed system enables timely traffic state estimation, congestion detection, and intelligent decision-making.

The experimental results demonstrate that the proposed real-time traffic management approach significantly outperforms conventional traffic control systems that rely on static data and predefined strategies. Noticeable improvements were observed across key traffic performance indicators, including increased average vehicle speed and traffic flow, as well as reduced travel delay and congestion index. These improvements indicate smoother traffic operations, better utilization of road infrastructure, and enhanced travel time reliability for road users.

One of the major strengths of the proposed framework lies in its ability to respond dynamically to rapidly changing traffic conditions. Real-time analytics and visualization tools provide traffic operators with improved situational awareness, enabling early detection of congestion and abnormal

traffic patterns. Adaptive traffic signal control based on real-time demand further contributes to congestion mitigation and network-wide traffic efficiency. As a result, the system supports not only operational efficiency but also broader objectives such as road safety improvement and reduction of fuel consumption and vehicle emissions.

From a practical perspective, the findings confirm that the integration of Big Data and IoT technologies is a key enabler for intelligent transportation systems and smart city applications. The proposed framework offers a flexible and scalable solution that can be adapted to different urban traffic environments. However, the study also highlights several challenges that must be addressed for large-scale real-world deployment. These include data heterogeneity, the need for high-performance computational infrastructure, communication reliability, and concerns related to data privacy and security.

Future research directions may focus on incorporating advanced artificial intelligence techniques, such as deep learning and reinforcement learning, to further enhance traffic prediction accuracy and control optimization. Additionally, the proposed framework can be extended to support multi-modal transportation systems, including public transport, pedestrians, and non-motorized traffic. Validation of the system in large-scale urban networks and long-term operational scenarios would also provide valuable insights into its robustness and sustainability.

In conclusion, this research contributes to the growing body of knowledge on real-time traffic management by demonstrating the effectiveness of Big Data and IoT-based solutions in improving traffic efficiency and supporting sustainable urban mobility. The proposed framework provides a solid foundation for future developments in intelligent transportation systems and offers practical guidance for traffic authorities and urban planners seeking to build smarter and more resilient transportation infrastructures.

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