

Review

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[Md Rafiur Rahman](#)^{*} and [Md Mohiuddin Mamun](#)

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Review

Smart Traffic Signal Optimization Using Real-Time Data: A Review

Md Rafiur Rahman ^{1,*} and Md Mohiuddin Mamun ²

¹ Department of Civil Engineering, Mymensingh Engineering College

² Department of Civil Engineering, Mymensingh Engineering College

* Correspondence: rafiur886@gmail.com

Abstract: Rapid urbanization and increased vehicular traffic demanded the creation of intelligent traffic management systems. Smart traffic signal optimization employing real-time data has emerged as a critical approach for improving traffic flow, reducing congestion, and increasing overall urban mobility. This research paper digs into improvements in traffic signal control systems, focusing on the integration of real-time data and artificial intelligence (AI) approaches. We investigate a variety of methodologies, including reinforcement learning, fuzzy logic, and connected car technologies, highlighting their strengths and limits. The report also analyses the problems and potential future approaches for deploying these intelligent systems.

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1. Introduction

Traffic congestion has become a serious worry in cities around the world, owing to rising population growth, fast urbanization, and an increase in the number of vehicles on the road. As cities grow and transportation demand rises, ineffective traffic management exacerbates delays, fuel waste, and environmental pollution. One of the biggest reasons of intersection congestion is the employment of antiquated fixed-time traffic signal control systems, which run on predetermined schedules that do not take into consideration real-time traffic circumstances. These traditional systems frequently fail to adjust flexibly to varying traffic patterns, causing unnecessary delays during low traffic periods and bottlenecks during busy hours.

To solve these restrictions, smart traffic signal optimization with real-time data has developed as a novel option. These systems may react to current traffic circumstances by combining Artificial Intelligence (AI), Internet of Things (IoT) sensors, and real-time traffic monitoring technologies, greatly increasing efficiency. Real-time traffic data is gathered via cameras, sensors, GPS devices, connected cars (CVs), and crowd-sourced platforms like guidance applications (e.g., Google Maps, Waze). This data is analyzed using AI-driven algorithms to dynamically change signal timings, resulting in smoother traffic flow, shorter wait times, and fewer emissions.

Smart traffic lights use machine learning, reinforcement learning, and predictive analytics to continually enhance their decision-making skills. Unlike traditional fixed-time controllers, AI-based systems assess historical and current traffic data to make proactive modifications, such as prioritizing public transportation vehicles, providing a green lane for emergency vehicles, or lowering idle time at low-traffic junctions. Studies have indicated that AI-powered adaptive traffic signal control may cut congestion by up to 40% and travel time by 20-30% when compared to traditional techniques. With the rapid deployment of 5G networks, linked vehicle technology (V2X), and blockchain-enhanced security, the future of smart traffic management appears bright. However, deploying these systems raises issues such as data dependability, scalability, and interoperability, all of which must be solved in order for urban traffic management to be widely adopted and successful.

2. Reinforcement Learning in Traffic Signal Control

Reinforcement Learning (RL), a branch of machine learning, has emerged as a significant strategy for improving traffic signals due to its capacity to adapt and learn optimal control strategies through constant contact with the environment. Unlike traditional traffic signal management systems, RL-based alternatives may dynamically modify signal timings in response to real-time traffic circumstances, resulting in greater efficiency and less congestion.

Gao et al. (2017) proposed an adaptive traffic signal management system based on deep RL, which includes experience replay and target networks. Their technique resulted in considerable reductions in vehicle delays when compared to traditional fixed-time control systems. The use of deep RL enables the system to learn from previous traffic circumstances and make more educated judgments about signal modifications. Similarly, Muresan et al. (2019) Created a deep learning model capable of detecting temporal traffic patterns. Their analysis found that the suggested model reduced average vehicle delays by 32% compared to actuated controls and 37% compared to fixed-time controls, demonstrating the efficiency of RL-based solutions.

Li et al. (2023) proposed a completely data-driven method to offline RL that combines traffic flow theory and machine learning techniques. This technique derived reward signals from coarse-grained traffic data, resulting in better performance than conventional and offline RL baselines. The study demonstrated the ability of RL to efficiently improve traffic flow, even with little real-time data. These developments show that RL-based traffic signal control may greatly improve urban mobility, reduce congestion, and improve transportation sustainability.

3. Fuzzy Logic Approaches

Fuzzy logic has been widely employed in traffic signal optimization to manage the inherent uncertainties of traffic systems, such as variable vehicle flow, unexpected driver behavior, and changing environmental circumstances. Unlike traditional rule-based traffic control, which depends on fixed threshold values, fuzzy logic provides for a more flexible and adaptable decision-making process by dealing with imprecise and incomplete data. (Zadeh, 1975).

Sari et al. (2020) conducted research on the application of fuzzy logic in smart traffic signal systems, which was published in the TELKOMNIKA Journal. The study shows how real-time data from sensors and cameras may be analysed by a fuzzy inference system to dynamically change traffic light timing. The program divides traffic situations into three categories: low, medium, and heavy congestion, and then calculates the ideal green light durations for each. When compared to standard fixed-time signals, the fuzzy-based system lowered average waiting time and congestion levels, increasing overall traffic flow efficiency.

Fuzzy logic-based traffic signal control is especially useful in complicated, uncertain metropolitan situations. It improves responsiveness, adaptation to real-world traffic situations, and eliminates wasteful vehicle idling, resulting in decreased fuel consumption and emissions (Sari et al., 2020).

4. Connected Vehicle Technologies

The incorporation of Connected Vehicle (CV) technology has emerged as a game-changing strategy to enhancing traffic signal regulation by enabling real-time vehicle-to-infrastructure (V2I) communication. CV technology enables cars to communicate data with traffic signals, roadside devices, and infrastructure elements, resulting in enhanced signal synchronization, traffic flow, and decreased congestion (Feng et al., 2015).

Feng et al. (2015) investigated a real-time adaptive traffic signal control system for a connected car environment. Their research found that by continually receiving data on vehicle locations, speeds, and queue lengths, smart traffic signals may dynamically change green light durations and decrease unnecessary pauses. The study showed considerable reductions in vehicle delays, fuel consumption, and pollutants. .

Similarly, Guler et al. (2014) looked at how CV-based communication improves intersection efficiency. Their findings demonstrated that cooperative traffic signal control using V2I communication results in smoother vehicle flow, less abrupt stops, and improved overall junction performance. Traffic signals can use real-time vehicle data to anticipate congestion patterns and change timings proactively, boosting throughput at congested crossings. CV-based traffic management is projected to play a crucial role in next-generation intelligent transportation systems, as 5G networks and powerful AI algorithms become more widely adopted. (ITS).

5. AI and Blockchain Integration

The combination of artificial intelligence (AI) and blockchain technology has emerged as a revolutionary method to improving traffic light management systems. Real-time decision-making is enabled by AI-driven algorithms that analyze traffic flow patterns, congestion levels, and vehicle density, and blockchain technology provides safe, transparent, and decentralized data management. Integrating these technologies addresses conventional traffic management concerns, including data tampering, inefficiencies, and lack of interoperability. .

Ahmed et al. (2023) introduced a novel matrix method that integrates AI and blockchain to optimize smart traffic signals. This method uses machine learning models to forecast congestion patterns and dynamically change signal timings. Simultaneously, blockchain technology is used to securely store and communicate traffic data across interconnected systems, providing tamper-proof data interchange between cars, infrastructure, and traffic control centers. The study found that combining AI with blockchain resulted in a 30% reduction in congestion, quicker reaction times, and more fair distribution of green signal durations among traffic streams.

One of the primary benefits of using blockchain into traffic signal systems is data security and transparency. Real-time traffic data is maintained in a decentralized ledger, which eliminates data tampering and security risks that are frequent in traditional smart traffic management systems. Furthermore, smart contracts may be used to automate decision-making, allowing traffic lights to adapt dynamically without human involvement using pre-set rules recorded in blockchain networks (Ahmed et al., 2023).

With the continuous growth of 5G networks, edge computing, and quantum AI, the combination of AI and blockchain is projected to transform urban traffic control, opening the way for more robust, efficient, and secure intelligent transportation systems.

6. Challenges and Future Directions

Despite significant advancements, several key challenges hinder the widespread adoption and effectiveness of smart traffic signal optimization systems. These challenges include **data quality and availability, scalability, and interoperability**. Each of these issues is detailed below:

1. Data Quality and Availability

Smart traffic signal optimization relies heavily on **real-time data** collected from various sources, such as **cameras, sensors, GPS data from vehicles, connected infrastructure (IoT), and traffic control centers**. The accuracy, completeness, and timeliness of this data directly impact decision-making algorithms.

Challenges:

Data Incompleteness: Missing or inconsistent data from sensors can lead to erroneous traffic signal adjustments, increasing congestion rather than reducing it.

- **Data Latency:** Delays in transmitting and processing real-time data can prevent signals from adapting to immediate traffic conditions.
- **Sensor Malfunction and Maintenance:** Traffic sensors, cameras, and IoT devices require **regular calibration and maintenance**, which adds to operational costs.

- **Privacy and Security Risks:** Traffic data collected from connected vehicles (CVs) and IoT devices may expose sensitive information, making security measures critical.

Potential Solutions:

- **Advanced Data Fusion:** Combining multiple sources of traffic data (e.g., video analytics, radar sensors, and GPS data) can improve accuracy.
- **Machine Learning for Data Imputation:** AI-driven models can estimate missing data points and enhance real-time decision-making.
- **Blockchain for Data Integrity:** Blockchain technology can secure and validate real-time traffic data to prevent tampering and ensure reliability.

2. Scalability

Many smart traffic signal control algorithms work well in **small-scale, controlled environments** (such as test intersections or pilot projects) but struggle when applied to **large urban areas**. The complexity increases exponentially as the number of vehicles, intersections, and traffic conditions vary significantly.

Challenges:

- **Computational Complexity:** Real-time optimization of multiple intersections requires **high computational power**, which is difficult to achieve with current urban infrastructure.
- **Network Congestion:** The transmission of large amounts of real-time data from multiple sensors can overload city networks, causing delays.
- **Heterogeneous Traffic Conditions:** Mixed traffic environments (bicycles, pedestrians, public transport, private vehicles) make optimization difficult.

Potential Solutions:

- **Edge Computing & Distributed Processing:** Deploying AI-driven traffic controllers closer to intersections (edge devices) can reduce response times.
- **Cloud-Based and 5G Connectivity:** High-speed, low-latency networks can support real-time decision-making for large-scale urban deployments.
- **Hierarchical Optimization Models:** Instead of optimizing each intersection separately, a city-wide hierarchical model can distribute traffic loads more effectively.

3. Interoperability

Smart traffic management requires the integration of various **technologies, software platforms, and infrastructure components**, such as:

- **Connected Vehicles (CVs)** using V2I (Vehicle-to-Infrastructure) communication
- **IoT-based sensors and cameras** that collect real-time traffic data
- **Traditional traffic management systems** (legacy signal controllers, urban planning databases)

If these systems do not communicate seamlessly, **inconsistent or conflicting signals** can worsen congestion instead of alleviating it.

Challenges:

- **Lack of Standardized Protocols:** Different manufacturers and city governments use varying communication protocols, leading to compatibility issues.
- **Integration with Legacy Systems:** Older traffic signal controllers may not support AI-driven real-time optimization, requiring costly upgrades.
- **Cybersecurity Threats:** Open communication between multiple devices increases vulnerability to cyberattacks, potentially disrupting traffic operations.

Potential Solutions:

- **Adoption of Global ITS Standards:** Cities should implement standardized protocols such as Dedicated Short-Range Communications (DSRC) or Cellular-V2X (C-V2X) for vehicle-to-infrastructure connectivity.

- **Hybrid Traffic Signal Systems:** A combination of AI-driven controllers and adaptive legacy systems can smoothen the transition.
- **Enhanced Cybersecurity Measures:** AI-driven anomaly detection and encryption-based authentication can protect smart traffic networks.

Future Research Directions

To address these challenges, future research should focus on:

- **Developing Robust AI Algorithms:** Machine learning models capable of handling diverse and unpredictable traffic conditions.
- **Enhancing Data Fusion Techniques:** Integrating multiple data sources (satellite, GPS, IoT, sensors) for more accurate decision-making.
- **Establishing Comprehensive System Integration Frameworks:** Cities need unified platforms where all smart traffic components (signals, CVs, IoT, AI) can interact seamlessly.

7. Conclusion

Smart traffic signal optimization using **real-time data** is a transformative advancement in modern traffic management, offering **adaptive, data-driven solutions** to alleviate congestion and enhance urban mobility. By integrating **Artificial Intelligence (AI), machine learning (ML), fuzzy logic, connected vehicle (CV) technology, and blockchain**, these intelligent systems can **dynamically adjust signal timings** based on real-time traffic conditions, significantly improving traffic flow and reducing delays (Feng et al., 2015; Ahmed et al., 2023).

Studies have shown that AI-driven **adaptive signal control systems** outperform traditional fixed-time traffic signals by responding to **changing vehicle density, pedestrian movement, and emergency vehicle priority** (Guler et al., 2014). **Fuzzy logic-based** approaches effectively handle traffic uncertainties by categorizing congestion levels and adjusting green light durations accordingly (Sari et al., 2020). Additionally, the use of **CV technology** enables seamless communication between vehicles and infrastructure, further optimizing signal coordination and improving intersection efficiency (Feng et al., 2015).

Recent advancements have also explored the **fusion of AI and blockchain** to enhance traffic management security, transparency, and efficiency (Ahmed et al., 2023). Blockchain technology ensures **tamper-proof traffic data storage**, preventing cyber threats and improving trust in traffic optimization decisions. Furthermore, **smart contracts** can automate traffic signal adjustments, reducing the need for manual intervention.

Despite these promising developments, challenges such as data quality, scalability, and interoperability remain significant hurdles. Future research must focus on refining AI algorithms, improving real-time data fusion, and developing standardized protocols for seamless system integration. By addressing these challenges, smart traffic signal optimization can lead to sustainable, efficient, and intelligent transportation networks in rapidly urbanizing cities.

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