AI-Based Optimization of Traffic Signal Control for Urban Transportation Efficiency

Bikas Swain
M. Tech. in Transportation Engineering, CBS Group of Institutions, Jhajjar, Haryana.

Vishal Panchal
A.P Civil Department, CBS Group of Institutions, Jhajjar, Haryana.

ABSTRACT

Urban transportation systems face growing challenges due to rapid urbanization, leading to severe traffic congestion. Traditional traffic signal control systems often fail to adapt to real-time traffic flow, contributing to travel delays, fuel waste, and high emissions. AI-based solutions such as Genetic Algorithms, Particle Swarm Optimization, and Reinforcement Learning have emerged to address these issues by optimizing traffic flow through adaptive signal timing. These intelligent systems can dynamically adjust signals, reducing congestion, improving road safety, and enhancing sustainability by minimizing travel time, fuel consumption, and carbon emissions. However, challenges such as real-time data requirements and integration with existing infrastructure remain.

Keywords: *Urban Transportation, Traffic Congestion, AI-Based Solutions, Traffic Signal Control.*

I. INTRODUCTION

Urban transportation systems are the backbone of economic growth and social connectivity; however, rapid urbanization and increasing vehicle ownership have significantly intensified traffic congestion across cities worldwide. Inefficient traffic signal timing at intersections remains one of the primary contributors to increased travel delays, excessive fuel consumption, and elevated greenhouse gas emissions. Traditional traffic signal control systems, which typically rely on fixed-time or pre-timed strategies, often fail to adapt to dynamic traffic conditions, resulting in suboptimal performance during peak and non-peak hours. In this context, the integration of Artificial Intelligence (AI) algorithms into traffic signal control has emerged as a transformative approach for optimizing urban mobility and enhancing sustainability (Jamal et al., 2020; Mancino, 2022). Traffic congestion has been identified as a major urban challenge, causing not only time loss but also significant environmental and economic impacts. According to Bhattacharyya et al. (2026), congestion leads to increased vehicle idling, fuel wastage, and pollutant emissions, thereby affecting air quality and public health. Conventional Traffic Signal Control (TSC) systems lack the capability to dynamically adjust signal timings based on real-time traffic flow variations, which limits their effectiveness. To address these challenges, researchers have increasingly focused on intelligent and adaptive traffic control systems that utilize AI-based optimization techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Reinforcement Learning (RL), and Artificial Neural Networks (ANN). These techniques enable the development of adaptive models capable of learning from traffic patterns and making real-time decisions to optimize signal timings and traffic flow (Bhattacharyya et al., 2026). Recent advancements in machine learning and deep learning have further enhanced the capabilities of intelligent traffic management systems. For instance, Fathimunnisa et al. (2026) demonstrated the use of Convolutional Neural Networks (CNN) and object detection techniques to monitor traffic density and dynamically adjust signal timings. Such systems not only improve traffic flow but also enhance road safety through real-time surveillance and violation detection. Similarly, Qiu (2025) proposed a machine learning-based framework that integrates predictive modeling and adaptive control to minimize carbon emissions and improve traffic efficiency. The study reported significant reductions in travel time, fuel consumption, and emissions, highlighting the potential of AI-driven solutions in achieving sustainable urban transportation. Reinforcement learning has gained particular attention in traffic signal optimization due to its ability to learn optimal policies through interaction with the environment. Loulhaci and Bensouna (2024) developed an AI-based adaptive traffic light system using reinforcement learning, which dynamically adjusted signal phases based on real-time traffic conditions, resulting in reduced congestion and improved traffic flow. Similarly, Maadi et al. (2022) introduced a reinforcement learning-based adaptive traffic signal control system integrated with vehicle speed guidance, demonstrating improved performance under both saturated and oversaturated traffic conditions. These approaches highlight the effectiveness of AI in handling the stochastic and non-linear nature of traffic systems. In addition to reinforcement learning, metaheuristic and hybrid optimization techniques have shown promising results in traffic signal timing optimization. Olayode et al. (2021) developed a hybrid ANN-PSO model that effectively predicted and optimized traffic flow at signalized intersections, achieving high accuracy in performance metrics. Jamal et al. (2020) employed Genetic Algorithms and Differential Evolution to optimize signal timing plans, reporting substantial reductions in vehicle delays and improvements in intersection performance. Bhattacharyya et al. (2026) further emphasized that hybrid approaches combining multiple algorithms tend to outperform single-method solutions, offering better convergence and adaptability in complex traffic environments. The emergence of smart transportation systems, supported by Internet of Things (IoT) technologies and connected vehicles, has further enhanced the potential of AI-based traffic management. Kadkhodayi et al. (2023) highlighted the role of IoT-enabled multi-agent systems in enabling distributed traffic control across multiple intersections, facilitating real-time data collection and decentralized decision-making. These systems leverage AI algorithms to process large volumes of traffic data, predict congestion patterns, and optimize signal timings in a coordinated manner. Moreover, the integration of autonomous vehicles and AI-driven infrastructure, as discussed by Mancino (2022), is expected to revolutionize urban traffic systems by enabling seamless communication between vehicles and traffic control systems. Despite the significant progress in AI-based traffic signal optimization, several challenges remain. These include the need for large-scale real-time data, computational complexity, model scalability, and integration with existing infrastructure. Additionally, the variability of traffic conditions across different urban environments necessitates the development of robust and adaptable models. Bagdatli and Dokuz (2021) emphasized the importance of accurate delay estimation models for effective traffic management, highlighting the role of machine learning techniques such as Random Forest and XGBoost in improving prediction accuracy.

II. RESEARCH BACKGROUND

Bhattacharyya et al. (2026) conducted a systematic review on traffic congestion and its effects on urban mobility, noting that it caused travel delays, increased fuel consumption, and higher emissions. They examined Traffic Signal Control (TSC) as a key strategy to mitigate these issues and analyzed 50 peer-reviewed studies from 2015 to 2025 using the PRISMA methodology, focusing on the application of Evolutionary Algorithms (EAs) and Swarm Intelligence (SI) in TSC optimization. Their review compared algorithmic performance, application contexts, and parameter adjustment strategies, and it was found that hybrid methods, such as Genetic Algorithms combined with Particle Swarm Optimization, outperformed single algorithms, reducing average vehicle delay by up to 28.9%. PSO was observed to be more resilient for real-time applications, whereas GA provided robustness for offline, multi-objective planning. They highlighted the importance of parameter tuning, with optimal GA mutation rates of 0.01–0.1 and PSO inertia coefficients around 0.7, and synthesized these findings into practical recommendations for researchers, transportation planners, and policymakers to enhance traffic management and environmental sustainability.

Fathimunnisa et al. (2026) examined the challenges of urban traffic congestion and inefficient signal management, highlighting the growing demand for real-time optimization solutions. They proposed a traffic signal control and vehicle detection system employing deep learning techniques, specifically convolutional neural networks (CNN) and object detection, which automatically adjusted signal timings based on traffic density. Their study reported that the system reduced traffic jams, optimized road flow, and enhanced surveillance by detecting traffic violations and monitoring road activity. The authors indicated that, compared to traditional methods, their approach offered improved accuracy, reduced waiting times, and greater flexibility. Experimental evaluations were cited as confirming the system's effectiveness for optimal urban traffic management, emphasizing that integrating AI-based strategies could provide scalable, hyper-efficient solutions for modern transportation needs.

Qiu (2025) reported that transportation systems accounted for approximately 28% of global carbon emissions, with urban road traffic representing the largest single source of vehicular pollution. The study presented a comprehensive Machine Learning (ML) framework aimed at minimizing carbon emissions through intelligent optimization of traffic flow patterns and dynamic routing algorithms. It was indicated that the proposed system integrated real-time traffic monitoring, predictive modeling, and adaptive control mechanisms to reduce vehicle emissions while maintaining transportation efficiency. The approach employed deep neural networks and reinforcement learning techniques to analyze traffic patterns, predict congestion hotspots, and optimize signal timing and route recommendations across urban networks. Empirical evaluation conducted across three metropolitan areas, covering 2,847 intersections and 156,000 vehicles over 24 months, was reported to show substantial reductions in carbon emissions averaging 19.4% compared to conventional traffic management systems. The framework was found to improve traffic flow efficiency with average reductions of 26.7% in travel time and 31.2% in fuel consumption per vehicle-kilometer. Furthermore, the system demonstrated high accuracy in congestion prediction (92.8% for 30-minute forecasts) and dynamic adaptation with average response times of 4.2 minutes, supporting the conclusion that ML-based traffic optimization was a highly effective strategy for sustainable urban transportation while enhancing overall system performance and user satisfaction, which averaged 4.3 out of 5.0.

Loulhaci and Bensouna (2024) investigated urban traffic congestion, highlighting its negative impact on drivers' and commuters' quality of life. They noted that conventional traffic lights exacerbated congestion due to their inability to respond to real-time traffic conditions, leading to delays and inefficiencies. Their study examined the application of artificial intelligence, particularly reinforcement learning, to develop an adaptive traffic light system capable of dynamically adjusting to fluctuating traffic scenarios. The authors reported that this approach was implemented in a district of Tlemcen, where congestion had been significant, and it demonstrated improvements in traffic flow, reduced congestion, and minimized vehicle waiting times at intersections. They concluded that the AI-based system provided a more efficient and responsive alternative to traditional traffic control methods, effectively optimizing traffic management for the local context.

Sreejith et al. (2024) examined the challenges posed by the rapid growth of vehicular traffic due to urbanization and population expansion, which had led to congested road networks. They noted that traditional and sensor-based adaptive traffic light management systems, while showing some progress, suffered from limitations that affected their effectiveness and scalability. To address these issues, they argued for the need for a dynamic and adaptable traffic control system and proposed an intelligent traffic management algorithm named IntelliSignal. This system leveraged map services to fetch real-time traffic information, calculated optimal green times, and applied a penalty-based road selection strategy to balance traffic flow, giving equal opportunity to all roads while prioritizing higher-density routes. The authors highlighted the incorporation of Q-learning as a reinforcement learning approach to allow the system to adapt to traffic patterns. They assessed IntelliSignal using the SUMO simulation platform and reported significant improvements in metrics such as average waiting time, vehicle density, travel time, CO_2 emissions, and queue length, with system throughput increasing by 30.52% over traditional methods, demonstrating its potential for practical implementation.

Kadkhodayi et al. (2023) investigated the application of the ant colony optimization algorithm within a distributed multi-agent framework, utilizing IoT technology, to address path routing issues in urban traffic. They highlighted the potential of advanced AI techniques and multi-agent systems to transform traffic management toward more efficient and sustainable urban transportation. The study addressed the persistent problem of traffic congestion in modern cities and the inadequacy of conventional solutions such as road expansion and standard network indicators. The authors examined strategies based on both macroscopic and microscopic traffic models, noting that traditional modeling approaches struggled to cope with the complexity of urban traffic systems. They emphasized that the emergence of IoT provided new opportunities for traffic analysis through the collection of large, uncertain datasets, but observed that existing systems were often limited to local event management. To overcome this, the study proposed multi-agent systems as a distributed approach across intersections, while AI techniques—including fuzzy logic, evolutionary algorithms, neural networks, and reinforcement learning—were recognized as effective tools for traffic control, with neural networks enhancing traffic flow prediction and meta-heuristic methods such as the artificial bee colony algorithm optimizing signal timings.

Mancino (2022) discussed how smart transportation systems had been rapidly evolving due to advancements in Artificial Intelligence (AI) and autonomous vehicle technologies, highlighting their potential to transform traffic management, route optimization, and predictive maintenance, thereby enhancing urban mobility. It was argued that autonomous vehicles equipped with AI-powered sensors and decision-making algorithms improved traffic flow efficiency by reducing human errors, which were identified as the primary causes of accidents and congestion. The study indicated that AI-driven traffic management systems analyzed real-time data from AVs, connected infrastructure, and mobile devices to optimize signal timings, detect incidents early, and dynamically reroute vehicles, thus minimizing delays and improving overall traffic conditions. Mancino further noted that machine learning algorithms processed extensive data on traffic patterns, road conditions, and historical trends to suggest the most efficient routes for both AVs and conventional vehicles, reducing travel times and fuel consumption. Additionally, the research emphasized the role of AI in predictive maintenance, where continuous monitoring of vehicle performance and infrastructure conditions allowed for proactive interventions, reducing downtime, extending asset life, and ensuring safer travel. The study concluded that as these technologies matured, their adoption was expected to reshape urban mobility and address numerous challenges faced by modern cities.

Maadi et al. (2022) examined adaptive traffic signal control (ATSC) as a method to mitigate traffic congestion in urban areas and reported that various studies had previously adopted approaches to adjust signal plans based on real-time traffic to improve network performance, particularly by minimizing delays. They noted that learning-based techniques, including reinforcement learning (RL), had recently shown promising results in signal plan optimization, though their adoption in future traffic scenarios involving connected and automated vehicles (CAVs) remained largely unaddressed. The study developed a real-time RL-based ATSC system designed to minimize total queue length while enabling CAVs to adjust speed using a fixed timing strategy to reduce stop delays. The authors highlighted the integration of a speed guidance system with RL-based signal control and implemented two performance measures to optimize queue length and stop delays. Their results suggested that the proposed method outperformed fixed timing plans with optimal speed advisory and traditional actuated control, particularly under saturated and oversaturated traffic conditions.

Bagdatli and Dokuz (2021) examined the importance of accurately determining average vehicle delays for effective management of signalized intersections. They noted that while field studies could provide delay measurements, such approaches were costly and time-consuming, and traditional analytical methods often failed to produce accurate estimates, especially under oversaturated traffic conditions. The authors highlighted that recent literature had introduced artificial intelligence-based delay estimation models, though the variety of AI or heuristic techniques applied remained limited. In their study, they developed estimation models using four machine learning methods—support vector regression (SVR), random forest (RF), k-nearest neighbor (kNN), and extreme gradient boosting (XGBoost)—which had not previously been applied for vehicle delay estimation at signalized intersections. Data were collected from 12 intersections in Ankara, Turkey, to test model performance, and comparisons were made with established delay models from the literature. The RF and XGBoost models were reported to demonstrate particularly high accuracy, indicating that these techniques could substantially enhance both academic research and practical traffic management applications.

Olayode et al. (2021) investigated the persistent issue of traffic congestion at signalized road intersections, noting that the rapid increase in vehicular navigation had continually exacerbated delays. They applied an artificial neural network trained by particle swarm optimization (ANN-PSO) to address traffic flow problems, considering variables such as vehicle speed, vehicle categories, traffic density, time, and traffic volumes as inputs and outputs for modelling non-autonomous vehicle flow. Data comprising 434 traffic observations from seven roads connecting to the N1 Allandale interchange, recognized as the busiest in Southern Africa, were analyzed across thirteen input variables and one output variable. The study reported training and testing performances of 0.98356 and 0.98220, indicating a strong positive correlation between the model's inputs and outputs. Optimal ANN-PSO performance was attained through concurrent tuning of neuron numbers, acceleration factors, and swarm population sizes. The findings suggested that the ANN-PSO model was effective for predicting and optimizing traffic flow, offering valuable guidance for traffic engineers in designing signal timings and traffic regulations.

Jamal et al. (2020) investigated traffic signal control as a crucial element of intelligent transportation systems (ITS), emphasizing its role in mitigating traffic congestion. They observed that poor management and inefficient operations at signalized intersections caused excessive vehicle delays, higher fuel consumption, and increased emissions. The study highlighted that operational performance could be significantly improved by optimizing phasing and signal timing plans using intelligent traffic control techniques. Previous research was noted to focus mainly on lane-based homogeneous traffic conditions, whereas traffic patterns were generally non-linear and highly stochastic during peak hours, limiting practical application. The authors developed metaheuristic-based approaches for isolated signalized intersections in Dhahran, Saudi Arabia, employing genetic algorithms (GA) and differential evolution (DE) to optimize signal timing and improve the intersection's level of service (LOS). They reported that both GA and DE systematically reduced average vehicle delays by 15–35%, with DE converging faster but GA providing superior solution quality. Validation against TRANSYT 7F simulation outputs confirmed the robustness and adequacy of the proposed methods.

III. KEY FINDINGS FROM STUDY

Author (Year)	Objective	Methodology	Key Findings
Bhattacharyya et al. (2026)	Review AI-based traffic signal optimization	PRISMA-based review of 50 studies	Hybrid GA+PSO reduced delay by 28.9%
Fathimunnisa et al. (2026)	Real-time traffic signal optimization	CNN + object detection	Reduced congestion and waiting time
Qiu (2025)	Minimize emissions using ML	ML + RL + predictive modeling	26.7% travel time and 31.2% fuel reduction
Loulhaci & Bensouna (2024)	Adaptive traffic signal system	Reinforcement Learning	Improved flow and reduced delays
Sreejith et al. (2024)	Intelligent signal system	Q-learning + SUMO	30.52% increase in

	(IntelliSignal)	simulation	throughput
Kadkhodayi et al. (2023)	AI-based traffic management	Multi-agent + IoT + ACO	Improved routing and coordination
Mancino (2022)	AI in smart transportation	Data-driven AI systems	Reduced delays and improved routing
Maadi et al. (2022)	Adaptive signal control	RL + speed guidance	Reduced queue length and delays
Bagdatli & Dokuz (2021)	Delay estimation	RF, XGBoost, SVR, kNN	High accuracy in delay prediction
Olayode et al. (2021)	Traffic flow modeling	ANN-PSO hybrid model	High prediction accuracy (0.98)
Jamal et al. (2020)	Signal timing optimization	GA & DE algorithms	15–35% delay reduction

IV. CONCLUSION

The comprehensive review of existing literature clearly establishes that Artificial Intelligence (AI)-based traffic signal optimization techniques provide a highly effective solution to the growing challenges of urban traffic congestion. Traditional traffic control systems, which rely on fixed-time or pre-programmed signal plans, are inherently limited in their ability to adapt to fluctuating traffic conditions. As a result, they often lead to increased vehicle delays, inefficient fuel usage, and higher emissions. In contrast, AI-driven approaches offer dynamic, data-driven, and adaptive mechanisms that significantly enhance the performance of traffic signal systems. A wide range of AI algorithms, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Reinforcement Learning (RL), and Artificial Neural Networks (ANN), have demonstrated strong capabilities in optimizing traffic signal timing. These methods effectively address the complex, nonlinear, and stochastic characteristics of urban traffic systems by continuously learning from real-time and historical data. For instance, reinforcement learning-based models adapt their control strategies through interaction with the traffic environment, enabling real-time decision-making that minimizes delays and queue lengths. Similarly, metaheuristic approaches such as GA and PSO provide robust optimization solutions for multi-objective problems, including minimizing travel time and fuel consumption simultaneously. Moreover, hybrid models that combine multiple AI techniques have shown superior performance compared to individual algorithms. These hybrid approaches leverage the strengths of different methods, resulting in faster convergence, improved accuracy, and better adaptability to varying traffic conditions. Real-time adaptive systems, supported by advanced sensors and data analytics, further enhance traffic management by continuously adjusting signal timings based on traffic density, vehicle flow, and congestion patterns. Such systems not only improve traffic flow efficiency but also contribute significantly to environmental sustainability by reducing idle time and lowering greenhouse gas emissions. The integration of Internet of Things (IoT) technologies and smart transportation infrastructure has further strengthened the potential of AI-based traffic signal optimization. IoT-enabled devices facilitate real-time data collection from multiple sources, such as traffic cameras, sensors, and connected vehicles, enabling more accurate and responsive traffic control systems. Additionally, the emergence of smart cities and connected transportation networks provides a conducive environment for implementing these advanced solutions on a large scale. AI-driven traffic systems can also support coordinated intersection control, predictive traffic management, and intelligent routing, thereby enhancing overall urban mobility. In conclusion, AI-based traffic signal optimization represents a transformative approach to modern traffic management. By significantly reducing congestion, travel delays, fuel consumption, and emissions, these techniques contribute to more efficient, sustainable, and environmentally friendly urban transportation systems. Their ability to adapt to real-time conditions, handle complex traffic scenarios, and integrate with emerging technologies makes them highly relevant for future urban planning and smart city development. As cities continue to grow and transportation demands increase, the adoption of AI-driven traffic control systems will play a crucial role in ensuring efficient mobility and improved quality of life.

V. FUTURE SCOPE

Future research in AI-based traffic signal optimization holds significant potential for advancing urban transportation systems toward greater efficiency and sustainability. One key direction is the development of hybrid AI models that combine reinforcement learning, deep learning, and metaheuristic algorithms. Such integrated approaches can leverage the strengths of each technique to achieve faster convergence, improved adaptability, and more accurate optimization of traffic signal timings under complex and dynamic conditions. Another important area is the integration of AI-driven traffic control systems with Connected and Autonomous Vehicles (CAVs). By enabling real-time communication between vehicles and infrastructure, cooperative traffic management strategies can be implemented to reduce congestion, enhance safety, and optimize traffic flow at intersections. This integration will play a crucial role in the evolution of intelligent transportation systems. The use of digital twins and smart city frameworks also presents a promising avenue for future research. Digital replicas of urban traffic networks can be used to simulate, analyze, and optimize traffic scenarios at a large scale before real-world deployment, thereby reducing risks and improving system reliability. Additionally, incorporating multi-objective optimization techniques can enable simultaneous consideration of critical factors such as travel time, fuel consumption, emissions, and road safety, leading to more balanced and sustainable traffic management solutions. Enhancing scalability and real-time processing capabilities through edge computing and cloud-based platforms is another critical focus area. These technologies can handle large volumes of traffic data efficiently, ensuring faster decision-making and system responsiveness. Furthermore, the exploration of explainable AI (XAI) is essential to improve transparency, interpretability, and user trust in AI-driven traffic systems. Finally, the deployment of low-cost sensor networks and IoT devices in developing regions can facilitate widespread data collection and implementation of intelligent traffic systems, ensuring inclusive and globally scalable solutions.

REFERENCES

1. Bhattacharyya, R., Gupta, S., Marisha, Kumar, A., Mishra, D., & Gupta, M. (2026). A systematic review of evolutionary and swarm intelligence approaches for traffic signal control optimization. *Artificial Intelligence Review*.
2. Fathimunnisa, M., Vemula Deepthi, L., Pavithra, A., & Archana, T. (2026) Real Time Traffic Signal Optimization and Vehicle Surveillance Using Deep Learning. *Proceedings Copyright*, *51*, 55.
3. Qiu, L. (2025). Machine Learning Approaches to Minimize Carbon Emissions through Optimized Road Traffic Flow and Routing. *Frontiers in Environmental Science and Sustainability*, *2*(1), 30-41.
4. LOULHACI, R., & BENSOUNA, B. (2024). *Real-time optimization of traffic lights using artificial intelligence* (Doctoral dissertation, Directeur: Mr ABDELLAOUI Ghouti/Co-Directeur: Mrs. SEBBAGH Hafidha).
5. Sreejith, K., Mathi, S., & Pradeep, P. (2024). Beyond sensors: Intellisignal's map-integrated intelligence in traffic flow optimization. *IEEE Access*, *12*, 39028-39040.

6. Kadkhodayi, A., Jabeli, M., Aghdam, H., & Mirbakhsh, S. (2023). Artificial intelligence-based real-time traffic management. *J. Electr. Electron. Eng*, *2*(4), 368-373.
7. Mancino, G. (2022, January). *The Role of Autonomous Vehicles and AI in Smart Transportation Systems: Enhancing Traffic Management, Route Optimization, and Predictive Maintenance*.
8. Maadi, S., Stein, S., Hong, J., & Murray-Smith, R. (2022). Real-time adaptive traffic signal control in a connected and automated vehicle environment: optimisation of signal planning with reinforcement learning under vehicle speed guidance. *Sensors*, *22*(19), 7501.
9. Bagdatli, M. E. C., & Dokuz, A. S. (2021). Vehicle delay estimation at signalized intersections using machine learning algorithms. *Transportation research record*, *2675*(9), 110-126.
10. Olayode, I. O., Tartibu, L. K., Okwu, M. O., & Ukaegbu, U. F. (2021). Development of a hybrid artificial neural network-particle swarm optimization model for the modelling of traffic flow of vehicles at signalized road intersections. *Applied Sciences*, *11*(18), 8387.
11. Jamal, A., Tauhidur Rahman, M., Al-Ahmadi, H. M., Ullah, I., & Zahid, M. (2020). Intelligent intersection control for delay optimization: Using meta-heuristic search algorithms. *Sustainability*, *12*(5), 1896.