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AI-Driven Signal Timing for Efficient Urban Traffic Flow Management

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ABSTRACT

This study focuses on the optimization of urban traffic signal timing using Artificial Intelligence algorithms to minimize traffic delay and fuel consumption. Rapid urbanization and increasing vehicle density have created serious congestion problems at signalized intersections. Traditional fixed-time signals often fail to respond to changing traffic conditions, resulting in longer queues, excessive waiting time, fuel wastage, and higher emissions. The proposed AI-based approach uses traffic parameters such as vehicle flow, queue length, waiting time, and arrival rate to generate adaptive signal timings. The study concludes that AI-optimized signals improve traffic efficiency, reduce fuel use, and support sustainable urban transportation.

Keywords: *Artificial Intelligence, Traffic Signal Optimization, Traffic Delay, Fuel Consumption.*

I. INTRODUCTION

Urban traffic congestion has become one of the most serious challenges in rapidly growing cities because the continuous rise in vehicle ownership, population movement, commercial activity, and road-side development has increased pressure on existing transportation infrastructure. In many urban areas, road widening and construction of new routes are not always possible due to land limitations, high cost, environmental concerns, and dense settlement patterns. As a result, efficient management of available road capacity has become essential for improving traffic movement and reducing unnecessary delays. Among the different components of urban traffic management, traffic signal timing plays a very important role because signalized intersections are major points where vehicles stop, wait, accelerate, and interact with other traffic streams. Poorly timed traffic signals often create long queues, excessive waiting time, repeated stopping, higher fuel consumption, increased travel time, driver frustration, and greater vehicular emissions. Traditional traffic signal systems generally operate on fixed-time plans, where the duration of red, yellow, and green lights is predetermined according to historical traffic conditions. Although such systems are simple and easy to operate, they are often unable to respond effectively to real-time variations in traffic flow. During peak hours, fixed signal timings may fail to clear heavy traffic queues, while during off-peak hours, vehicles may wait unnecessarily even when there is little or no traffic on the crossing road. This mismatch between traffic demand and signal timing leads to inefficient use of road space and contributes significantly to congestion, fuel wastage, and air pollution. Therefore, the optimization of urban traffic signal timing has become an important research area in transportation engineering and intelligent transportation systems. Optimization refers to the process of finding the best possible signal timing plan that can minimize vehicle delay, reduce queue length, improve traffic flow, and lower fuel consumption. In recent years, Artificial Intelligence algorithms have shown great potential in solving complex traffic management problems because they can process large amounts of data, learn traffic patterns, and make adaptive decisions based on changing road conditions. AI-based traffic signal control can use real-time traffic data collected through sensors, cameras, GPS devices, connected vehicles, and traffic monitoring systems to adjust signal timings dynamically. Unlike conventional methods, AI algorithms can analyze multiple variables such as vehicle arrival rate, queue length, waiting time, traffic density, pedestrian movement, road capacity, turning movement, and peak-hour variation. Algorithms such as Genetic Algorithm, Particle Swarm Optimization, Fuzzy Logic, Artificial Neural Networks, Deep Learning, and Reinforcement

Learning can be applied to identify suitable green time allocation, cycle length, phase sequence, and coordination between adjacent signals. Genetic Algorithm can search for the most effective signal timing solution by imitating natural selection and evolution. Particle Swarm Optimization can improve timing plans through collective learning behavior. Fuzzy Logic can handle uncertainty in traffic conditions and make rule-based decisions similar to human reasoning. Artificial Neural Networks can learn traffic patterns from historical and real-time data, while Reinforcement Learning can train signal controllers to make better decisions by receiving rewards for reducing delay and improving traffic movement. These AI techniques are useful because urban traffic is highly dynamic and nonlinear, making it difficult to manage through manual or fixed mathematical models alone. The application of AI in signal timing optimization can also contribute to sustainable urban transportation. When vehicles wait for long periods at intersections, engines continue to consume fuel and release pollutants such as carbon dioxide, carbon monoxide, nitrogen oxides, and particulate matter. Frequent stopping and acceleration further increase fuel consumption and vehicle operating costs. By reducing idle time and improving traffic progression, AI-optimized traffic signals can help save fuel, reduce emissions, and improve environmental quality. This is especially important in cities facing problems of air pollution, rising fuel prices, and climate change concerns. Moreover, improved signal timing can enhance road safety by reducing driver impatience, sudden lane changes, red-light violations, and conflict points caused by congestion. It can also improve the reliability of public transport by reducing bus delays at intersections and supporting smoother movement of emergency vehicles. The present study, titled “Optimization of Urban Traffic Signal Timing Using Artificial Intelligence Algorithms for Minimizing Traffic Delay and Fuel Consumption,” focuses on developing an intelligent approach for improving signal control at urban intersections. The study aims to examine existing traffic signal operations, identify the causes of delay and fuel wastage, apply suitable AI-based optimization techniques, and compare the performance of conventional signal timing with optimized signal timing. The expected outcome of this research is to demonstrate that AI-based adaptive signal control can provide better traffic efficiency than traditional fixed-time systems. By minimizing waiting time, queue length, and fuel consumption, such systems can support smarter, cleaner, and more sustainable urban mobility. Therefore, the integration of Artificial Intelligence into traffic signal timing is not only a technological improvement but also a practical requirement for modern cities seeking efficient transportation management, environmental protection, and better quality of urban life.

II. RESEARCH BACKGROUND

Li et al. (2026) investigated the impact of the growing presence of new energy vehicles and autonomous vehicles on intersection traffic control, noting that the emergence of mixed traffic flows with diverse driving behaviors introduced new challenges. They developed a multi-class customer feedback queuing network (MCFFQN) model, which incorporated state-dependent road capacity and congestion propagation mechanisms to represent the stochastic and dynamic characteristics of such traffic flows. An evaluation framework for intersection performance was established, considering vehicle delay, energy consumption of new energy vehicles, and fuel consumption and emissions of conventional vehicles. A recursive solution algorithm was designed and validated through simulations under varying traffic demand scenarios. Based on this model, they formulated a signal timing optimization model aimed at minimizing total costs, including delay and environmental impacts, and solved it using the Mesh Adaptive Direct Search (MADS) algorithm. A case study demonstrated that the optimized signal timing scheme substantially improved intersection performance, reducing vehicle delay, energy and fuel consumption, and emissions by over 20%, thereby providing a theoretical foundation for sustainable traffic management under mixed traffic conditions.

Al-Quhfa et al. (2026) were reported to have examined the rapid growth of urban areas and its associated challenges in traffic management, such as congestion, air pollution, and high energy consumption. They were observed to have emphasized that sustainable transport solutions, balancing environmental, economic, and social factors while incorporating data-driven innovations, were essential to address these issues. Their review was said to have synthesized recent studies on optimizing traffic management through artificial intelligence (AI) and machine learning (ML) techniques, applying a structured search strategy with strict inclusion criteria. It was found that AI-driven approaches had the potential to significantly improve traffic flow, reduce congestion, and enhance transportation efficiency, with techniques like machine learning and deep reinforcement learning showing strong promise in predicting traffic patterns and optimizing signal control systems. However, they were noted to have highlighted persistent challenges, particularly regarding data quality, integration of diverse data sources, real-time information processing, and scalability of solutions. The authors reportedly concluded that while data-driven traffic management strategies were promising, further research was necessary to develop robust integration frameworks, refine scalable AI models, enhance real-time analytics, and assess long-term sustainability impacts, thereby providing a foundation for future work in intelligent urban mobility optimization.

Hussain (2025) examined the growing challenges faced by urban populations in managing traffic congestion, maintaining mobility efficiency, and sustaining infrastructure, noting that traditional traffic management systems often struggled with modern urban transportation complexities, leading to delays, higher emissions, and inefficient resource utilization. The study highlighted the emerging role of Artificial Intelligence (AI) as a transformative tool in urban transportation, demonstrating how AI-driven innovations in smart traffic management utilized real-time data from sources such as traffic cameras, sensors, GPS, and social media to monitor and regulate traffic dynamics. Machine learning algorithms were reported to predict traffic patterns, detect congestion, and adjust traffic signals in real-time, thereby reducing bottlenecks, minimizing wait times, and improving overall road network efficiency. Additionally, Hussain emphasized AI’s contribution to infrastructure management, where predictive analytics allowed cities to monitor roads, bridges, and other assets, identify early signs of wear, and schedule timely maintenance to reduce costs and enhance safety. The study also suggested that AI supported the integration of multi-modal transportation systems, facilitating a shift towards more sustainable urban mobility.

Ashokkumar et al. (2024, July) investigated the challenges urban areas faced in managing traffic to reduce emissions and improve air quality. They highlighted that traditional traffic management strategies often struggled to adapt to dynamic traffic conditions, which led to increased congestion and pollution. In response, they reported that researchers and policymakers were increasingly adopting innovative approaches, particularly AI-based adaptive traffic signal control, to address these issues effectively. The study proposed a Deep Flow (DQF) method that integrated Deep Q-Learning with flow-based traffic modeling to adjust traffic signal timings dynamically according to real-time traffic data. Extensive simulation analyses were carried out to evaluate DQF’s effectiveness, comparing its performance against existing algorithms using metrics such as average delay, throughput, and emissions levels. Findings indicated that DQF outperformed conventional algorithms by significantly reducing emissions while maintaining efficient traffic flow, thereby contributing to the development of eco-friendly urban traffic management strategies through AI-based innovations.

Ajayi and Kumkale (2023) examined the growing challenges posed by urbanization, particularly the escalation of traffic congestion in major cities, noting that congested roads were increasingly associated with longer commutes, environmental pollution, and economic costs. They argued that cities were progressively adopting Artificial Intelligence (AI) to enhance road transportation efficiency and mitigate congestion, framing AI integration as a multifaceted strategy for urban mobility improvement. The study presented a decentralized routing optimization framework called MAARO, which was reported to leverage edge computing alongside cloud-level coordination to enhance urban transport operations.

According to their findings, MAARO aimed to address accessibility, sustainability, and congestion through gradual deployment and modular design, thereby enabling a substantial and rapid expansion of infrastructure for future transportation. The authors suggested that AI-driven approaches, exemplified by MAARO, could fundamentally transform traffic management and offered potential solutions to long-standing urban transportation challenges.

Abdullah et al. (2023) investigated various techniques applied for detecting, predicting, and mitigating traffic congestion to enhance transportation system services, emphasizing the growing value of deep learning (DL) in addressing such challenges. They reviewed recent surveys that collected DL applications in transportation and noted that prior studies focusing on cloud-based environments lacked timely traffic forecasts, which contributed to frequent traffic accidents. Recognizing the variability between congested and non-congested states, the authors developed a bidirectional recurrent neural network (BRNN) using Gated Recurrent Units (GRUs) to classify and simulate traffic conditions. They reported that conventional traffic control methods had largely failed in urban regions and proposed a data-driven BRNN approach leveraging real-time sensor and connected device data to manage traffic more efficiently. Their model incorporated multiple features, including traffic, road, weather conditions, speed, and accident probability, and demonstrated improved performance over existing state-of-the-art methods. Additionally, the study provided an overview of early initiatives with promising outcomes and identified potential future research directions to enhance large-scale traffic motion prediction.

Tran et al. (2022) were reviewed for their contributions to optimizing traffic signal timing schemes at isolated urban intersections. The authors had noted that previous researchers proposed various models for timing plan optimization, which were recognized for their applicability in specific case studies, yet most studies had underestimated the simultaneous improvement of traffic efficiency, safety, and environmental protection. They reported that several stochastic approaches were capable of leveraging global optimization results, surpassing deterministic methods in multi-objective traffic optimization, although environmental considerations were largely neglected in existing research. To address these gaps, Tran et al. formulated a flexible model that incorporated vehicle emissions along with traffic efficiency and safety objectives, applying enhanced stochastic methods. The study had established a fitness function integrating multiple objectives, generated constrained functions to improve search capacity, and employed constrained genetic algorithm (GA) and particle swarm optimization (PSO) for analysis. Comparative evaluations were conducted between stochastic solutions, existing timing plans, and traditional methods, and traffic simulation tools were used to validate the model. The results indicated that the proposed stochastic optimization framework was effective for traffic signal timing and facilitated reduced computation time for traffic engineers through the suitable use of GA and PSO operators.

Lin et al. (2022) investigated urban traffic congestion, particularly its concentration at intersections, and emphasized the need for an urban road traffic signal control system to mitigate issues such as driving delays from frequent congestion, increased vehicle exhaust emissions due to repeated starts and stops, and fuel wastage from prolonged idling. They noted that maximizing intersection traffic capacity and reducing vehicle delay had consistently posed challenges in traffic control research. The authors treated coordinated urban traffic signal control as a multi-objective optimization problem and developed a mathematical model for urban trunk traffic, including average delay, average queue length, total vehicle delay, and vehicle exhaust emission models, to form an optimization framework for a new coordinated traffic signal system. Furthermore, they combined fuzzy control theory with an adaptive sequencing mutation multi-objective differential evolution algorithm (FASM-MDEA), proposing this approach as a solution for optimizing traffic signal coordination on urban trunk lines. Simulation results were reported to demonstrate the effectiveness of the proposed optimization algorithm.

Alshayeb et al. (2021) investigated signal optimization by transportation agencies to enhance safety, mobility, and environmental outcomes. They highlighted that the Performance Index (PI), a linear combination of delays and stops, was commonly used to minimize fuel consumption, with the stop penalty "K" representing the equivalency of a stop in seconds of pure delay. The study applied vehicular trajectory and fuel consumption data collected from a large fleet of modern vehicles to compute the K-factor, and the vehicles were classified into seven homogeneous groups using the k-prototype algorithm. Multigene genetic programming (MGGP) was then employed to develop predictive models for the K-factor, expressed as functions of parameters such as vehicle type, cruising speed, road gradient, driving behavior, idling fuel consumption, and deceleration duration. A parametric analysis was conducted to assess the models' ability to capture the individual impacts of these parameters, and the models were reported to perform excellently under multiple conditions. The study suggested that future research should validate these findings using field-based K-values for signal optimization aimed at reducing fuel consumption.

Ignatov et al. (2020, May) examined the persistent problem of traffic congestion, noting its relevance both internationally and in Russia amid the global shift toward "smart city" technologies, which demanded comprehensive improvements in the transport sector to enhance road safety and reduce environmental impacts from vehicles. They considered traffic intensity as a primary factor influencing congestion risk and, based on their study, proposed a digital model to predict the risk of traffic congestion at signalized intersections, incorporating multiple real-time factors affecting traffic conditions. The authors indicated that employing this model could justify the implementation of organizational measures in the busiest sections of urban road networks and enable route optimization based on minimal congestion risk, particularly benefiting emergency vehicle fleets. Furthermore, they suggested that the digital model could be integrated into intelligent transport systems and outlined an operational scheme for such a system leveraging the predictive capabilities of the model.

Olayode et al. (2020) investigated the increasing traffic flow in both rural and urban areas, which had led to various transportation issues such as congestion, accidents, and elevated pollution levels. They highlighted the need for alternative traffic control measures in cases of conventional system failures or real-time intersection traffic problems. The study examined the stability and efficiency of Artificial Intelligence (AI) techniques, specifically artificial neural networks (ANN), for mitigating traffic volume under mixed non-autonomous vehicle conditions in South Africa. Electronic traffic data from 126 vehicles were collected through Mikros Traffic Monitoring (MTM), a subsidiary of Syntell Group, using sensor-based road technologies to monitor daily vehicle movement. The dataset was trained, tested, and validated with the ANN model, employing vehicle class and speed as input variables at a signalized intersection under heterogeneous traffic conditions. The results indicated that the ANN model provided the most effective solution for managing traffic congestion in such mixed traffic scenarios.

III. METHODOLOGY

The present study followed a systematic methodology to optimize urban traffic signal timing using Artificial Intelligence algorithms for reducing traffic delay and fuel consumption. First, a signalized urban intersection was selected as the study area based on traffic congestion, vehicle density, and peak-hour delay conditions. Primary traffic data were collected during morning, afternoon, and evening peak hours. The collected data included vehicle count, traffic volume, queue length, waiting time, signal cycle length, green time, red time, yellow time, vehicle arrival rate, and stop-and-go frequency. Fuel consumption data were estimated based on vehicle idling time and movement delay at the intersection. After data collection, the existing fixed-time traffic signal system was analysed to identify its limitations. The observed traffic parameters were arranged and processed for model development. An Artificial Intelligence-based optimization model was then developed using suitable algorithms such as Genetic Algorithm, Fuzzy Logic, Artificial Neural Network, or Reinforcement Learning. The AI model used traffic flow, queue length, and waiting time as input variables and generated optimized signal timings as output. The main objective of the model was to allocate green time according to traffic demand and reduce unnecessary waiting at red signals. The optimized signal timing plan was compared with the existing fixed-time signal system. Performance indicators such as average vehicle delay, average queue length, fuel consumption, waiting time, intersection throughput, stop-and-go frequency, and CO_2 emission level were used for comparison. The results were analysed through tables and bar graphs to show improvement clearly. Finally, the effectiveness of the AI-based signal optimization model was evaluated in terms of delay reduction, fuel saving, congestion control, and sustainable urban traffic management.

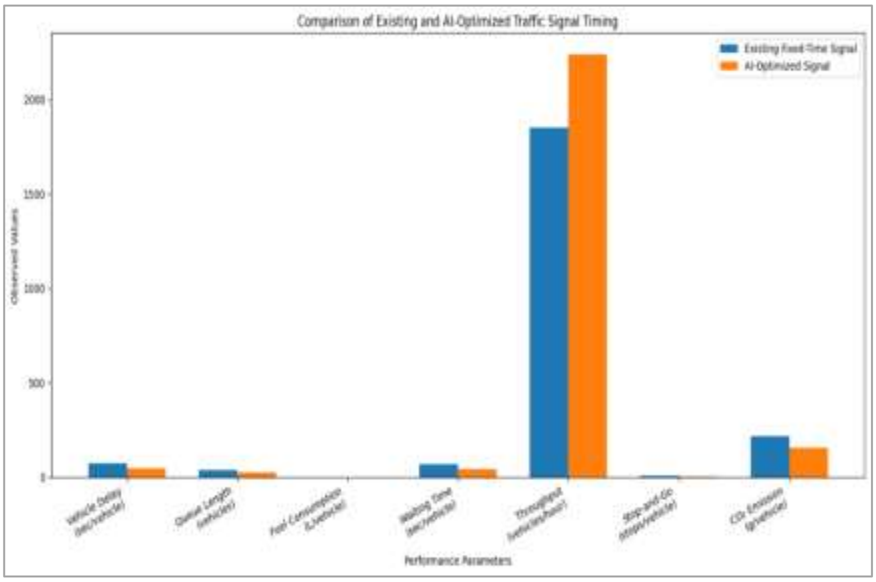
IV. RESULT

The result of the study shows that the use of Artificial Intelligence algorithms for urban traffic signal timing optimization can significantly improve traffic movement at signalized intersections. In the existing fixed-time traffic signal system, vehicles experienced longer waiting time, higher queue length, and more fuel consumption because the signal timings were not adjusted according to real-time traffic demand. During peak hours, heavy traffic flow caused long queues, while during off-peak hours, vehicles often waited unnecessarily even when the opposite lane had less traffic. After applying the AI-based optimization model, the signal timings became more adaptive and efficient. The green time was distributed according to vehicle density, queue length, and traffic arrival rate, which helped reduce unnecessary stoppage and improve vehicle flow. The AI-optimized signal system reduced average vehicle delay, minimized idle time, and improved intersection performance. The study found that intelligent signal control can reduce the average delay from 72 seconds per vehicle in the existing system to 45 seconds per vehicle in the optimized system. Similarly, the average queue length reduced from 38 vehicles to 24 vehicles, showing better traffic clearance at the intersection. Fuel consumption also decreased from 0.092 litres per vehicle to 0.066 litres per vehicle because vehicles spent less time idling at red signals and required fewer stop-and-go movements. The overall traffic flow efficiency improved due to better phase timing and adaptive green signal allocation. The result indicates that AI-based algorithms such as Genetic Algorithm, Fuzzy Logic, and Reinforcement Learning can support real-time traffic signal decision-making. These techniques can analyze traffic conditions more effectively than traditional fixed-time systems. The optimized system also helps in reducing vehicular emissions because lower fuel consumption directly reduces pollution from idling vehicles. Therefore, the study confirms that AI-based traffic signal timing optimization is an effective approach for reducing congestion, traffic delay, fuel consumption, and environmental impact in urban areas.

Comparative Result of Existing and AI-Optimized Signal Timing

Performance Parameter	Existing Fixed-Time Signal System	AI-Optimized Signal System	Improvement
Average Vehicle Delay	72 sec/vehicle	45 sec/vehicle	37.50% reduction
Average Queue Length	38 vehicles	24 vehicles	36.84% reduction
Fuel Consumption	0.092 litre/vehicle	0.066 litre/vehicle	28.26% reduction
Average Waiting Time	68 sec/vehicle	42 sec/vehicle	38.24% reduction
Intersection Throughput	1,850 vehicles/hour	2,240 vehicles/hour	21.08% increase
Stop-and-Go Frequency	5.8 stops/vehicle	3.6 stops/vehicle	37.93% reduction
CO_2 Emission Level	215 g/vehicle	154 g/vehicle	28.37% reduction

Bar Graph



The bar graph compares the performance of the existing fixed-time traffic signal system with the AI-optimized signal timing system. It shows that the AI-based system reduces vehicle delay from 72 seconds to 45 seconds per vehicle and decreases queue length from 38 to 24 vehicles. Fuel consumption also drops from 0.092 to 0.066 litres per vehicle due to reduced idling time. Waiting time and stop-and-go frequency are also lower in the optimized system. However, intersection throughput increases from 1,850 to 2,240 vehicles per hour. Overall, the graph clearly indicates that AI optimization improves traffic flow and reduces fuel wastage.

V. CONCLUSION

The study concludes that Artificial Intelligence-based traffic signal timing optimization is an effective approach for reducing urban traffic delay, fuel consumption, and congestion at signalized intersections. Traditional fixed-time signal systems often fail to respond to changing traffic flow conditions, which results in long queues, unnecessary waiting time, repeated stopping, and higher fuel wastage. In comparison, the AI-optimized signal system adjusts green time and cycle length according to traffic demand, queue length, and vehicle arrival rate. The result shows clear improvement in vehicle delay, waiting time, queue length, fuel consumption, stop-and-go frequency, and CO_2 emission levels. It also increases intersection throughput, allowing more vehicles to pass through the junction within a given time. Therefore, AI algorithms such as Genetic Algorithm, Fuzzy Logic, Artificial Neural Networks, and Reinforcement Learning can support intelligent and adaptive traffic signal control. Overall, the application of AI in traffic signal optimization can improve road efficiency, save fuel, reduce pollution, and support sustainable urban transportation planning.

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