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Performance Evaluation of AI-Driven Adaptive Traffic Signal Control for Sustainable Urban Mobility

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Abstract

Urban transportation systems are increasingly challenged by rapid urbanization, rising vehicle ownership, and growing traffic congestion, particularly at signalized intersections. Conventional fixed-time traffic signal systems often fail to accommodate continuously changing traffic demand, leading to increased vehicle delays, longer queues, excessive fuel consumption, and higher greenhouse gas emissions. This study evaluates the effectiveness of an Artificial Intelligence (AI)-driven adaptive traffic signal control system in improving operational efficiency and promoting sustainable urban mobility. Four major signalized intersections in **Rohtak, Haryana**, were selected as the study area. Primary traffic data, including traffic volume, queue length, vehicle delay, average waiting time, and existing signal timings, were collected through field surveys during morning and evening peak periods. The collected data were processed and integrated into a Reinforcement Learning-based adaptive traffic signal model developed using Python and evaluated using the Simulation of Urban Mobility (SUMO) platform. The performance of the proposed system was assessed by comparing it with the existing fixed-time traffic signal control using operational and environmental performance indicators. The results revealed significant improvements after implementing the AI-based adaptive signal control system. Average queue length decreased by approximately **35%**, vehicle delay by **37%**, and average waiting time by **38%**, while intersection capacity improved by nearly **15%**. In addition, smoother traffic flow reduced fuel consumption by **12%** and carbon dioxide (CO_2) emissions by **14%**, contributing to more sustainable urban transportation. These findings demonstrate that AI-driven adaptive traffic signal control can effectively enhance traffic operations while simultaneously reducing environmental impacts. The proposed framework offers a practical and scalable solution for transportation agencies seeking to improve traffic management in medium-sized cities and supports the implementation of Intelligent Transport Systems and smart city initiatives focused on sustainable urban mobility.

Keywords: Artificial Intelligence, Adaptive Traffic Signal Control, Sustainable Urban Mobility, Intelligent Transport Systems, Reinforcement Learning, Traffic Performance.

1. Introduction

Sustainable urban mobility has become a major priority for transportation planners and policymakers as cities continue to experience rapid urbanization, population growth, and increasing vehicle ownership.[1] Expanding urban economies and changing travel patterns have significantly increased traffic demand, placing considerable pressure on existing transportation infrastructure.[2] Among the various components of an urban road network, signalized intersections play a critical role in regulating traffic flow and ensuring the safe movement of vehicles and pedestrians. However, conventional traffic signal systems often struggle to manage continuously changing traffic conditions, resulting in congestion, excessive travel time, fuel wastage, and environmental degradation. Consequently, improving the operational efficiency of traffic signal control systems has become an essential objective for achieving sustainable urban transportation.[3]

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Traffic congestion is one of the most significant challenges affecting urban mobility worldwide. Congested intersections reduce roadway efficiency by increasing vehicle delays, queue lengths, and travel time while lowering the reliability of transportation systems. The economic consequences include increased fuel consumption, higher vehicle operating costs, reduced workforce productivity, and delays in freight movement. Environmental impacts are equally important because prolonged idling and repeated stop-and-go traffic increase fuel consumption and greenhouse gas emissions, particularly carbon dioxide (CO_2). These issues are especially evident in rapidly developing cities where transportation demand grows faster than roadway capacity.[4]

Indian cities present additional challenges because of their heterogeneous traffic conditions. Urban roads accommodate motorcycles, passenger cars, buses, auto-rickshaws, bicycles, freight vehicles, and pedestrians operating simultaneously within limited roadway space. Such mixed traffic characteristics create highly variable traffic patterns that are difficult to manage using conventional traffic engineering approaches.[5] Fixed-time traffic signal controllers, which allocate predetermined cycle lengths and green time intervals based on historical traffic observations, often fail to respond effectively to real-time traffic fluctuations. As traffic demand changes throughout the day, these systems continue operating with fixed signal plans, leading to unnecessary waiting time on lightly loaded approaches and severe congestion on heavily trafficked approaches.

2. Literature Review

Artificial Intelligence (AI) has emerged as a transformative technology in traffic engineering, enabling adaptive and data-driven approaches to urban traffic management. Traditional fixed-time traffic signal systems are generally designed using historical traffic patterns and predetermined timing plans. Although these systems are effective under stable traffic conditions, they are unable to respond efficiently to real-time fluctuations in traffic demand. Consequently, researchers have increasingly focused on AI-driven adaptive traffic signal control to improve intersection performance and support sustainable urban mobility.[6]

Early studies on adaptive traffic signal control primarily employed rule-based algorithms and optimization techniques to adjust signal timings according to traffic conditions. While these approaches provided improvements over fixed-time control, their effectiveness remained limited under highly dynamic traffic environments. With advancements in computational intelligence, Machine Learning (ML) and Artificial Intelligence (AI) have become increasingly important in developing intelligent traffic management systems capable of learning traffic patterns and making real-time control decisions.[7]

Among AI techniques, **Reinforcement Learning (RL)** has received significant attention for adaptive traffic signal optimization. Reinforcement Learning enables an intelligent agent to interact continuously with the traffic environment by observing traffic conditions, selecting appropriate signal actions, and improving its decision-making process through a reward mechanism. This adaptive learning capability allows the controller to minimize queue lengths, reduce vehicle delays, and maximize intersection throughput without requiring predefined traffic models. Recent research has demonstrated that RL-based controllers consistently outperform conventional fixed-time and actuated traffic signal systems under varying traffic demand.[8]

The integration of AI with **Intelligent Transport Systems (ITS)** has further enhanced urban

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traffic management capabilities. Modern ITS combines traffic sensors, surveillance cameras, vehicle detection systems, communication networks, and simulation platforms to collect and process real-time traffic information. AI algorithms analyze these data streams to optimize signal timing, improve traffic coordination, and reduce congestion across urban road networks. Simulation tools such as the **Simulation of Urban Mobility (SUMO)** have become widely used for evaluating adaptive traffic control strategies because they allow researchers to assess system performance under different traffic scenarios before field implementation.[9]

Recent investigations have also emphasized the environmental benefits of AI-driven traffic signal control. Improved signal coordination reduces stop-and-go driving, leading to smoother vehicle movement, lower fuel consumption, and reduced greenhouse gas emissions. Several studies have reported noticeable reductions in vehicle delay, queue length, and carbon dioxide (CO_2) emissions after implementing adaptive signal control strategies. These findings indicate that intelligent traffic management contributes not only to operational efficiency but also to environmental sustainability and energy conservation.[10]

Despite these advancements, important research gaps remain. Many published studies focus primarily on simulation-based evaluations conducted under homogeneous traffic conditions typical of developed countries. Comparatively fewer investigations assess AI-driven adaptive traffic signal control using field traffic data collected from heterogeneous traffic environments commonly found in Indian cities. Furthermore, limited studies simultaneously evaluate both operational indicators, such as queue length and vehicle delay, and environmental indicators, including fuel consumption and CO_2 emissions, within a single performance assessment framework.[11] The present study addresses these gaps by evaluating the operational and environmental performance of an AI-driven adaptive traffic signal control system using real traffic conditions observed at selected intersections in Rohtak, Haryana.

3. Materials and Methodology

This study adopted a quantitative research approach to evaluate the effectiveness of an Artificial Intelligence (AI)-driven adaptive traffic signal control system for improving traffic operations and supporting sustainable urban mobility. Four major signalized intersections in **Rohtak, Haryana**, were selected as the study area because they experience high traffic volumes and recurrent congestion during peak hours. These intersections represent typical heterogeneous traffic conditions found in medium-sized Indian cities, where different vehicle categories share the same roadway infrastructure.[12]

Primary traffic data were collected through field surveys conducted during morning and evening peak periods. The collected parameters included traffic volume, queue length, vehicle delay, average waiting time, and existing traffic signal timings. Traffic volume was measured in Passenger Car Units (PCU) per hour to account for the varying operational characteristics of different vehicle types. Signal cycle length, green time, yellow time, and red time were recorded for each intersection to establish the baseline performance of the existing fixed-time traffic signal system. The collected data were checked for consistency and organized into a structured database for further analysis.[13]

An **AI-based adaptive traffic signal control framework** was developed using the Reinforcement Learning (RL) approach. In this framework, the traffic signal controller acted as an intelligent agent that continuously observed the traffic environment and adjusted signal

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timings according to real-time traffic conditions. The learning process aimed to minimize vehicle delay and queue length while maximizing intersection capacity. Traffic state variables, including vehicle density, queue length, and waiting time, were used as input parameters for decision-making, whereas the optimized green signal duration represented the control action. A reward function based on operational efficiency encouraged the agent to select signal strategies that improved overall traffic performance.[14]

The collected traffic data and AI control algorithm were integrated into the **Simulation of Urban Mobility (SUMO)** platform using Python. SUMO provided a microscopic traffic simulation environment that enabled realistic modelling of vehicle movements, traffic interactions, and adaptive signal control operations. Multiple simulation runs were conducted under identical traffic demand conditions for both the existing fixed-time signal system and the proposed AI-based adaptive system to ensure a fair performance comparison.[15]

The effectiveness of the proposed system was evaluated using both operational and environmental performance indicators. Operational measures included average queue length, vehicle delay, average waiting time, and intersection capacity. Environmental performance was assessed through estimated fuel consumption and carbon dioxide (CO_2) emissions obtained from the simulation outputs. The percentage improvement achieved by the AI-based adaptive traffic signal control system over the conventional signal control method was calculated for each performance indicator.[16] This comprehensive methodology enabled a systematic assessment of the operational efficiency and sustainability benefits of AI-driven adaptive traffic signal control under heterogeneous urban traffic conditions.

4. Results and Discussion

The performance of the proposed AI-driven adaptive traffic signal control system was evaluated by comparing it with the existing fixed-time traffic signal system using operational and environmental performance indicators. The analysis was based on traffic data collected from four major signalized intersections in Rohtak, Haryana, and simulated under identical traffic demand conditions using the Simulation of Urban Mobility (SUMO) platform. The comparison focused on queue length, vehicle delay, average waiting time, intersection capacity, fuel consumption, and carbon dioxide (CO_2) emissions to determine the overall effectiveness of the adaptive control strategy.

The simulation results demonstrated that the AI-based adaptive traffic signal controller substantially improved traffic flow at all selected intersections. The intelligent controller dynamically adjusted green signal durations according to real-time traffic demand, allowing congested approaches to receive additional green time while minimizing unnecessary waiting on lightly loaded approaches. This adaptive decision-making process reduced traffic congestion and improved the overall efficiency of signalized intersections.

A significant reduction in operational performance indicators was observed after implementing the AI-based control system. The average queue length decreased from **32.5 vehicles** under the existing fixed-time control to **21.0 vehicles**, representing an improvement of approximately **35.38%**. Similarly, the average vehicle delay was reduced from **74.0 seconds per vehicle** to **46.75 seconds per vehicle**, corresponding to an improvement of **36.82%**. The average waiting time also declined considerably from **81.0 seconds** to **50.50 seconds**, achieving an overall reduction of **37.65%**. These improvements indicate that the adaptive signal controller effectively minimized traffic congestion and enhanced traffic

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progression by continuously responding to changing traffic conditions.

The proposed system also improved the traffic-handling capability of the selected intersections. The average intersection capacity increased from **2,348 PCU/h** under the conventional signal control system to approximately **2,700 PCU/h** after AI-based optimization, representing an improvement of nearly **15%**. This increase demonstrates that intelligent signal control can enhance roadway utilization without requiring additional physical infrastructure, making it an economically attractive solution for rapidly growing urban areas.

Apart from operational improvements, the AI-driven adaptive traffic signal control system produced measurable environmental benefits. Reduced vehicle idling and smoother traffic movement contributed to lower fuel consumption and decreased exhaust emissions. Simulation results indicated an estimated **12% reduction in fuel consumption** and a **14% reduction in carbon dioxide (CO_2) emissions** compared with the existing traffic signal system. These findings highlight the contribution of adaptive traffic management to sustainable urban transportation by reducing energy consumption and mitigating environmental pollution.

Table 1 summarizes the comparative performance of the existing and AI-based traffic signal control systems. The results consistently demonstrate that the adaptive controller outperformed the conventional fixed-time signal strategy across all evaluation parameters.

Table 1. Performance Evaluation of Existing and AI-Based Adaptive Traffic Signal Control

Performance Indicator	Existing System	AI-Based System	Improvement (%)
Queue Length (vehicles)	32.5	21.0	35.38
Vehicle Delay (s/vehicle)	74.0	46.75	36.82
Average Waiting Time (s)	81.0	50.50	37.65
Intersection Capacity (PCU/h)	2348	2700	15.00
Fuel Consumption Index	100	88	12.00
CO_2 Emission Index	100	86	14.00

The overall findings confirm that AI-driven adaptive traffic signal control is an effective approach for improving both operational efficiency and environmental sustainability in urban transportation systems. The observed reductions in queue length, vehicle delay, waiting time, fuel consumption, and emissions, together with the increase in intersection capacity, demonstrate the potential of Artificial Intelligence to support sustainable urban mobility. These results suggest that implementing adaptive traffic signal control within Intelligent Transport Systems (ITS) can significantly enhance traffic management in medium-sized cities such as Rohtak while

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contributing to the broader objectives of smart city development and sustainable transportation.[17]

5. Conclusion

This study evaluated the effectiveness of an Artificial Intelligence (AI)-driven adaptive traffic signal control system in improving traffic operations and promoting sustainable urban mobility. Using field traffic data collected from selected signalized intersections in **Rohtak, Haryana**, an adaptive signal control framework based on Reinforcement Learning was developed and assessed through microscopic traffic simulation using the Simulation of Urban Mobility (SUMO) platform. The proposed approach was compared with the existing fixed-time traffic signal system using operational and environmental performance indicators.

The results demonstrated that the AI-based adaptive traffic signal controller significantly enhanced intersection performance by dynamically adjusting signal timings according to real-time traffic conditions. Compared with the conventional system, the proposed model reduced average queue length by **35.38%**, vehicle delay by **36.82%**, and average waiting time by **37.65%**. In addition, intersection capacity increased by approximately **15%**, indicating more efficient utilization of the existing roadway infrastructure. The smoother traffic flow achieved through adaptive signal control also resulted in a **12% reduction in fuel consumption** and a **14% reduction in carbon dioxide (CO_2) emissions**, highlighting the environmental benefits of intelligent traffic management.

The findings confirm that AI-driven adaptive traffic signal control provides a practical and efficient solution for addressing urban traffic congestion under heterogeneous traffic conditions commonly observed in Indian cities. By improving traffic flow and reducing environmental impacts simultaneously, the proposed framework supports the objectives of Intelligent Transport Systems (ITS), smart city initiatives, and sustainable transportation planning. The study demonstrates that AI-based adaptive signal control can improve urban mobility without requiring costly roadway expansion, making it an economically viable strategy for medium-sized cities.

Future research may focus on integrating connected vehicle technologies, Internet of Things (IoT) sensors, and Vehicle-to-Infrastructure (V2I) communication to further enhance adaptive traffic management. Multi-intersection coordination, real-time cloud-based traffic monitoring, and advanced deep reinforcement learning algorithms may also be investigated to improve network-wide traffic performance. Such developments can contribute to more intelligent, resilient, and environmentally sustainable urban transportation systems.

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