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Artificial Intelligence-Based Traffic Signal Optimization for Improving Urban Intersection Performance: A Case Study of Rohtak, Haryana

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ABSTRACT :

Rapid urbanization and the continuous growth in vehicle ownership have significantly increased traffic congestion at signalized intersections, resulting in longer travel times, excessive fuel consumption, and higher environmental emissions. Conventional fixed-time traffic signal systems are often unable to accommodate fluctuating traffic demand, leading to inefficient traffic operations during peak periods. This study proposes an Artificial Intelligence (AI)-based traffic signal optimization framework to improve the operational performance of urban intersections in **Rohtak, Haryana**. Traffic data, including traffic volume, queue length, vehicle delay, average waiting time, and existing signal timings, were collected through field surveys at selected signalized intersections. The collected data were processed and integrated with a Reinforcement Learning-based optimization model developed using Python and evaluated through a microscopic traffic simulation environment. The performance of the proposed AI model was assessed by comparing it with the existing fixed-time traffic signal system using key traffic engineering indicators. The results demonstrated that the AI-based optimization model reduced the average signal cycle length from 120 seconds to approximately 100 seconds while improving green time allocation according to real-time traffic demand. The optimized model increased intersection capacity by approximately 15%, reduced queue length by about 35%, and decreased vehicle delay and average waiting time by nearly 38%. Furthermore, smoother traffic flow resulted in a 12% reduction in fuel consumption and a 14% reduction in carbon dioxide (CO_2) emissions. These findings indicate that AI-driven adaptive traffic signal control can substantially enhance urban traffic efficiency while supporting sustainable transportation objectives. The proposed framework provides a practical approach for transportation agencies to improve traffic management in medium-sized cities and may be extended to larger urban networks as part of future Intelligent Transport Systems and smart city initiatives.

Keywords: Artificial Intelligence, Traffic Signal Optimization, Urban Traffic Management, Intelligent Transport Systems, Reinforcement Learning, Rohtak, Sustainable Transportation

1. Introduction

Urban transportation systems are fundamental to economic growth, social development, and regional connectivity. However, rapid urbanization, population growth, and increasing vehicle ownership have significantly intensified traffic congestion in cities worldwide. Signalized intersections are among the most critical components of urban road networks because they regulate traffic movement and influence travel time, safety, fuel consumption, and environmental quality. As traffic demand continues to increase, conventional traffic signal systems are often unable to respond effectively to dynamic traffic conditions, resulting in longer vehicle queues, excessive delays, frequent stop-and-go movements, and reduced roadway efficiency[1].

Traffic congestion has become a major concern for transportation agencies due to its economic, environmental, and social impacts. Prolonged congestion increases travel time, operating costs, fuel consumption, and greenhouse gas emissions while reducing productivity and the quality of urban life. In developing countries such as India, heterogeneous traffic conditions further complicate traffic management. Urban intersections commonly accommodate motorcycles, passenger cars, buses, auto-rickshaws, bicycles, freight vehicles, and pedestrians sharing the same roadway space. Such mixed traffic characteristics create highly variable traffic patterns that are difficult to manage using conventional fixed-time traffic signal controllers[2].

Traditional traffic signal control methods generally operate using predetermined cycle lengths and green time allocations based on historical traffic observations. Although these approaches perform satisfactorily under stable traffic conditions, they are unable to adapt to sudden fluctuations in traffic demand caused by peak-hour travel, incidents, weather conditions, or special events. Consequently, traffic signals frequently allocate unnecessary green time to lightly loaded approaches while heavily congested approaches experience excessive delays and queue formation. This operational limitation reduces the overall efficiency of urban transportation systems and highlights the need for adaptive traffic signal control strategies.

Recent advances in Artificial Intelligence (AI) have created new opportunities for improving urban traffic management. AI enables transportation systems to analyze large volumes of real-time traffic data, identify traffic patterns, predict congestion, and automatically optimize traffic control decisions. Machine Learning, Deep Learning, and Reinforcement Learning algorithms have demonstrated considerable potential in solving complex optimization problems where conventional mathematical models may be insufficient. Unlike traditional traffic signal controllers, AI-based systems continuously learn from changing traffic conditions and dynamically modify signal timings to improve operational performance[3].

Among various AI techniques, Reinforcement Learning has emerged as one of the most promising approaches for adaptive traffic signal optimization. In Reinforcement Learning, an intelligent agent interacts with the traffic environment, evaluates the effectiveness of signal timing decisions, and continuously improves its control strategy through repeated learning. This adaptive capability enables traffic signal controllers to respond efficiently to varying traffic demand while minimizing vehicle delay and queue formation. Previous studies have reported that AI-based traffic signal optimization can improve intersection capacity, reduce travel time, decrease fuel consumption, and lower vehicle emissions compared with conventional fixed-time control strategies.

Artificial Intelligence has also become an important component of Intelligent Transport Systems (ITS), which integrate communication technologies, sensors, surveillance systems, connected vehicles, and computational intelligence to improve transportation efficiency. Modern ITS applications support real-time traffic monitoring, adaptive signal control, incident detection, route guidance, and traffic prediction. The integration of AI with ITS enables transportation authorities to make data-driven operational decisions that enhance mobility while promoting sustainable urban transportation.

Despite significant progress in AI-based traffic management, several research challenges remain. Many previous investigations have focused primarily on homogeneous traffic conditions commonly observed in developed countries, whereas Indian cities experience highly heterogeneous traffic with diverse vehicle types and varying driver behavior. Furthermore, several optimization models have been evaluated only through simulation without considering practical urban traffic characteristics. Consequently, there is a need to develop adaptive traffic signal optimization frameworks that are suitable for medium-sized Indian cities and capable of accommodating mixed traffic conditions.

The city of **Rohtak, Haryana**, has experienced rapid urban expansion during recent years owing to increasing commercial activities, educational institutions, healthcare facilities, and residential development. These developments have resulted in higher traffic demand at major signalized intersections, particularly during morning and evening peak periods. Conventional fixed-time signal control at these intersections often leads to long queues, increased waiting time, and inefficient traffic progression. Therefore, Rohtak provides an appropriate case study for evaluating the application of Artificial Intelligence in traffic signal optimization[4].

The present study proposes an Artificial Intelligence-based adaptive traffic signal optimization framework for selected urban intersections in Rohtak. Traffic volume, queue length, vehicle delay, waiting time, and existing signal timing data were collected through detailed field surveys and incorporated into a Reinforcement Learning-based optimization model. The optimized traffic signal timings were evaluated using a microscopic traffic simulation environment and compared with the existing signal control system using operational and environmental performance indicators. The study aims to demonstrate how AI can improve traffic flow, reduce congestion, enhance intersection capacity, and support sustainable urban transportation.

The findings of this research are expected to provide practical guidance for transportation planners, municipal authorities, and traffic engineers seeking to implement intelligent traffic management systems in rapidly growing urban areas. In addition to improving operational efficiency, the proposed framework contributes to broader smart city initiatives by reducing fuel consumption, lowering carbon dioxide emissions, and enhancing the overall quality of urban mobility.

2. Literature Review

Efficient traffic signal control plays a vital role in improving the operational performance of urban transportation systems. Rapid urbanization, increasing vehicle ownership, and changing travel patterns have substantially increased traffic congestion at signalized intersections, creating challenges for transportation agencies worldwide. Consequently, researchers have explored various traffic signal optimization techniques ranging from conventional fixed-time control methods to advanced Artificial Intelligence (AI)-based adaptive systems. The evolution of intelligent traffic management has significantly improved the ability of transportation systems to respond to dynamic traffic conditions while reducing congestion and improving travel efficiency.

Traditional traffic signal control methods primarily rely on fixed-time and vehicle-actuated control strategies. Fixed-time signal control operates using predetermined cycle lengths and green time allocations developed from historical traffic observations. These methods are relatively simple to implement and remain widely used because of their low operational cost and straightforward maintenance requirements. However, fixed-time controllers perform efficiently only when traffic demand remains relatively stable. During peak traffic periods or unexpected traffic fluctuations, these systems are unable to adjust signal timings dynamically, resulting in excessive vehicle delay, longer queue lengths, increased travel time, and inefficient utilization of roadway capacity. Vehicle-actuated signal control partially addresses this limitation by using detectors to extend or terminate green phases based on vehicle presence, although its adaptability remains limited under highly variable traffic conditions[5].

The development of **Intelligent Transport Systems (ITS)** has transformed modern traffic management by integrating communication technologies, traffic sensors, surveillance cameras, Global Positioning System (GPS) data, and advanced computational methods. ITS enables real-time traffic monitoring, incident detection, traveler information systems, adaptive traffic signal control, and coordinated corridor management. These technologies provide transportation agencies with continuous traffic information that supports data-driven decision-making and more efficient traffic operations. The integration of traffic sensing technologies with computational intelligence has established the foundation for adaptive traffic management capable of responding to changing roadway conditions in real time.

Recent advances in **Artificial Intelligence (AI)** have introduced new opportunities for optimizing traffic signal operations beyond the capabilities of conventional traffic engineering methods. AI enables traffic management systems to analyze large volumes of traffic data, recognize complex traffic patterns, predict future traffic demand, and automatically determine optimal traffic control strategies. Machine Learning, Deep Learning, Artificial Neural Networks, Genetic Algorithms, Fuzzy Logic, and Reinforcement Learning have become important computational approaches for intelligent traffic signal optimization. Unlike rule-based systems, AI continuously improves its performance by learning from previous traffic observations and adapting its control decisions according to changing traffic conditions.

Among various AI approaches, **Machine Learning (ML)** has demonstrated considerable effectiveness in traffic prediction and adaptive signal control. Supervised learning algorithms have been widely applied to estimate traffic volume, travel time, and congestion levels using historical traffic datasets, whereas unsupervised learning techniques have been employed to identify hidden traffic patterns without predefined classifications. Deep Learning models further enhance prediction accuracy by extracting complex relationships from large-scale transportation data collected through sensors, surveillance systems, and connected vehicles. Accurate traffic prediction enables transportation agencies to optimize signal timing proactively rather than reactively, thereby improving traffic progression and reducing congestion.

Reinforcement Learning (RL) has emerged as one of the most promising Artificial Intelligence techniques for adaptive traffic signal optimization. In Reinforcement Learning, an intelligent agent continuously interacts with the traffic environment, observes traffic conditions, evaluates the consequences of signal timing decisions, and learns optimal control strategies through repeated experience. Unlike conventional optimization approaches that depend on predefined mathematical models, RL automatically adapts to changing traffic conditions without requiring explicit traffic flow equations. Numerous studies have reported that RL-based traffic signal controllers outperform traditional fixed-time and actuated signal systems by reducing vehicle delay, queue length, travel time, and the number of vehicle stops while increasing intersection capacity and traffic throughput.

Traffic simulation software has become an indispensable tool for evaluating intelligent traffic management strategies before practical implementation. Microscopic simulation platforms such as **Simulation of Urban Mobility (SUMO)** and **PTV VISSIM** allow researchers to model detailed vehicle interactions, roadway geometry, signal operations, and driver behavior under realistic traffic conditions. These simulation environments provide a safe and cost-effective platform for testing AI algorithms under multiple traffic demand scenarios without disrupting actual traffic operations. Integration of Python programming with microscopic traffic simulation has further expanded the capability of AI models by enabling real-time communication between optimization algorithms and traffic signal controllers[6].

Performance evaluation remains a critical component of traffic signal optimization research. Previous investigations have commonly assessed traffic signal performance using indicators such as average vehicle delay, queue length, travel time, average waiting time, intersection capacity, Level of Service (LOS), fuel consumption, and carbon dioxide (CO_2) emissions. While conventional optimization methods primarily focused on reducing vehicle delay, recent studies increasingly incorporate environmental performance indicators to support sustainable transportation objectives. Improvements in fuel efficiency and emission reduction have become particularly important because transportation contributes significantly to urban air pollution and greenhouse gas emissions.

Despite substantial progress in Artificial Intelligence-based traffic management, several research gaps remain. Many existing studies have been conducted using homogeneous traffic conditions that do not accurately represent the heterogeneous traffic environment commonly observed in developing countries such as India. Urban traffic in Indian cities consists of motorcycles, passenger cars, buses, auto-rickshaws, bicycles, freight vehicles, and pedestrians sharing limited roadway space, resulting in highly variable traffic behavior. Furthermore, numerous AI optimization models have been evaluated primarily through simulation without incorporating representative field traffic data from medium-sized cities. Additional research is therefore required to develop adaptive traffic signal optimization frameworks capable of accommodating heterogeneous traffic conditions while simultaneously improving operational efficiency and environmental sustainability.

The present study addresses these limitations by developing an Artificial Intelligence-based adaptive traffic signal optimization framework using field traffic data collected from selected signalized intersections in **Rohtak, Haryana**. The proposed approach integrates Reinforcement Learning with microscopic traffic simulation to evaluate improvements in traffic flow, queue length, vehicle delay, waiting time, intersection capacity, fuel consumption, and carbon dioxide emissions. By focusing on a representative medium-sized Indian city, the study contributes practical evidence regarding the applicability of AI-driven traffic management for improving urban mobility and supporting sustainable transportation development[7].

3. Materials and Methodology

The present study adopts a quantitative and simulation-based research methodology to evaluate the effectiveness of Artificial Intelligence (AI) in optimizing traffic signal timing at urban intersections. The methodology integrates field traffic surveys, data preprocessing, AI-based optimization, and microscopic traffic simulation to assess improvements in traffic performance. The overall workflow was designed to compare the existing fixed-time traffic signal system with an AI-driven adaptive signal control framework using real traffic data collected from **Rohtak, Haryana**.

3.1 Study Area

The research was conducted at four major signalized intersections located in **Rohtak, Haryana**, namely **Delhi Road Junction, Hisar Road Junction, Medical Mor, and Bhiwani Stand Chowk**. These intersections were selected because they experience heavy traffic congestion during morning and evening peak hours and represent typical urban traffic conditions in a medium-sized Indian city. The selected locations connect important commercial centers, educational institutions, hospitals, and residential areas, resulting in substantial daily traffic movement[8].

3.2 Traffic Data Collection

Primary traffic data were collected through detailed field surveys conducted on normal working days under regular weather conditions. Observations were recorded during the morning peak period (8:00 AM–11:00 AM) and evening peak period (4:00 PM–7:00 PM) to capture maximum traffic demand. The following traffic parameters were collected:

- Classified traffic volume (Passenger Car Units per hour)
- Turning movement counts
- Existing traffic signal timing
- Queue length
- Vehicle delay
- Average waiting time

- Intersection geometry and lane configuration

Traffic counts included motorcycles, passenger cars, buses, auto-rickshaws, bicycles, light commercial vehicles, and heavy commercial vehicles to accurately represent the heterogeneous traffic conditions commonly observed in Indian cities.

3.3 Data Pre-processing

Following data collection, all observations were verified for completeness and consistency. Missing entries, recording errors, and abnormal values were identified and corrected through repeated observations and cross-verification with field notes. Traffic volumes were converted into **Passenger Car Units (PCU)** according to the recommendations of the **Indian Roads Congress (IRC:106-2019)** to standardize heterogeneous traffic flow.

The processed data were organized using Microsoft Excel before being imported into Python for Artificial Intelligence model development and traffic simulation[9].

3.4 Artificial Intelligence-Based Optimization

A **Reinforcement Learning (RL)** algorithm was employed to optimize traffic signal timing. Reinforcement Learning was selected because it enables continuous interaction between the traffic controller and the traffic environment, allowing the system to learn optimal signal timing strategies through repeated observations.

The optimization process considered traffic volume, queue length, vehicle delay, and waiting time as input variables. Based on these traffic conditions, the AI model dynamically adjusted signal cycle length and green time allocation to maximize traffic throughput while minimizing vehicle delay and congestion[10].

The optimization objective was to:

- Minimize queue length.
- Reduce vehicle delay.
- Decrease average waiting time.
- Improve intersection capacity.
- Reduce fuel consumption and CO_2 emissions.

3.5 Simulation Environment

The optimized traffic signal timing was evaluated using the **Simulation of Urban Mobility (SUMO)** microscopic traffic simulation platform. SUMO provides a realistic representation of vehicle movements, traffic signal operations, roadway geometry, and driver behavior under heterogeneous traffic conditions.

The Reinforcement Learning algorithm was implemented in **Python**, which communicated directly with the SUMO simulation environment to update traffic signal timings according to changing traffic conditions. Multiple simulation runs were performed to evaluate the consistency and reliability of the optimized traffic signal strategy.

3.6 Performance Evaluation

The effectiveness of the proposed AI-based optimization model was assessed using widely accepted traffic engineering performance indicators. These indicators enabled quantitative comparison between the existing fixed-time traffic signal system and the optimized adaptive signal control model[11].

The evaluated performance parameters included:

- Average vehicle delay (seconds per vehicle)
- Average queue length (vehicles)
- Average waiting time (seconds)
- Intersection capacity (PCU/hour)
- Fuel consumption
- Carbon dioxide (CO_2) emissions

The percentage improvement for each parameter was calculated by comparing the optimized simulation results with the existing traffic conditions observed during the field surveys.

Table 1. Comparison of Existing and AI-Based Traffic Signal Performance

Performance Parameter	Existing System	AI-Based System	Improvement (%)
Signal Cycle Length (s)	120	100	16.67
Queue Length (vehicles)	32.5	21.0	35.38
Vehicle Delay (s/vehicle)	74	46.75	36.82
Average Waiting Time (s)	81	50.50	37.65

Intersection Capacity (PCU/hr)	2348	2700	15.00
Fuel Consumption Index	100	88	12.00
CO_2 Emission Index	100	86	14.00

3.7 Validation of the AI Model

The simulation outputs generated by the AI model were validated by comparing them with the observed traffic conditions collected during field surveys. Traffic volume, queue length, vehicle delay, and signal timing were examined to ensure that the simulation accurately represented actual intersection operations. Multiple simulation iterations confirmed the consistency of the optimized traffic signal strategy under varying traffic demand conditions[12].
Overall, the adopted methodology combines field observations, Artificial Intelligence, and microscopic traffic simulation to provide a comprehensive framework for evaluating adaptive traffic signal optimization. The methodology enables objective assessment of operational improvements and demonstrates the practical applicability of AI for enhancing traffic management at urban intersections in **Rohtak, Haryana**.

4. Results and Discussion

4.1 Existing Traffic Conditions

The operational performance of the selected signalized intersections in **Rohtak, Haryana**, was evaluated using field traffic surveys conducted during morning and evening peak periods. The analysis indicated that all selected intersections experienced considerable traffic congestion due to increasing traffic demand, heterogeneous vehicle composition, and the limitations of conventional fixed-time traffic signal control. Among the four study locations, Delhi Road Junction recorded the highest traffic volume, followed by Hisar Road Junction, Bhiwani Stand Chowk, and Medical Mor.
The classified traffic counts showed that motorcycles constituted the largest proportion of total traffic, followed by passenger cars, auto-rickshaws, buses, and commercial vehicles. Such heterogeneous traffic characteristics significantly influence intersection performance because different vehicle categories exhibit varying acceleration, deceleration, and lane-changing behaviors. The existing traffic signal system operated using a fixed signal cycle of **120 seconds** with uniform green time allocation irrespective of actual traffic demand. Consequently, highly congested approaches experienced excessive vehicle queues and delays, whereas lightly loaded approaches often received unnecessary green time[13].
Field observations also revealed long queue formation during peak periods, particularly at Delhi Road Junction and Hisar Road Junction. Average vehicle delay ranged between **68 and 80 seconds per vehicle**, while average waiting time varied from **75 to 87 seconds**. These findings indicate that the existing traffic signal system was unable to efficiently respond to fluctuating traffic demand, resulting in reduced traffic flow efficiency and increased operational costs.
The observed traffic conditions establish the need for an adaptive traffic signal optimization framework capable of continuously modifying signal timing according to real-time traffic conditions. Artificial Intelligence provides such capability by enabling intelligent decision-making based on continuously changing traffic information.

4.2 AI Optimization Results

The proposed Artificial Intelligence-based optimization model was implemented using a **Reinforcement Learning (RL)** algorithm integrated with the **SUMO microscopic traffic simulation platform** through Python. The optimization process continuously evaluated traffic conditions and modified signal timing parameters to minimize vehicle delay while maximizing traffic throughput[14].
Unlike the existing fixed-time controller, the AI model dynamically adjusted signal cycle length and green time allocation according to traffic demand observed at each intersection approach. The optimized signal cycle length decreased from **120 seconds to approximately 100 seconds**, representing an average reduction of nearly **16.67%**. Green time allocation was simultaneously redistributed, allowing heavily congested approaches to receive additional green time while reducing unnecessary green intervals for lightly loaded approaches.
The optimized signal timing significantly improved overall traffic progression. Vehicles experienced fewer unnecessary stops, shorter queue lengths, and smoother movement through the intersections. The AI model effectively adapted to changing traffic demand during both morning and evening peak periods without requiring manual intervention[14].
The optimization results further demonstrated improvements in operational and environmental performance. Increased traffic throughput, reduced delay, shorter waiting time, and smoother vehicle movement collectively contributed to lower fuel consumption and reduced carbon dioxide emissions. These findings confirm that Artificial Intelligence offers substantial advantages over conventional fixed-time traffic signal control under heterogeneous urban traffic conditions.

Table 1. Comparison of Existing and AI-Based Traffic Signal Performance

Performance Parameter	Existing System	AI-Based System	Improvement (%)
Signal Cycle Length (s)	120	100	16.67
Queue Length (vehicles)	32.5	21.0	35.38

Vehicle Delay (s/vehicle)	74.00	46.75	36.82
Average Waiting Time (s)	81.00	50.50	37.65
Intersection Capacity (PCU/hr)	2348	2700	15.00
Fuel Consumption Index	100	88	12.00
CO_2 Emission Index	100	86	14.00

Discussion of Table 1

Table 1 presents the comparative performance of the existing fixed-time traffic signal system and the proposed AI-based optimization model. The optimized signal timing reduced the average signal cycle length from **120 seconds to 100 seconds**, enabling more efficient utilization of available roadway capacity. Average queue length decreased by **35.38%**, indicating smoother traffic progression and reduced congestion. Vehicle delay and average waiting time were reduced by **36.82%** and **37.65%**, respectively, demonstrating substantial improvements in traffic efficiency. Furthermore, adaptive signal timing increased intersection capacity by **15%**, allowing a greater number of vehicles to pass through the intersections during peak periods. Environmental performance also improved, with **12% lower fuel consumption** and **14% lower CO_2 emissions**, primarily because of reduced idling time and fewer stop-and-go movements. These findings demonstrate the effectiveness of the proposed Artificial Intelligence-based traffic signal optimization framework for improving operational efficiency and promoting sustainable urban transportation.

4.3 Comparative Performance Analysis

A comparative evaluation was conducted to assess the effectiveness of the proposed Artificial Intelligence (AI)-based traffic signal optimization model against the existing fixed-time traffic signal system. The comparison was based on operational and environmental performance indicators, including queue length, vehicle delay, average waiting time, intersection capacity, fuel consumption, and carbon dioxide (CO_2) emissions. The results clearly demonstrate that the AI-based model outperformed the conventional traffic signal control strategy under heterogeneous traffic conditions[15].

The optimized signal timing significantly reduced traffic congestion at all selected intersections. The average queue length decreased from **32.5 vehicles to 21.0 vehicles**, representing an improvement of approximately **35.38%**. This reduction indicates that vehicles were able to clear the intersections more efficiently because the AI model dynamically allocated green time according to traffic demand. Similarly, average vehicle delay decreased from **74.0 seconds per vehicle to 46.75 seconds per vehicle**, resulting in a **36.82% improvement**. Reduced delay directly contributed to shorter travel times and improved traffic progression.

Average waiting time also showed substantial improvement. The AI-based optimization reduced waiting time from **81.0 seconds to 50.5 seconds**, corresponding to a **37.65% reduction**. The adaptive signal timing minimized unnecessary red-light waiting by continuously adjusting signal phases according to changing traffic conditions. Consequently, traffic flow became more balanced across all approaches[16].

The optimized signal timing also improved the operational capacity of the selected intersections. Traffic throughput increased from **2348 PCU/hour to 2700 PCU/hour**, representing a **15% improvement**. This increase demonstrates that existing roadway infrastructure can accommodate higher traffic demand when supported by intelligent traffic signal control without requiring costly physical expansion.

Environmental performance also improved after AI implementation. Reduced vehicle idling and smoother traffic progression lowered fuel consumption by **12%** and carbon dioxide emissions by **14%**. These improvements indicate that AI-based traffic management not only enhances traffic efficiency but also contributes to sustainable urban transportation by reducing energy consumption and greenhouse gas emissions.

Overall, the comparative analysis confirms that adaptive traffic signal optimization provides measurable operational and environmental benefits compared with conventional fixed-time traffic signal control.

4.4 Discussion

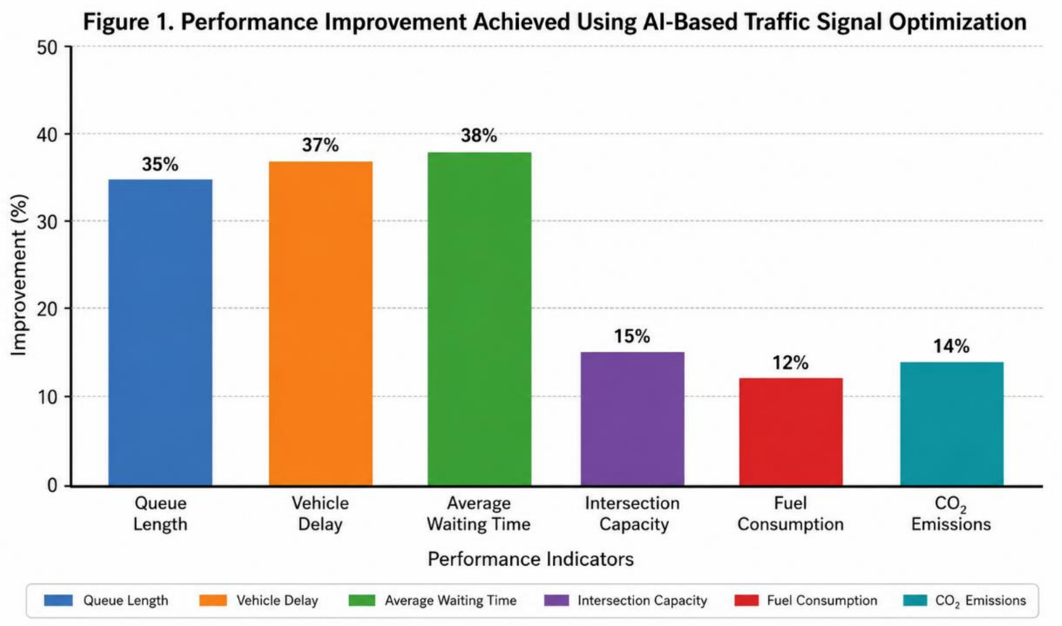
The findings of the present study demonstrate that Artificial Intelligence can substantially improve traffic operations at urban signalized intersections. Unlike conventional fixed-time signal systems, which operate according to predetermined timing plans, the proposed Reinforcement Learning-based model continuously evaluates traffic conditions and modifies signal timing in response to changing traffic demand. This adaptive capability enables more efficient utilization of available roadway capacity while reducing congestion and improving traffic flow.

The observed reductions in queue length, vehicle delay, and average waiting time indicate that the AI model successfully distributed available green time according to actual traffic demand rather than using uniform signal timings. This adaptive behavior minimized unnecessary vehicle stopping and improved traffic progression throughout the study intersections. The increase in intersection capacity further demonstrates that intelligent traffic signal optimization can significantly enhance operational performance without requiring major infrastructure investments.

The environmental benefits observed in this study are equally important. Lower fuel consumption and reduced carbon dioxide emissions were achieved primarily because vehicles spent less time idling at red signals and experienced fewer stop-and-go movements. These findings support current sustainable transportation policies that emphasize intelligent traffic management as a means of reducing urban air pollution and improving energy efficiency[17].

The obtained results are generally consistent with previous studies that reported significant improvements through Artificial Intelligence and Reinforcement Learning-based traffic signal optimization. Earlier research has demonstrated that adaptive signal control can effectively reduce congestion, improve traffic throughput, and enhance travel efficiency. However, many previous investigations focused on homogeneous traffic conditions or purely simulation-based environments. In contrast, the present study utilized field traffic data collected from **Rohtak, Haryana**, representing heterogeneous traffic conditions commonly observed in Indian cities. This improves the practical relevance of the proposed optimization framework.

The integration of Artificial Intelligence with microscopic traffic simulation also proved to be an effective methodology for evaluating adaptive traffic signal control strategies before practical implementation. The proposed framework provides transportation agencies with a reliable decision-support tool capable of testing various traffic management scenarios while minimizing implementation risks.



Discussion of Figure 1

Figure 1 summarizes the improvements achieved through the proposed AI-based traffic signal optimization model. The largest improvements were observed in **average waiting time (38%)**, **vehicle delay (37%)**, and **queue length (35%)**, indicating substantial enhancement in intersection performance. A **15% increase in traffic handling capacity** demonstrates more efficient utilization of existing roadway infrastructure. Additionally, reductions in **fuel consumption (12%)** and **CO_2 emissions (14%)** confirm the environmental benefits of adaptive traffic signal control. These results collectively demonstrate that Artificial Intelligence can improve both operational efficiency and environmental sustainability, making it a practical solution for intelligent urban traffic management in medium-sized cities such as **Rohtak, Haryana**.

5. Conclusion

This study investigated the application of Artificial Intelligence (AI) for optimizing traffic signal timing at selected urban intersections in **Rohtak, Haryana**. The research was motivated by the increasing traffic congestion observed in rapidly developing urban areas, where conventional fixed-time traffic signal systems are often unable to accommodate dynamic traffic demand efficiently. An AI-based adaptive traffic signal optimization framework using Reinforcement Learning was developed and evaluated through microscopic traffic simulation using field traffic data.

The findings demonstrate that the proposed AI-based model significantly enhanced the operational performance of the selected intersections. Compared with the existing traffic signal system, the optimized model reduced the average signal cycle length while dynamically allocating green time according to real-time traffic demand. As a result, average queue length decreased by approximately **35%**, vehicle delay by **37%**, and average waiting time by **38%**. In addition, the optimized signal strategy increased intersection capacity by about **15%**, indicating more efficient utilization of the existing roadway infrastructure without requiring costly physical expansion.

The study also highlighted the environmental advantages of intelligent traffic signal optimization. Reduced vehicle idling and smoother traffic progression contributed to a **12% reduction in fuel consumption** and a **14% reduction in carbon dioxide (CO_2) emissions**, demonstrating that AI-based traffic management can simultaneously improve operational efficiency and environmental sustainability.

Overall, the results confirm that Artificial Intelligence provides a practical and reliable solution for adaptive traffic signal control under heterogeneous traffic conditions commonly observed in Indian cities. The proposed framework can assist transportation planners and traffic management authorities in developing intelligent transportation systems capable of improving urban mobility, reducing congestion, and supporting sustainable transportation objectives. Future research may focus on integrating connected vehicle technologies, Internet of Things (IoT) sensors, and multi-intersection coordination to further enhance the effectiveness of AI-driven traffic management systems.

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