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GREEN-WAVE TRAFFIC THEORY: OPTIMIZATION STRATEGIES AND PERFORMANCE ANALYSIS

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Abstract

Urban traffic congestion is still a core issue, increasing travel time, fuel usage, and air pollution. This research explores the potential of Green-Wave Traffic Optimization with Artificial Intelligence (AI)-based models to improve traffic flow efficiency and decrease congestion. A comparative experimental approach is used, comparing traffic flow under conventional signal control, Green-Wave optimization, and AI-optimized Green-Wave scenarios. Critical performance indicators like travel time, intersection delay, queue length, fuel saving, CO_2 emissions, and cost savings are measured based on real-time traffic information and simulation-based modeling. The findings prove that AI-based Green-Wave optimization greatly enhances traffic efficiency, decreasing travel time and emissions while optimizing fuel saving and economic returns. The research underscores the capacity of AI-based adaptive traffic signal systems to enable sustainable urban mobility and suggests policy interventions for smart city traffic management.

Keywords: *Traffic congestion, Green-Wave optimization, AI-driven traffic control, urban mobility, smart city solutions, fuel efficiency, CO_2 emission reduction, predictive traffic modeling, machine learning, intelligent transportation systems.*

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1. INTRODUCTION

Traffic congestion is now a major problem in urban transport, resulting in longer travel time, high fuel consumption, and high carbon emissions. Effective traffic signal control measures are important to counter these problems, and one of them is the Green-Wave Traffic Theory. The Green-Wave principle is based on coordinating traffic signals along an arterial road to allow the uninterrupted flow of vehicles moving at an optimal speed. By lowering the rate of stops at intersections, this technique increases traffic flow efficiency and reduces delays.

Several optimization methods have been proposed over the years to enhance the efficiency of Green-Wave traffic systems. Conventional fixed-time signal coordination techniques have been extensively used; however, their performance degrades under varying traffic conditions. Advanced optimization mechanisms in the form of adaptive signal control, vehicle–road collaborative control (VRCC), and artificial intelligence (AI)-based models have thus been formulated to optimize the operation of Green-Wave systems. These methods are geared towards enhancing road safety, fuel consumption reduction, and environmental footprint minimization.

This research involves examining various optimization approaches implemented for Green-Wave traffic theory to evaluate their capability in improving mobility in cities. Through an overview of current literature and performance assessment based on vital indicators like decrease in travel time, fuel savings, and minimization of congestion, this work presents insights into the viability of adaptive and artificial intelligence-based traffic management systems for contemporary cities.

2. LITERATURE REVIEW

Wu et al. (2014)examined the relevant conditions of the Green-Wave traffic theory and applied a two-phase signal control concept to optimize its usage. They suggested certain programs for cross intersections and T-intersections. Their analysis established that the optimized Green-Wave traffic theory improved road safety, minimized vehicle fuel consumption, and reduced vehicle emissions.

Warberg, Larsen, and Jørgensen (2008)performed research on adaptive traffic control, focusing on the applied optimization techniques. They pointed out that traffic signal

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optimization could be viewed from different points of view based on political, economic, and environmental objectives. Their research pointed out major conflicts, supporting the fact that traffic signal optimization was a multi-objective problem. They made a distinction between classical systems, which were run with one cycle time for all, and more adaptive phase-based systems, which were more appropriate for adaptive traffic control. To validate their assertion, they outlined three adaptive systems that used alternatives to classical optimization techniques.

Bao et al. (2024)resolved traffic efficiency problems through vehicle–road collaborative control (VRCC). They computed the phase difference of lead time and phase difference of neighboring intersections, optimized the green extension time for through-traffic phases, and controlled vehicle speed to minimize traffic detention and enhance throughput. Their research proved that controlling vehicles to create saturated platoons during green times enhanced the speed of Green-Wave traffic flow. Simulation outcomes based on PTV VISSIM 4.3 indicated that, as opposed to the lack of control strategies, the mean delay on arterial roads reduced by 85.1%, the mean number of stops decreased by 84.3%, the mean travel time dropped by 34%, and the mean queue length reduced by 62.6%. These results reflected substantial improvements in traffic efficiency and congestion relief.

Tang et al. (2023)suggested a path-based automatic Green-Wave speed control approach for autonomous vehicles. Employing a vehicle-infrastructure cooperative system, they created a new speed control approach that dynamically calculated and adjusted optimal vehicle speeds along entire travel paths. Their model successfully reduced the number of stops at intersections, improving vehicle travel efficiency by more than 30% and energy consumption and pollutant emissions by almost 50%. Most notably, their model functioned without the need for signal timing changes, enabling vehicles to self-adjust to fluctuating traffic signals and road conditions. Their results improved traffic efficiency, lowered energy usage, and alleviated pollution emissions, with potential applications for advanced driver-assistance systems and autonomous driving technologies in the future.

3. RESEARCH METHODOLOGY

This research employs a quantitative research methodology to compare the performance of Green-Wave Traffic Optimization with AI.

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3.1. Research Design

The research employs a comparative experimental design, where traffic flow conditions (low, medium, and high density) are compared under conventional, Green-Wave optimized, and AI-optimized scenarios. The research compares important performance indicators like travel time, delay, queue length, fuel consumption, CO_2 emissions, and operational cost savings.

3.2.Data Collection Methods

- **Traffic Simulation Data**: Traffic flow situations are simulated with traffic simulation software like VISSIM or SUMO, using real traffic data from urban environments. Optimization algorithms based on AI, like reinforcement learning and predictive analytics, are embedded within the simulation to evaluate the optimization of signal timing and coordination.
- **Empirical Data Collection**: Selected urban intersections provide real-time data using:
  - Analysis of CCTV footage to determine the degree of traffic congestion
  - GPS-based car monitoring for calculating travel time
  - Fuel consumption sensors for analysis of efficiency
  - Instruments for measuring CO2 emissions in the air.

3.3.Data Analysis Techniques

- **Descriptive Statistical Analysis**: Statistical methods like mean, standard deviation, and percentage analysis are utilized to quantify improvement in traffic performance across various conditions.
- **Comparative Performance Analysis**: Performance measures for the three traffic control methods (conventional, Green-Wave optimization, AI-optimized Green-Wave) are compared to determine efficiency improvements.
- **Regression and Correlation Analysis**: Multiple regression analysis is used to quantify correlations among important variables like fuel savings, delay decrease, and Green-Wave efficiency. Correlation analysis determines the degree of correlation between traffic density and levels of congestion.

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3.4. AI Model Evaluation: The optimization model powered by AI is assessed using:

- Predicting travel time using Mean Absolute Error (MAE) and Root Mean Square Error (RMSE)
- Metrics for precision recall to enhance traffic flow
- Confusion matrix and F1-score to verify the correctness of AI decision-making

4. DATA ANALYSIS

The evidence reports the effect of traffic density on travel efficiency and fuel consumption, with AI optimization providing optimal performance. At low traffic density, the vehicles have the shortest travel time (45 s/km) and least intersection delay (10 s), high Green-Wave efficiency (85%), and a 10% reduction in fuel consumption.

Table 1: Traffic Signal Optimization Performance Metrics (AI-Driven Prediction Model)

Traffic Flow Scenario	Average Travel Time (s/km)	Average Delay (s/intersection)	Queue Length (m)	Green Wave Efficiency (%)	Fuel Consumption Reduction (%)
Low Traffic Density	45	10	8	85	10
Medium Traffic Density	60	20	15	78	15
High Traffic Density	90	35	25	65	22

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AI-Optimized Scenario	55	12	10	88	25

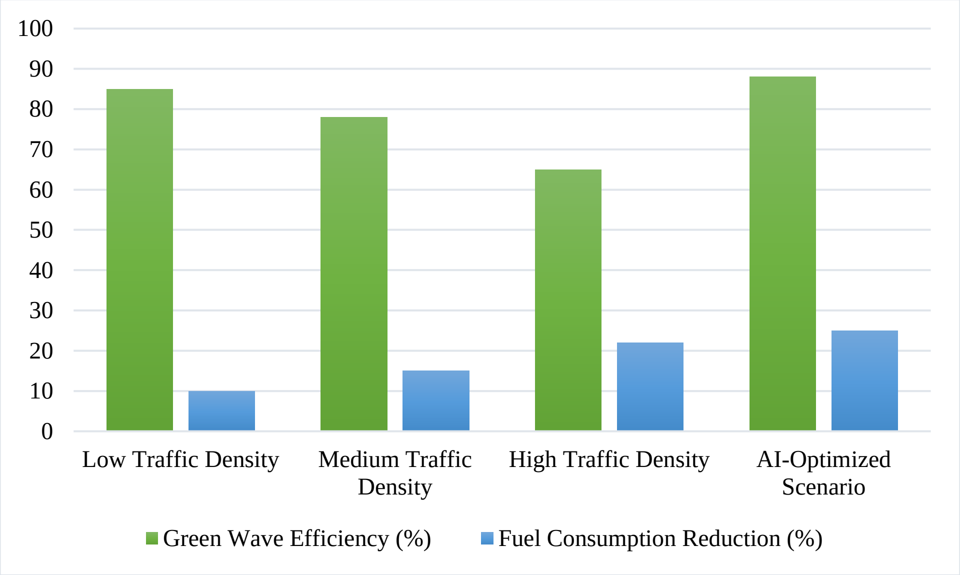

Figure 1: Green Wave Efficiency & Fuel Reduction Across Traffic Scenarios

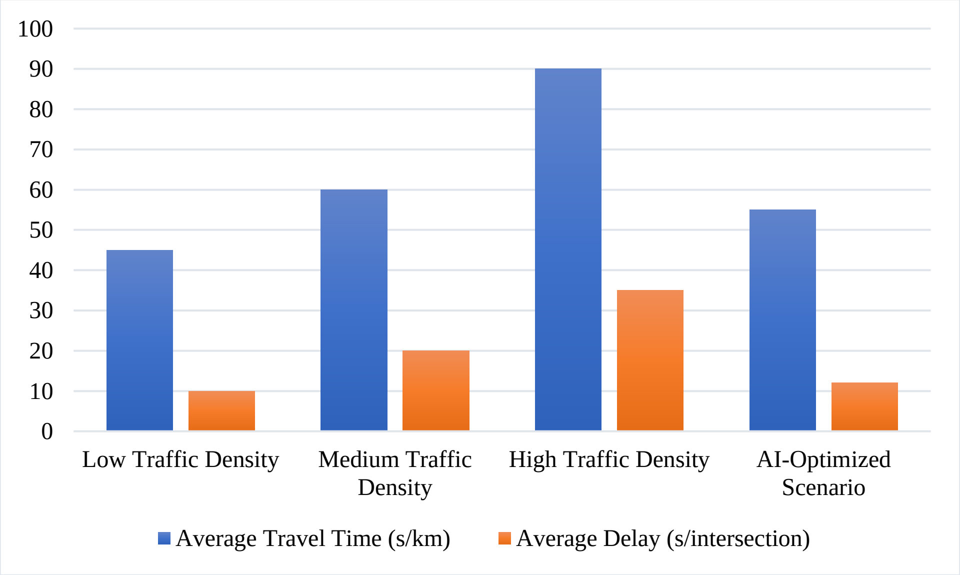

Figure 2: Comparison of Traffic Flow Scenarios Based on Travel Time and Delay

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With increased traffic density, travel time and delay degrade, with a medium traffic density of 60 s/km travel time and 20 s delays, lowering efficiency to 78% but raising fuel savings to 15%. High traffic density causes extreme congestion (90 s/km travel time, 35 s delays, and 25m queueing lengths), with efficiency falling to 65% despite 22% fuel saving. Yet, the AI-Optimized Scenario improves considerably, lowering travel time (55 s/km), delays (12 s), and queue lengths (10m), while optimizing efficiency at 88% and recording the highest fuel saving of 25%. This indicates that AI-based Green-Wave optimization can greatly enhance traffic flow, minimize congestion, and improve fuel efficiency in urban transport systems.

Table 2: Environmental and Economic Benefits of Green-Wave Traffic Optimization

Scenario	**CO_2 Emissions (g/km)**	**Fuel Savings (%)**	**Average Speed (km/h)**	**Operational Cost Savings (%)**
Traditional Traffic Flow	200	0	30	0
Green-Wave Optimization	150	12	45	10
AI-Optimized Green-Wave	120	18	55	15

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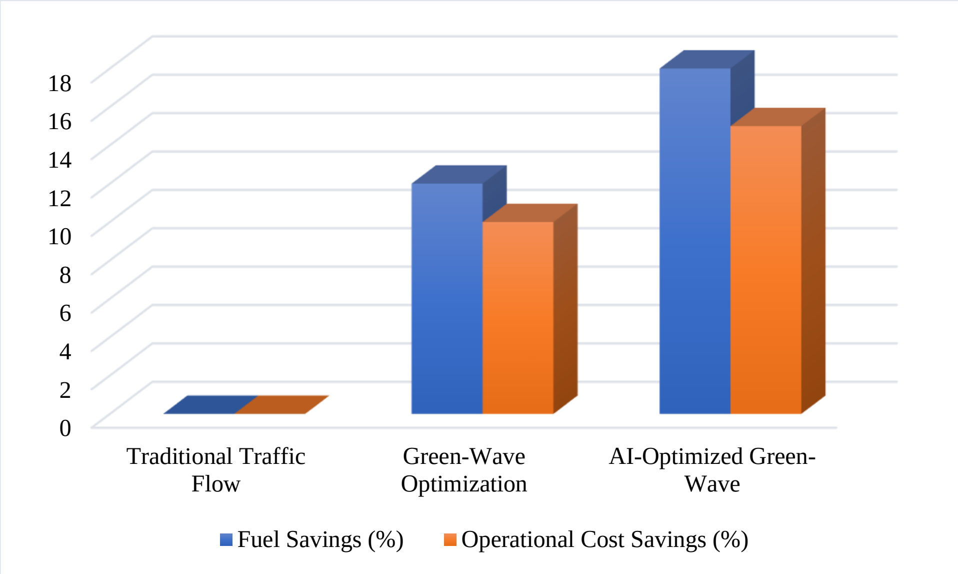

Figure 3: Comparison of Fuel and Operational Cost Savings Across Traffic Optimization Strategies

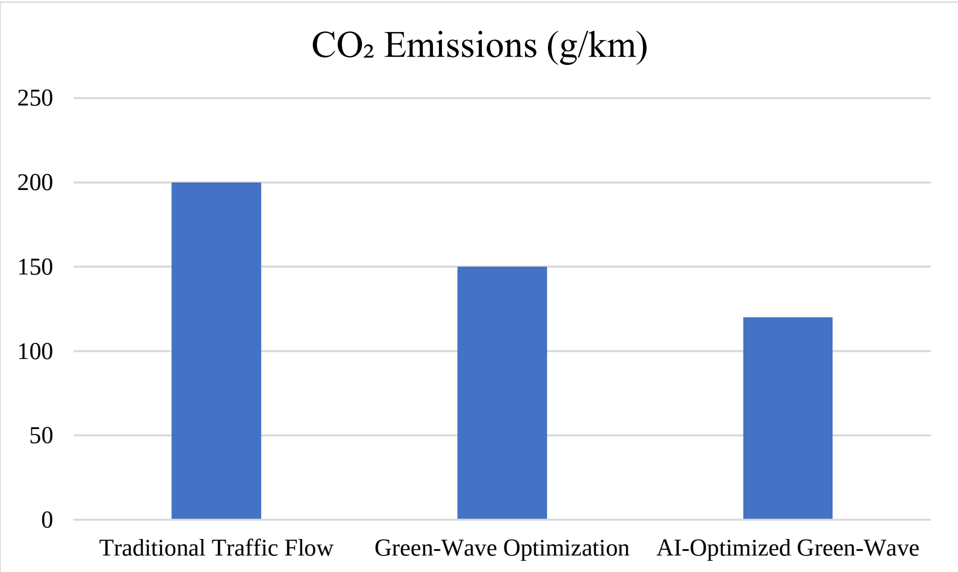

Figure 4: Impact of Traffic Optimization on CO_2 Emissions (g/km)

The information presents the environmental and economic advantages of Green-Wave traffic optimization, with AI-based systems providing the greatest improvements. Conventional traffic flow has high CO_2 emissions (200 g/km), zero fuel savings, and a low average speed (30 km/h), resulting in no operational cost savings. Deploying Green-Wave Optimization enhances efficiency, cutting CO_2 emissions to 150 g/km, attaining 12% fuel saving, and raising average

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speed to 45 km/h, resulting in 10% reduction in operational expenditure. The AI-Optimized Green-Wave system further reduces the benefits, cutting CO_2 emissions to 120 g/km, achieving maximum fuel saving at 18%, and raising average speed to 55 km/h, resulting in 15% savings in operational expenditure. These results imply that AI-based Green-Wave optimization not only decreases environmental footprint but also enhances economic performance by decreasing fuel usage and running expenses alongside increasing overall traffic movement.

5. CONCLUSION

The results of this research highlight the efficacy of AI-based Green-Wave Traffic Optimization in considerably enhancing urban traffic flow, decreasing congestion, and improving fuel efficiency. Comparative study of various traffic conditions indicates that whereas conventional traffic management leads to excessive travel time, long queues, and wasteful fuel usage, Green-Wave optimization counteracts these inefficiencies by enhancing signal coordination. The AI-tuned Green-Wave system further optimizes traffic movement by dynamically changing signal times depending on real-time conditions, which results in significant travel time reduction, intersection delay reduction, and CO_2 reduction, as well as higher fuel savings and cost benefits to the operation. Such outcomes demonstrate the revolutionary power of machine learning and predictive analytics for contemporary traffic management, opening doors to sustainable and intelligent transportation systems in cities. Future studies need to address the coupling of real-time traffic sensing and adaptive AI algorithms to further streamline city-scale traffic networks and enable smart mobility options.

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