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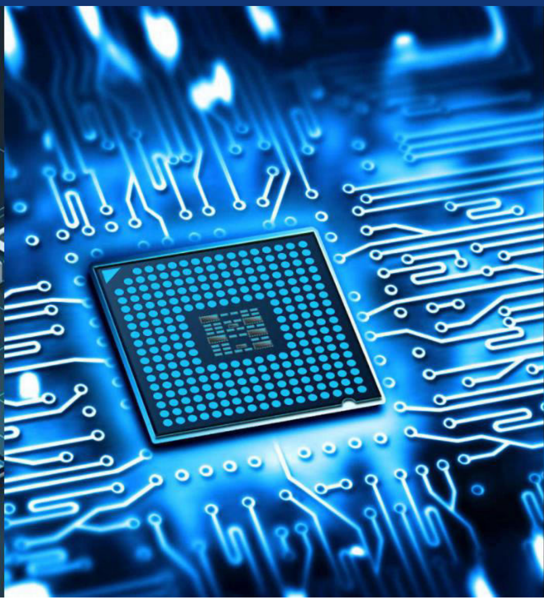

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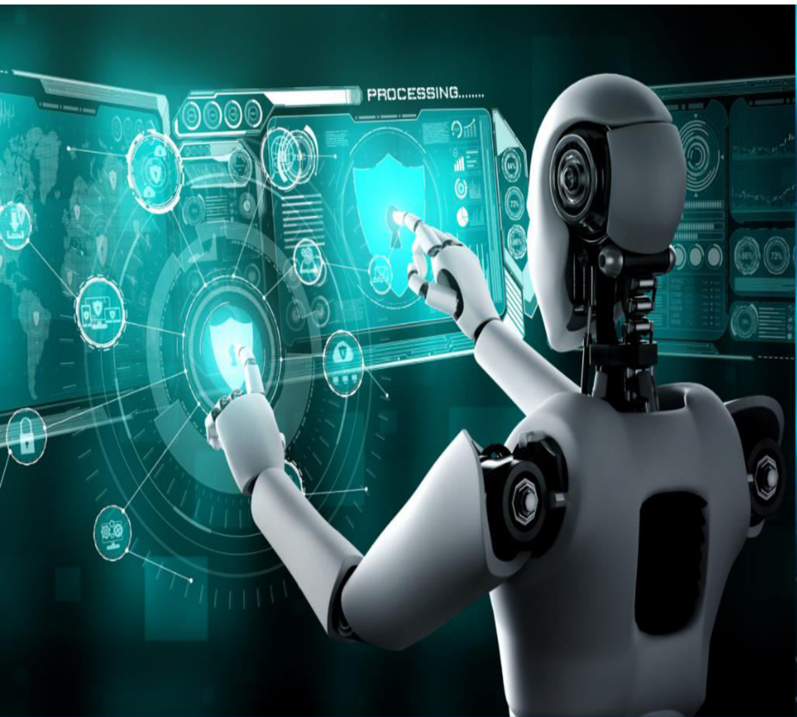

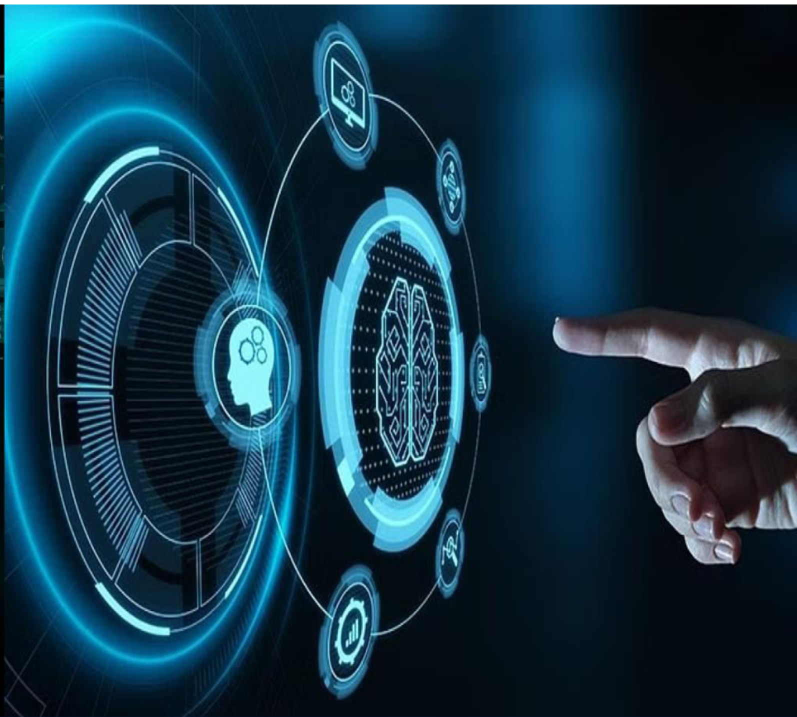

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AI Signal OptiSense: A Real-Time Simulation Based Intelligent Traffic Signal Optimization System

Sarita Krushna Parte, Chetan Mukund Patil, Sanika Kashinath Suryavanshi, Harshada Bhimarao Sawant, Priya Anil More, Samindar Vibhute

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

Department of Computer Science, Sanjeevan Group of Institute, Panhala, Maharashtra, India

ABSTRACT: Urban traffic congestion has become a major challenge in rapidly growing smart cities, leading to increased travel time, fuel consumption, and environmental pollution. Traditional traffic signal systems operate on fixed timing mechanisms, which are inefficient in handling dynamic traffic conditions [1][4]. This research presents AI Signal OptiSense, an intelligent traffic management system designed to optimize signal timings using real-time traffic data and simulation-based analysis. The proposed system integrates SUMO (Simulation of Urban Mobility) with TraCI interface to dynamically monitor vehicle density, waiting time, and junction congestion levels. A real-time web dashboard is developed to visualize traffic conditions, signal phases, and vehicle activity. The system also uses JSON-based data exchange for seamless communication between simulation and dashboard modules [2][5]. Experimental results show that adaptive signal timing significantly reduces congestion and improves traffic flow efficiency compared to traditional systems.

KEYWORDS: Traffic Management System, Smart Traffic Signals, SUMO Simulation, TraCI, Real-Time Dashboard, Traffic Optimization, Intelligent Transportation System (ITS), Congestion Control

I. INTRODUCTION

Rapid growth in urban population and vehicle utilization has resulted in traffic congestion being a critical problem affecting daily life and economic productivity. Traditional traffic systems use fixed signal timings that do not respond to real-time traffic conditions, resulting in poor utilization of the road and long waiting times [1][3]. The recent progress in Intelligent Transportation Systems (ITS) highlights the importance of intelligent and adaptive traffic control schemes that can analyze live data and modify signal timings accordingly.

A. Background and Context

Traffic congestion is one of the most significant problems faced by modern cities. Studies show that fixed time traffic signals are not able to handle varying traffic density especially during peak hours leading to increase in delays and fuel wastage [1][4]. Simulation tools such as SUMO have been extensively utilized in research to simulate real-world traffic scenarios and to investigate the behavior of traffic flow under various conditions [2].

B. Problem Statement

The current systems still present several challenges despite the availability of traffic management technologies. Traditional traffic lights operate on fixed timing cycles and do not take into account the existing traffic conditions, resulting in congestion and inefficient traffic flow [1][3].

C. Research Objectives

The primary objective of this research is to design and develop an intelligent traffic signal optimization system using simulation and real-time data processing. To develop a system that dynamically adjusts traffic signal timings based on vehicle density and congestion levels using SUMO simulation [2][5].To integrate TraCI interface for real-time communication between the simulation environment and the control system.To design a live web dashboard that displays junction status, vehicle data, and signal timings for better monitoring and analysis [6].

II. LITERATURE REVIEW

A. Domain and Problem Context

The primary objective of this research is to design and develop an intelligent traffic signal optimization system using simulation and real-time data processing. To develop a system that dynamically adjusts traffic signal timings based on vehicle density and congestion levels using SUMO simulation [2][5].To integrate TraCI interface for real-time communication between the simulation environment and the control system.To design a live web dashboard that displays junction status, vehicle data, and signal timings for better monitoring and analysis [6].

B. Review of Existing Systems

The current systems for signal management and optimization can be generally divided into fixed-time systems, sensor-based systems and manual monitoring systems. While these systems offer basic functionality, they are limited in their application to modern, dynamic environments. The most common solutions are fixed-time signal systems These systems are based on pre-defined schedules and do not take into account real-time conditions. This often results in inefficient signal management, especially in peak hours or in case of unexpected situations. For example, a signal might remain green for a certain amount of time even if there is no traffic, but other lanes are very congested.

C. Technical Literature

The importance of Artificial Intelligence (AI), Machine Learning (ML) and Internet of Things (IoT) technologies in the development of intelligent systems is highlighted in the technical literature. These technologies give systems the ability to analyze massive data sets, identify patterns, and make intelligent decisions on the fly. AI-based systems have algorithms that can analyze complex datasets and identify patterns that are difficult to detect with traditional methods.

D. Summary of Research Gaps

However, the literature review shows that the current systems still have several critical gaps that limit their effectiveness, despite the advancement of the technology. One of the largest gaps is the absence of real-time intelligent decision-making, as most systems are not capable of handling and responding to dynamic data efficiently. Another important issue is the lack of predictive and adaptive features. Traditional systems do not learn from previous data and thus cannot improve their performance over time. This leads to repetitive inefficiencies and reduced system performance.

III. METHODOLOGY

A. Purpose

This section discusses the design, development, and evaluation of the AI Signal OptiSense, an intelligent traffic signal optimization system. The main goal of the system is to ease traffic congestion and speed up vehicle flow through the real-time adjustment of traffic signal timings according to current traffic conditions. The system is built on simulation analysis, real-time data processing and visualization through a live dashboard.Previous studies on Intelligent Transportation Systems (ITS) have shown that adaptive traffic signal control can significantly improve traffic efficiency compared with fixed-time systems [2][5].

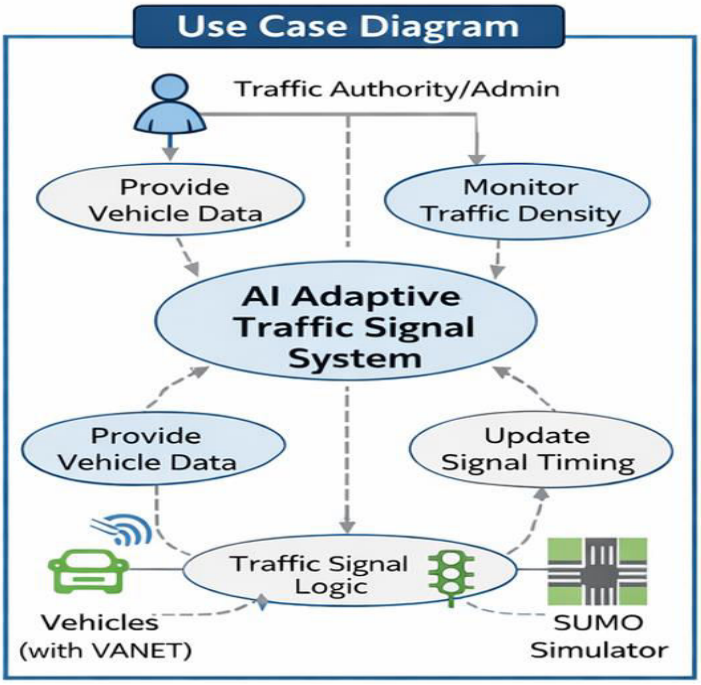

Fig 1. Use Case Diagram of AI Signal OptiSense

B. Content

i: Least Expensive Materials:-

A set of simulation tools, programming techniques, and real time data processing methods were employed. SUMO simulation provided traffic scenarios and Python and TraCI allowed interaction with the simulation environment. The dashboard was built using JSON-based data handling and web technology. Research on traffic simulation and smart signal system has identified effective strategies for congestion control and signal optimization [1][4].

ii. Step-by-Step:-

Step 1: Requirement Analysis

Existing traffic signal systems were analyzed and system requirements were identified. The common problems were fixed signal timings, lack of flexibility and handling of traffic congestion during peak hours was inefficient.Studies of traditional traffic systems have shown that static timing increases waiting time and fuel consumption [1][3]. In view of these limitations, requirements such as real-time monitoring, adaptive signal control and dashboard visualization have been defined.

Step 2: System Design

A modular system was developed including simulation, processing and visualization components. The main features are:

* Traffic monitoring in real-time
* Adaptive signal timings
* Detection of congestion
* Live dashboard visualization

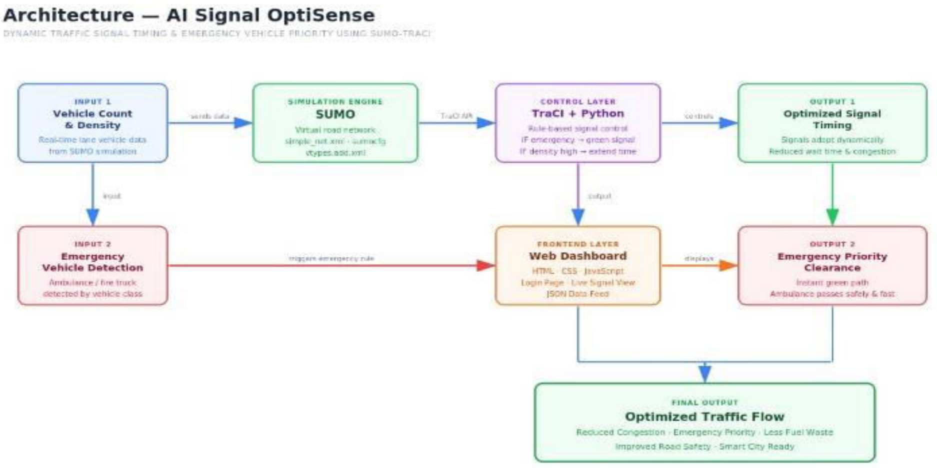

Fig 2. System Architecture of AI Signal OptiSense

Step 3: Technology Selection and Implementation
Python was used for the backend processing and integration with SUMO via TraCI. We use SUMO for traffic simulation as it can simulate complex traffic scenarios.A real-time dashboard was created using HTML, CSS and JavaScript for the front-end.

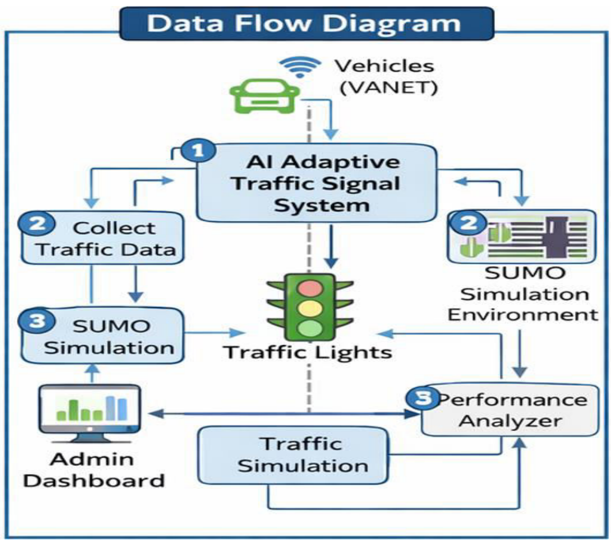

Fig 3. Data Flow Diagram of AI Signal OptiSense

Step 4: Signal Timing Optimization Implementation
A dynamic signal timing mechanism was developed based on traffic density and waiting time. The system constantly monitors the number of cars and adjusts the signal timings accordingly. Studies have shown that adaptive signal control has reduced congestion and improved the efficiency of traffic compared to static systems [4][5].

Step 5: Real-Time Data Synchronization
The system updates the traffic data continuously with TraCI and saves it in JSON format. The dashboard fetches real-time data through APIs and shows live traffic conditions. This ensures the synchronization of simulation and visualization modules which is important for intelligent traffic systems [2][6].

Step 6: Visualization and Monitoring
* Development of a live dashboard to display
* Junction status (free, active, congested)
* Number of vehicles, waiting time
* Per phase signal timings.

iii. Equipment/Tools/Instruments

The system is built on off-the-shelf tools and technologies. Traffic simulation was done using SUMO. Back end processing was done using Python and real time communication was done using TraCI.The dashboard was developed with web technologies such as HTML, CSS, and JavaScript, and data exchange was made using JSON. The evaluation was done using simulation data, such as vehicle count, waiting time and congestion levels. These tools are widely used in intelligent transportation research for traffic system modeling and analysis [2][5].

C. Algorithms Used

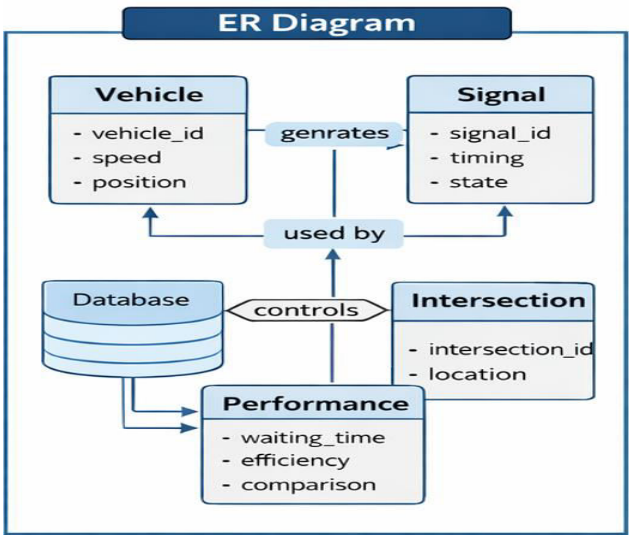

Fig 4. Traffic Signal Optimization Flow Diagram

1. Traffic Density-Based Signal Control

This algorithm changes signal timing based on the number of vehicles present in the junction. The duration of the green signals is increased with an increase in density and decreased with a decrease in density of the system [4][5].

2. Waiting Time Optimization Algorithm

The algorithm gives priority to lanes with longer waiting times, in order to reduce delays and to improve fairness among vehicles [3].

3. Congestion Detection Algorithm

The system divides traffic into three categories:
* Open and transparent
* Active
* Too many people

This classification assists the decision making in the signal optimization [5].

4. Real-Time Data Processing Algorithm

Data is collected from SUMO via TraCI, processed and updated in real time on the dashboard through JSON and APIs [2][6].

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i.Key Aspect: Reliability and Transparecy

Reliability is guaranteed by continuously updating the traffic data and by consistently applying the signal timing logic. The system applies strict rules for congestion detection, signal control and data visualization, which guarantees the consistent performance of the system [4][5]. Real-time dashboard visualisation provides the user with visibility on all system data like vehicle count, signal timings and junction status. Research indicates that real-time visibility enhances system trust and usability in intelligent systems [3][6]. The modular design, use of standard tools and clear workflow make the system reproducible and scalable .

ii. Key Aspect: Scalability and Flexibility

Scalability is an important design aspect of AI Signal OptiSense. The system is designed with a modular architecture with separate simulation processing and visualization modules. This means that the system can be easily scaled up to cater for multiple junctions, larger road networks and higher traffic volumes without affecting performance. Flexibility is provided by configurable signal timing parameters and adaptable algorithms.

iii. Key Aspect: Efficiency and Performance Optimization

Efficiency is a primary goal of the AI Signal OptiSense system. The system is constantly checking traffic conditions and adjusting signal timings to minimize vehicle waiting time and congestion. The system dynamically adapts signal phases based on real-time data to improve the use of road infrastructure. Performance optimization by real-time data processing and lightweight communication with JSON and APIs. The system prioritizes congested lanes and adjusts signal durations to minimize unnecessary delays. Studies indicate that adaptive traffic systems provide considerable improvement in throughput and reduction in travel time compared to conventional fixed signal systems [4][5]. Furthermore, the simulation based testing can be used to test the performance in different traffic scenarios, which guarantees the efficient operation of the system before the actual deployment in the real world [2][6].

IV. RESULT AND DISCUSSION

A. Purpose

This section presents the results obtained after the implementation and testing of the AI Signal OptiSense system and evaluates how the proposed system addresses the limitations of traditional traffic signal systems. Existing traffic management systems primarily rely on fixed signal timings, which fail to adapt to real-time traffic conditions, leading to congestion, increased waiting time, and inefficient traffic flow [1][4].The evaluation of the proposed system focuses on its ability to dynamically adjust signal timings, reduce congestion, and improve overall traffic efficiency. The results are analyzed based on simulation data and real-time monitoring using the dashboard. Previous research in intelligent transportation systems highlights that adaptive traffic control significantly improves performance compared to static systems [2][5].

B. Content

1. Data (Visual Representation)

The data for evaluation was collected using SUMO simulation under different traffic scenarios, including low, medium, and high traffic conditions. The collected data includes vehicle count, average waiting time, signal timing per phase, and junction congestion status.The results were visualized using bar graphs, line graphs, and pie charts to better understand system performance.

For example:

- Bar graphs represent vehicle count at different junctions
- Line graphs show variation in waiting time over simulation steps
- Pie charts represent congestion levels (clear, active, congested)

This type of graphical analysis is widely used in traffic system research to evaluate system efficiency and performance [3][6].

2. Results (Analysis Based on Core Modules)

The core components of the AI Signal OptiSense system, i.e., traffic monitoring, signal optimization, congestion detection and dashboard visualization were evaluated for the performance of the system. The Traffic Monitoring Module monitored real-time vehicle data successfully such as vehicle count, waiting time. The system allowed for the precise detection of the congestion levels at each junction. The real-time monitoring provided better insights into the traffic conditions than the traditional systems[2]. The Signal Optimization Module showed a significant improvement of the traffic flow. The system reduced waiting time and eliminated long queues by dynamically changing signal timings to match the density of vehicles. Simulation results showed the better performance of adaptive signal control than fixed timing particularly during peak traffic conditions [4][5].

3. Discussion (Interpretation of Results)

Results show that the proposed AI Signal OptiSense system can overcome the limitations of traditional traffic management systems. Unlike fixed signal systems, the proposed system is adaptive to real time traffic and hence, reduces congestion and improves traffic flow. Another important observation is the decrease of the average waiting time. The shorter delay of vehicles was caused by the dynamic adjustment of the signal which is in accordance with the previous work on adaptive traffic control system [4][5]. The congestion detection mechanism was also important in system performance. This helped the system to prioritize those lanes and improve the overall traffic distribution by identifying the high density traffic areas. This is consistent with results from intelligent transportation studies where congestion-aware systems are more efficient [2][6].

V. CONCLUSION

The paper proposes and studies an intelligent and adaptive traffic signal control system which combines simulation-based modelling and communication technologies. This research combines the strengths of SUMO (Simulation of Urban Mobility) and VANET (Vehicular Ad hoc Network) effectively to optimize traffic signal timings dynamically based on real-time vehicular data. Unlike conventional fixed-time traffic control systems which operate based on a fixed schedule irrespective of traffic conditions, the proposed approach adapts continuously to varying traffic densities and patterns.The system uses a rule-based adaptive control logic based on inputs such as vehicle count, traffic density and signal timing. This allows the effective decision making for the adjustment of the signal phase, thus eliminating the unnecessary waiting times and improving the traffic flow in general. The simulation results clearly indicate that the proposed adaptive approach is able to significantly outperform the existing fixed-time system with respect to important performance metrics such as average waiting time, congestion level and throughput. VANET also provides continuous communication between vehicles and infrastructure, enabling accurate and timely data acquisition. This real-time data exchange is critical for increasing the responsiveness and reliability of the system. The incorporation of AI-driven decision mechanisms into simulation tools also provides a scalable and flexible framework that can be extended to more complex urban traffic situations. A further important contribution of this work is the comparative analysis between the existing system and the proposed adaptive model using a defined performance metric. The results indicate a significant improvement in the traffic efficiency and confirm the effectiveness of the proposed methodology. This shows the potential of intelligent traffic management systems to solve real world problems such as traffic congestion, fuel consumption and environmental pollution.

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