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AI-Driven Smart Traffic Signal Control using Computer Vision for Real-Time Traffic Optimization

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***Abstract*— Rapid urban growth has increased vehicle density, making traditional fixed-timing traffic systems inefficient and unable to handle real-time conditions or prioritize emergency vehicles. In this research AI-based traffic management framework is developed that leverages computer vision techniques to monitor vehicle density and adapt traffic signal timings in real time. The system dynamically adjusts traffic signal timings in response to live traffic conditions, specifically vehicle density at intersections. The system analysis video feeds using a mathematical model to detect and classify vehicles, enabling adaptive signal timing for easy traffic flow and reduced waiting time. A key feature is the automatic detection of emergency vehicles, allowing immediate signal override for faster response. It employs a modular system architecture that includes detection, control, and monitoring modules. Experimental results show improved traffic efficiency and quicker emergency handling, contributing to smarter city traffic management.**

***Index Terms*— Traffic Management, Artificial Intelligence, Computer Vision, YOLOv8, Adaptive Traffic Signal Control, Emergency Response Vehicles.**

I. INTRODUCTION

Rapid urban growth and the increasing volume of vehicles on the road population. Conventional traffic signals operate on fixed-time schedules and cannot adapt to the dynamic traffic flow conditions. Additionally, the lack of priority for emergency vehicles further worsens the situation, often causing critical delays Recent progress in artificial intelligence and computer vision has made it possible to design smart traffic management systems capable of analysing traffic conditions in real time [1]. This study presents an intelligent traffic management framework that automatically modifies signal timings according to real-time traffic conditions. This research presents an adaptive traffic management system capable of adjusting signal timings in response to real-time traffic patterns public safety.

II. LITERATURE SURVEY

Recent developments in intelligent transportation systems have emphasized the integration of advanced technologies to improve traffic management integrating Artificial Intelligence (AI), Internet of Things (IoT), and rooted in data models to improve traffic efficiency and reduce congestion.

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Various research studies have proposed innovative approaches to note the limitations of traditional traffic management systems.[2]

Miao and Liao proposed an IoT-based traffic prediction model combines CNNs, Particle Swarm Optimization (PSO) to improve forecasting accuracy. CNNs catches spatial features from traffic data, while PSO optimizes model parameters. The approach significantly increased prediction accuracy from about 76% to over 90% and improved traffic flow efficiency, demonstrating the effectiveness of integrating deep learning models.

Xu and Li proposed a real-time traffic congestion prediction framework using a Dynamic Risk Field Model combined with multi-source data fusion. Their approach integrates physical modelling with machine learning, including Gaussian-based spatial analysis and LSTM for traffic prediction. The model achieved high accuracy and lower computational cost compared to past methods, while supporting real-time traffic control strategies such as adaptive speed limits and lane management [3].

A brief review conducted by Fadila et al. explored the role, Fourth Industrial Revolution (4IR) technologies in smart traffic management. The study analysed various approaches involving AI, IoT, machine learning, and blockchain-based systems. The study shows that these technologies significantly enhance traffic efficiency, sustainability, and system automation. However, the analysis also emphasizes challenges such as data privacy concerns, scalability issues, and the need for standardized implementation across urban environments [4].

Cui and Le proposed an intelligent transportation system based on IoT and Artificial Intelligence using a layered architecture for real-time data collection and analysis. Their system improves traffic flow and road safety through AI-driven optimization. However, most present analysis focus on prediction and large-scale design, with limited emphasis on real-time adaptive signal control and emergency vehicle prioritization. Therefore, there is a need for a practical system in real time manages traffic signals while ensuring priority for critical vehicles, which the proposed system aims to achieve using computer vision and adaptive control logic[5].

III. MOTIVATION

The increasing traffic congestion n urban areas has resulted in prolonged travel times, increased fuel consumption, and environmental concerns, highlighting the need for more efficient traffic management systems. A key motivation for this work is the congestion-induced delay of emergency vehicles, which can result in severe consequences.

Innovation in Artificial Intelligence and Computer Vision provide an opportunity to develop intelligent systems capable of real-time traffic analysis and adaptive control [6]. Additionally, the growing concept of smart cities encourages the use of automated and data-driven solutions to improve urban mobility.

Overall, this work moto to develop an intelligent, efficient, and practical traffic management system that increases traffic flow, supports emergency response, and be part of safer and smarter transportation systems.

IV. PROBLEM DOMAIN

The problem domain focuses on adaptive transportation systems aimed at addressing urban traffic congestion. Faster growth in population and vehicle usage has led to increased delays, pollution, and inefficient road utilization due to fixed-time traffic signals that do not adapt to real-time conditions.

A key challenge is the lack of responsiveness in existing systems, which fail to consider real factors such as traffic density and peak-hour variations [7]. Additionally, the absence of automated prioritization for emergency vehicles results in critical delays.

The domain also involves leveraging advanced technologies such as Artificial Intelligence and Computer Vision, along with IoT to develop adaptive and efficient traffic solutions, while ensuring scalability and cost-effectiveness. Overall, the focus is on creating a real-time, cognitive traffic management system that improves efficiency and public safety.

A. Problem Statement

Modern traffic congestion has become a critical issue due to the increasing number of vehicles and the limitations of existing road infrastructure. Conventional traffic signal systems operate on fixed timing schedules without considering real-time traffic conditions, resulting in suboptimal traffic flow, increased waiting times, and longer waiting times, and increased fuel consumption [8]. Furthermore, these systems lack the capability to prioritize emergency vehicles, causing delays in critical situations. Hence, a need for an intelligent, adaptive, and real-time traffic arrangement system that can dynamically control signal timings based on traffic density and ensure timely passage for emergency vehicles to improve overall efficiency and safety.

B. Innovation Content

The proposed system introduces a novel approach to urban traffic management by integrating real-time computer vision, adaptive signal control, and automated decision-making emergency vehicle prioritization into a unified framework [9]. Unlike conventional traffic systems that rely on fixed timing schedules or expensive sensor-based infrastructure, this system utilizes camera-based input and and deep learning techniques for real-time traffic condition analysis dynamically. A key innovation of this work is the use of a live object detection model to accurately identify and classify vehicles from video feeds. This enables precise estimation of traffic density across different lanes, allowing the system to allocate signal timings driven by actual demand rather than predefined cycles. The real-time adaptive control system for traffic signals" ensures more efficient utilization of road space and reduces unnecessary waiting time. Another significant contribution is the integration of an automated emergency vehicle detection feature within the traffic control logic. The system is capable of identifying critical vehicles such as ambulances and immediately prioritizing their movement by overriding normal signal operations. This reduces response time in critical situations and enhances public safety without requiring additional hardware such as RFID or acoustic sensors. The proposed architecture is designed to be modular and scalable, making it suitable for deployment in smart city environments [10]. By leveraging existing camera infrastructure and software-based intelligence, the system offers a cost-effective alternative to the system incorporates data analytics and predictive modelling to improve decision-making solutions. Additionally, the framework can be extended to incorporate data analytics and predictive capabilities for future traffic optimization.

Overall, the innovation lies in developing an intelligent, adaptive, and practical traffic management solution that Sum-upvarious modern technologies into a cohesive system single system to address real-world challenges effectively [11].

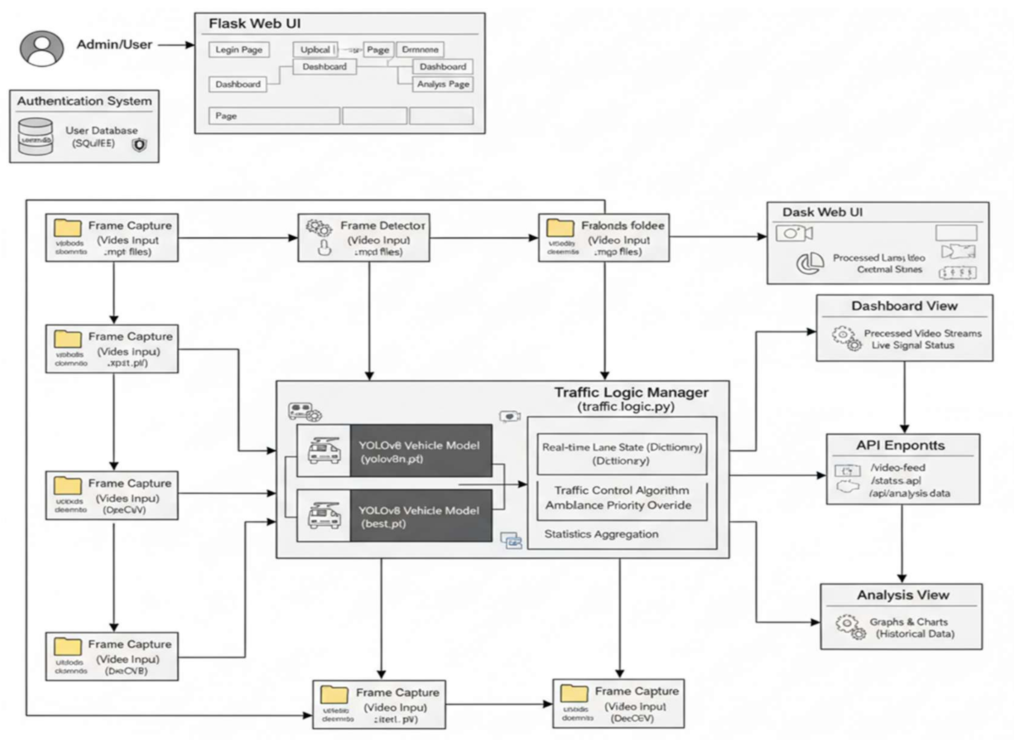

Fig.1 System Architecture

V. Problem Formulation And System Representation

A. Problem Formulation

Most traffic management systems today are built around people that are primarily based on manual control or fixed-timer mechanisms, which operate without considering real-time traffic conditions. These systems lack the capability to collect and process live traffic data that fails to provide a mechanism for prioritizing emergency vehicles. Additionally, the lack of a centralized monitoring mechanism contributes to traffic congestion and increased delays [12]. Furthermore, current systems do not provide an effective method for prioritizing emergency vehicles, resulting in inefficient traffic management.

To look into these limitations, the problem is formulated as the design of an intelligent traffic management system that can adaptively control traffic signals based on real-time traffic density [13]. The system aims to improve overall traffic efficiency by adapting signal timings based on live road conditions.

The key components of the proposed system include developing a real-time automate vehicle detection module, implementing adaptive signal timing logic, designing an emergency vehicle override mechanism, and enabling traffic data analysis for improved decision-making.

B. System Representation

The Intelligent Traffic Management System (ITMS) is a data-driven framework that processes real-time inputs to generate dynamic traffic control decisions. Traffic cameras capture live video, from which key metrics such as vehicle count and traffic density are extracted [14]. The data is analysed using computer vision techniques implemented with OpenCV and deep learning models for precise detection.

System Modules

The system consists of multiple modules working together for efficient traffic management. The data acquisition module captures real-time video and converts it into frames, while the vehicle detection module utilizes computer vision techniques to identify vehicles in traffic scenes. The density estimation module calculates congestion levels based on detected vehicle data. The vehicle detection module utilizes computer vision techniques to identify vehicles [15]. Based on the detected vehicle density, the signal control module adaptively updates traffic signal timings in real time.

Fig. 2. User Input Dashboard

Fig.3. Live Traffic Dashboard

Mathematical Representation

The system follows a proportional relationship between traffic density and signal timing. Let V_idenote the total number of vehicles detected in lane iand T_irepresent the signal time allocated. Signal timing is directly proportional to vehicle density, ensuring that lanes with higher traffic receive longer green signals while maintaining minimum time for all lanes.

System Workflow

The overall operation of the system follows a continuous cycle. Initially, traffic video is captured and converted into frames that are then analysed to detect vehicles present in each lane. Based on the congestion density of detected vehicles, traffic density is calculated and compared across all lanes. The system subsequently assigns appropriate signal timings based on this comparison [16]. This process is repeated continuously to ensure real-time adaptability and signal timings determined by real-time traffic conditions.

VI. METHODOLOGY

The proposed system operates through the following steps a structured sequence of steps. Traffic data acquisition is first captured using cameras and converted into frames for analysis followed by vehicle detection is then performed using computer vision techniques, where OpenCV handles preprocessing and a trained deep learning model identifies vehicles such as cars, bikes, and buses. Based on the detected vehicles, traffic density and queue length are deliberated for each lane. The system compares these values and assigns priority to lanes with higher density, allocating longer green signal durations while ensuring minimum time for all lanes [17]. Traffic signal timings are adaptively adjusted based on traffic conditions and executed through the control module in real time. The model constantly updates its control decisions through a feedback loop, enabling adaptive and efficient traffic management under changing conditions.

VII. RESULTS AND SENSITIVITY ANALYSIS

A. Experimental Results

The proposed AI Driven Smart Traffic Controlling was evaluated using traffic video and image data to assess its real-time performance. The system effectively detected vehicles and accurately derived traffic density value for each lane, enabling dynamic adjustment of signal timings. The output show improved traffic efficiency, reduced waiting time, and better clearance of congested lanes [18]. Compared to fixed-timer systems, the proposed approach demonstrates higher adaptability and responsiveness to changing traffic conditions.

B. Performance Evaluation

A comparative analysis between the present traffic system and the invented AIDSTM highlights significant improvements across multiple parameters. The traditional system operates with approximately 80% accuracy, whereas the proposed system achieves a precision of up to 98% due to the use of latest object sensing techniques [19]. Unlike fixed signal timing in conventional systems, the proposed approach dynamically adjusts signal durations based on lively traffic volume.

Furthermore, the handling of emergency vehicles is automated in the proposed system, ensuring immediate prioritization without manual intervention. In contrast, existing systems rely on manual control, which may lead to delays [20]. The designed architecture also includes a real-time monitoring dashboard, enabling centralized supervision, while traditional systems lack such monitoring capabilities. Additionally, the shift from rule-based signal control to an AI-powered detection model significantly enhances the overall decision-making process.

TABLE I. PERFORMANCE EVALUATION

Accuracy	80%	98%
Signal Timing	Fixed Timing	Dynamic (Density-Based) Light Timing
Ambulance Handling	Manual	Automated Priority
Monitoring	None (No monitoring available)	Real-time dashboard available
Technology	Rule-Based Light Control	AI-Powered YOLOv8 Algorithm

Sensitivity Analysis

The performance of the designed system is influenced by several environmental and system-related factors. Lighting conditions and shadows can affect detection accuracy, while improper camera positioning may lead to incorrect vehicle counting. High traffic density can cause overlapping vehicles and misdetection, whereas very low traffic may result in inefficient signal allocation. The exactness of the detection model and the processing speed of video frames also play a critical role, as errors or delays directly impact signal timing decisions. Traffic conditions also affect system performance. In highly dense traffic scenarios, overlapping vehicles can lead to misdetection or counting errors. Conversely, in very low traffic conditions, inefficient signal allocation may occur if not properly managed [21]. The precision of the detection model is another critical factor, as false positives or false negatives directly influence signal timing decisions and overall system effectiveness.

Additionally, the processing speed of video frames determines the responsiveness of the system. Slower processing due to hardware limitations can introduce delays in signal updates, reducing the real-time efficiency of the system.

Overall, parameters such as model accuracy, lighting conditions, camera setup, and processing speed have a high impact on system performance, while traffic overlap introduces moderate variability. Addressing these factors is essential for ensuring consistent and reliable operation in real-world scenarios.

Lane	Cars	Buses	Trucks	Motorcycles	Ambulances	Total
Lane 1	643	22	71	66	0	802
Lane 2	512	145	50	11	0	718
Lane 3	248	11	25	0	0	284
Lane 4	1174	26	113	0	0	1313

Fig .4. Analysis Dashboard of Vehicles

Fig.5. Analysis Dashboard of Vehicles

TABLE. II. KEY PARAMETERS AFFECTING INTELLIGENT TRAFFIC SYSTEM PERFORMANCE

PARAMETER	DESCRIPTION
Lane ID	Unique identification number for each lane
Density	Total number of vehicles currently detected
Ambulance Status	Boolean value indicating ambulance presence
Signal Status	Current signal color (Red, Green, Orange)
Vehicle Count	Number of Cars, Buses, Trucks, and Motorcycles
Green Duration	Dynamically calculated green signal timing

Data Model

The AI Driven Smart Traffic Management System is built on a structured data model that supports real-time monitoring, decision-making, and traffic analysis. Each lane is treated as an independent unit, maintaining parameters such as vehicle density, vehicle count, signal status, and signal timing [22]. This data is efficiently managed using a dictionary-based structure, enabling fast and accurate decisions. User authentication is handled through a secure SQLite database, ensuring controlled access to the system dashboard. Additionally, the system maintains historical traffic records by logging vehicle counts during each signal cycle. This data is used for generating reports and analysing traffic patterns, improving long-term system efficiency. The structure enables the system to make quick and accurate decisions based on the real-time traffic conditions.

The user authentication data is stored in a separate SQLite database named usersdb. It gives secure administrative access to the dashboard of the system [23].

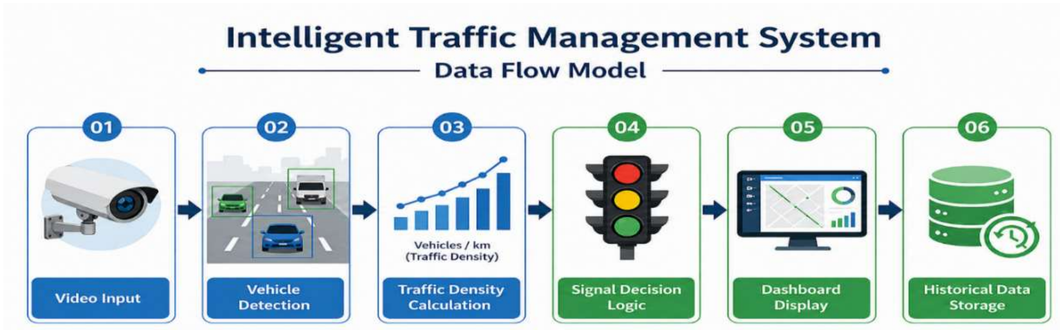

Fig.6. Data Flow Model of Traffic Management System

Comparison of Results

The performance improvements are evaluated by comparing the proposed Intelligent Traffic Management System with the traditional fixed-time traffic signal system.

In conventional system, green signal duration is same for every lane regardless of traffic volume. This often leads to unnecessary delays, as empty lanes are still given the green signal, while congested lanes are still blocked.

In the proposed system, real-time vehicle density detected using YOLOv8 is used to dynamically adjust the signal timing [24]. Lanes with more traffic density get more green time and less crowded lanes get less green time.

There was a big improvement in handling ambulances. Traditional systems don't automatically prioritize ambulances, which can lead to dangerous delays. The proposed system detects ambulances in real time and creates a green corridor automatically.

TABLE III: COMPARISON BETWEEN EXISTING AND PROPOSED SYSTEM

Parameter	Existing System	Proposed System
Accuracy	80%	98%
Signal Timing	Fixed Timing	Dynamic (Density-Based) Light Timing
Ambulance Handling	Manual	Automated Priority
Monitoring	None. No moniriting can be done	Real-time Dashboard available for monitoring
Technology	Rule-Based Light Control	AI-Powered YOLOv8 Algorithm

In addition to managing traffic density, the proposed system also improves the handling of emergency vehicles such as ambulances. In conventional traffic signal systems, there is usually no automatic mechanism to give priority to emergency vehicles, which can cause serious delays during critical situations [25]. The proposed system addresses this issue by detecting ambulances in real time and providing signal priority automatically. Once an ambulance is identified, the system creates a green corridor along its route, allowing it to move through intersections without unnecessary stops. This capability helps ensure faster response times and safer movement for emergency vehicles.

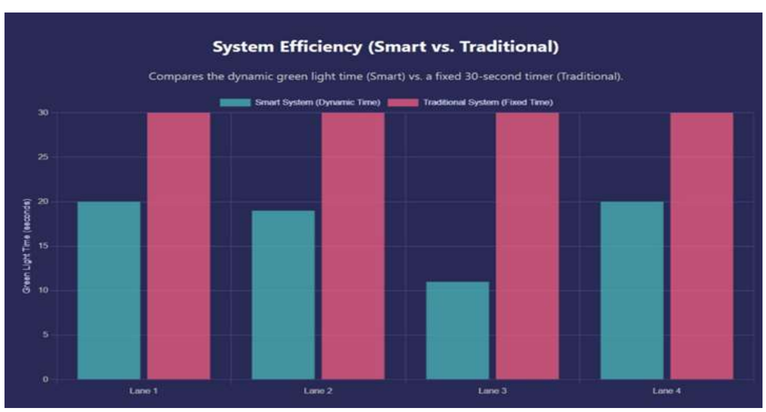

Fig.7.System Efficiency for Smart Vs. Traditional

The results clearly show that the proposed system can improve the traffic flow, reduce the congestion and improve the efficiency of emergency response [26].

Justification of Results: With YOLOv8 at the helm, real-time vehicle detection seems effortless. It tracks what's out on the road and how many there are, so you actually know what's happening. The method it uses for handling traffic lights is fairly clever, too. Traffic signals don't only function based on timers—they modify timing depending on traffic volume, ensuring you don't spend time unnecessarily at low-traffic crossings. Ambulances receive support as well. Although surrounded by city sounds, the system identifies emergency vehicles and clears the route for them when every second counts. Plus, you get loads of traffic data to help with future planning [27]. Assemble all the parts, and you obtain a solution that is workable, effective, and addresses all the primary needs of the project.

VIII. CONCLUSION

The AI-driven Traffic Management System introduces AI alongside computer vision technology directly into the core of current traffic control [28]. Instead of relying on old, fixed-timed signals, this setup uses a smart, density-based approach that actually pays attention to what's happening on the roads in real time.

With YOLOv8 object detection, the system reliably counts vehicles and spots ambulances the moment they appear. When traffic piles up in certain lanes, the lights stay green longer where they're needed most. So, jams clear faster. And when an ambulance shows up, the emergency override kicks in, opening up a green corridor straight through—all on its own [29]. That means emergency crews reach people faster, and those few saved minutes can make all the difference.

There's also a live dashboard built using Flask. It lets you see what's happening on the roads with real-time visuals and graphs—so you get a clear picture of traffic patterns as they unfold. This combination of automation and data in real time is a significant upgrade from old fashioned systems. Overall, this project proves what smart automation can do [30]. It can speed things up, make the roads safety more effective, and helps cities work smarter.

FUTURE WORK

The current system handles simulations pretty well, but honestly, there's a lot that could make it even better when it's set up for the real world. First off, if we replace those old pre-recorded videos with live CCTV or IP camera feeds, the system will finally start to make sense for smart cities. Toss reinforcement learning into the mix and now we will get a setup that learns how traffic behaves so it can catch congestion early and react way faster [32]. And we don't have to stop at one intersection. We can take it citywide, connect everything, and keep traffic flowing smoothly, so drivers hit more green lights and fewer jams. Plugging everything into the cloud gives traffic authorities a way to monitor and adjust things remotely. And, integrating the hardware with IoT-enabled traffic signals is really the last piece to make the whole thing work on a city scale.

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