

IoT-Enabled Density-Based Traffic Light Control System

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Abstract— This paper presents an AI-based intelligent traffic light control system that integrates ESP32 microcontrollers with AI-powered cameras, utilizing the YOLO (You Only Look Once) object detection algorithm. The system is designed to dynamically manage and optimize traffic signal timings based on real-time vehicle density at a four-way junction. Each junction is equipped with red, yellow, and green LED traffic signals on the north, south, east, and west sides—totaling twelve LEDs. The ESP32 microcontroller serves as the central processing unit, connected to the Google Cloud via the Internet for real-time data processing and synchronization. The system continuously analyzes live video feeds using the YOLO algorithm to determine traffic density on each lane. Based on this data, the traffic control server intelligently adjusts signal durations: extending green light intervals during high-density conditions and reducing them when traffic is minimal, thereby improving flow efficiency and reducing waiting times. An additional emergency vehicle prioritization mechanism instantly activates the green signal on the path of an approaching ambulance or fire truck, while setting red lights on all other sides, ensuring a clear route for emergency response. To enhance connectivity monitoring, a dedicated Wi-Fi connection LED blinks during active communication and remains steadily lit when disconnected. Furthermore, the system uploads real-time traffic density data to the cloud, enabling the public to access live traffic information for better route planning and congestion avoidance. In an era of escalating urban traffic challenges, this AI-driven intelligent traffic control system offers a scalable, responsive, and efficient solution to reduce congestion, enhance emergency vehicle response times, and empower the public with actionable traffic insights.

Index Terms- Artificial Intelligence (AI), Intelligent Traffic Light Control System, Real-Time Traffic Monitoring, Cloud Computing, YOLO (You Only Look Once), Object Detection, Smart Transportation, Emergency Vehicle Prioritization, Four-Way Junction Control

I. INTRODUCTION

Traffic congestion has become a major global challenge due to rapid urbanisation and the continuous growth in the number of vehicles. Conventional traffic management systems mainly rely on fixed-time signal control, which does not adapt to real-time traffic density. This often results in unnecessary waiting times, increased fuel consumption, higher carbon emissions, and frustration among road users. In addition, emergency vehicles such as ambulances and fire

trucks frequently face delays at intersections, which can have serious consequences.

This paper proposes an IoT-based smart traffic management system that dynamically controls traffic signals based on real-time vehicle density. The system integrates AI-powered cameras using the YOLO (You Only Look Once) algorithm for vehicle detection and counting, along with an ESP32 microcontroller for intelligent signal control. The traffic signals automatically adjust their green light duration according to the number of vehicles present in each lane. Furthermore, the system provides priority access to emergency vehicles by instantly switching signals to ensure faster and safer movement.

Real-time traffic data is transmitted to the cloud using Google Cloud Platform and stored in Google Firebase Realtime Database, enabling continuous monitoring and analysis. A mobile application allows users and authorities to view live traffic density, signal status, and emergency vehicle updates. This reduces manual monitoring efforts and improves overall traffic coordination.

By combining IoT, artificial intelligence, and cloud computing, the proposed system aims to reduce congestion, minimize fuel wastage, lower greenhouse gas emissions, and improve road safety. The solution supports smart city development and promotes sustainable urban transportation management.

II. LITERATURE SURVEY

Traditional traffic management systems struggle to maintain efficiency and sustainability due to rapid urbanization and the continuous growth of vehicles. Fixed-time traffic signals cannot adapt to real-time traffic density, leading to congestion, fuel wastage, increased travel time, and environmental pollution. Recent advancements in the Internet of Things (IoT), Artificial Intelligence (AI), and cloud computing have enabled the development of smart traffic management systems that optimize signal timing, improve traffic flow, and reduce manual intervention. By providing real-time vehicle detection, automated signal control, and data-driven decision-making, IoT-enabled traffic monitoring significantly enhances operational efficiency and urban mobility. The integration of AI algorithms, wireless communication, and cloud-based monitoring transforms conventional traffic systems into intelligent and adaptive solutions that reduce operational costs and environmental

impact. For this review, we analysed five key research works related to smart and density-based traffic management systems: [1] Traffic Signal Timing Optimization Model Using YOLO-X and LSTM. [2] Real-Time Vehicle Detection and Tracking on Fisheye Traffic Video. [3] Smart Traffic Light Using YOLO with Deep Reinforcement Learning. [4] Real-Time Traffic Light Optimization Using AI, IoT, and YOLO. [5] AI-Driven Smart Traffic Management System Using YOLO and OpenCV.

A. *Traffic Signal Timing Optimization Model Using YOLO-X and LSTM*

The paper titled “Traffic Signal Timing Optimization Model Using YOLO-X and LSTM” presents an advanced AI-based approach for improving traffic signal control at road intersections. The system uses YOLOX for real-time vehicle detection and counting from live traffic camera feeds. This model accurately identifies different types of vehicles and determines traffic density at each lane of the intersection.

In addition to real-time detection, the study integrates Long Short-Term Memory (LSTM), a deep learning technique used for time-series prediction. LSTM analyses historical traffic data to forecast future traffic flow patterns. By combining current vehicle density with predicted traffic conditions, the system optimizes signal timing more intelligently than traditional fixed-time or simple density-based methods.

Although the model provides improved accuracy in traffic prediction and signal optimization, it requires complex algorithms, high computational resources, and powerful hardware for real-time implementation. This makes the system more suitable for large-scale smart city infrastructures rather than low-cost or small-scale implementations.

B. *Real-Time Vehicle Detection and Tracking on Fisheye Traffic Video*

The “Real-Time Vehicle Detection and Tracking on Fisheye Traffic Video” presents a traffic monitoring system that uses fisheye cameras to observe large and complex road intersections. Fisheye cameras provide a wide-angle view, allowing a single camera to capture multiple lanes and directions simultaneously. This makes them suitable for monitoring busy urban junctions where installing multiple normal cameras may be expensive or difficult.

The system applies advanced computer vision techniques, often based on deep learning models such as YOLO, to detect and track vehicles in real time. It identifies moving vehicles from the distorted fisheye video frames and follows their movement across the intersection. The main objective of the research is accurate vehicle detection and tracking for traffic analysis and surveillance purposes.

However, the study primarily focuses on traffic monitoring and data collection rather than adaptive traffic signal control. While it provides reliable real-time vehicle tracking and improves intersection visibility, it does not directly integrate dynamic signal timing adjustments based on traffic density.

C. *Smart Traffic Light Using YOLO with Deep Reinforcement Learning*

The project titled “Smart Traffic Light Using YOLO with Deep Reinforcement Learning” proposes an advanced intelligent traffic control system that combines real-time vehicle detection with adaptive decision-making algorithms.

In this system, vehicles are detected and counted from live traffic video feeds using YOLO. The algorithm accurately identifies different types of vehicles and measures traffic density at each lane of an intersection.

The detected vehicle data is then provided to a Deep Reinforcement Learning (DRL) model, which learns the optimal signal timing strategy through continuous interaction with traffic conditions. Unlike traditional fixed-time or simple density-based systems, reinforcement learning enables the traffic signal controller to make dynamic decisions based on both current traffic states and learned patterns from previous situations. Over time, the system improves its performance by minimizing waiting time, congestion, and overall delay.

By integrating YOLO with Deep Reinforcement Learning, the proposed model can handle complex and unpredictable traffic scenarios more effectively than conventional methods. However, the system requires higher computational resources and careful training of the learning model to achieve stable and reliable performance in real-world environments.

D. *Real-Time Traffic Light Optimization Using AI, IoT, and YOLO*

The intelligent traffic management system that combines artificial intelligence and Internet of Things (IoT) technologies to improve signal control at road intersections. The system uses cameras and connected sensors to continuously monitor traffic conditions, while YOLOv7 is applied for accurate real-time vehicle detection and counting from video streams.

The detected vehicle data is transmitted through IoT communication to a central controller, where traffic density is analyzed. Based on the number of vehicles present in each lane, the system dynamically adjusts the duration of green signals to optimize traffic flow. This adaptive approach helps reduce unnecessary waiting times, improve vehicle throughput, and minimize congestion at busy intersections.

By integrating AI-based object detection with IoT-enabled communication, the system provides real-time responsiveness and efficient signal management. However, its effectiveness depends on reliable network connectivity and consistent camera performance to ensure accurate detection and timely signal adjustments.

E. *AI-Driven Smart Traffic Management System Using YOLO and OpenCV*

An adaptive traffic control solution that uses computer vision techniques to improve signal timing at road intersections. The system captures live video from traffic cameras and processes the frames using OpenCV for image preprocessing and analysis. For vehicle detection and counting, it employs YOLO, which enables accurate identification of vehicles in real time.

Based on the detected vehicle density in each lane, the system dynamically adjusts traffic signal durations instead of following fixed-time intervals. This allows the traffic lights to respond immediately to changing traffic conditions, reducing congestion and unnecessary waiting times. By integrating YOLO with OpenCV-based image processing, the project enhances detection accuracy and system responsiveness compared to traditional traffic management methods.

Although the system significantly improves traffic flow efficiency, its performance depends on camera quality,

lighting conditions, and processing capability to maintain real-time operation in practical environments.

III. PROPOSED SYSTEM

The proposed system is an IoT-enabled density based traffic light control system designed to manage traffic at a four-way junction using real-time vehicle detection and adaptive signal control. AI cameras capture live traffic, and the YOLO algorithm detects and counts vehicles in each lane, including emergency vehicles.

The detected traffic density data is sent to the ESP32, which automatically adjusts the green signal duration based on vehicle count. If an emergency vehicle is identified, the system instantly provides priority by switching that lane to green.

All traffic data and signal status are stored and monitored through Google Cloud Platform using Google Firebase Realtime Database. A mobile application allows users and authorities to view real-time traffic updates.

A. ESP32 Microcontroller

The main controller manages traffic signals and Wi-Fi communication.

B. AI Camera(4)

To capture live traffic from the North, South, East, and West sides

C. LED Lights(12)

Red, Yellow, and Green LEDs (3 per direction)

D. 5V Voltage Regulator

To provide stable power to the ESP32 and LEDs

E. Relay Module or LED Driver

To control high-power traffic LEDs

F. Power Supply Unit (12V)

G. Connecting wires and PCB/Breadboard

H. Arduino IDE

For programming the ESP32

I. Python with YOLO

For vehicle detection and counting

J. Google Firebase Realtime Database

For storing traffic data

K. Google Cloud Platform

For Cloud infrastructure

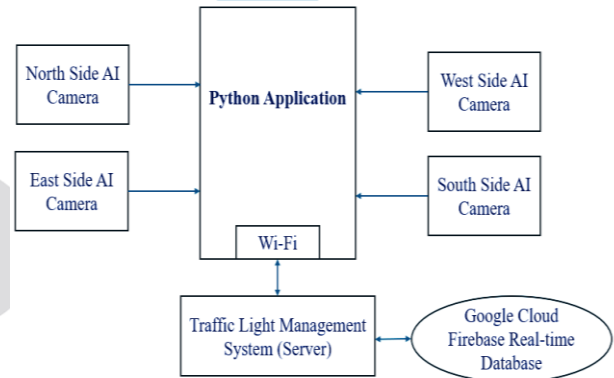
L. MIT App Inventor

For developing the Android monitoring app

the YOLO model. YOLO performs real-time object detection by identifying and classifying vehicles such as cars, buses, trucks, and motorcycles. It also detects emergency vehicles like ambulances and fire trucks. The system calculates vehicle count and density level for each lane and generates structured traffic data. This detection process ensures accurate and fast analysis suitable for real-time applications.

Fig 1. YOLO Python Application

The signal control unit is built around the ESP32, which acts as the central processing and decision-making component. The ESP32 receives vehicle density information through Wi-Fi communication. Based on predefined



threshold values and adaptive control logic, it dynamically determines the sequence and duration of traffic signals. If a lane has a higher vehicle density compared to others, the green signal duration is extended proportionally. Conversely, if traffic is minimal, the green time is reduced to prevent unnecessary delays. In the case of emergency vehicle detection, the controller immediately overrides normal operation and switches the corresponding lane to green while setting all other lanes to red. This ensures rapid and safe passage for emergency services.

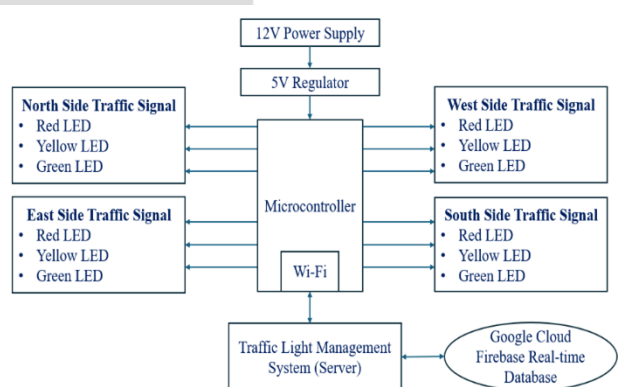


Fig 2. Traffic Signal Controlling System

IV. PROPOSED SYSTEM DESIGN

The proposed system presents an integrated IoT- and AI-based traffic management framework designed to intelligently control signal operations at a four-way intersection. The architecture consists of three major subsystems: the vehicle detection unit, the signal control unit, and the cloud-based monitoring unit. These subsystems work together to enable real-time traffic analysis, adaptive decision-making, and remote monitoring.

In the vehicle detection unit, AI cameras are positioned in all directions of the intersection to continuously capture live traffic video streams. The captured frames are processed using a Python-based application integrated with

The cloud-based monitoring unit enhances system scalability and transparency. Traffic density data, signal status, and emergency alerts are transmitted to Google Cloud Platform and stored in Google Firebase Realtime Database. This enables real-time visualization, historical data analysis, and remote supervision. A mobile application provides live updates of traffic conditions, signal timings, and emergency vehicle movement to both authorities and users. The cloud integration also allows future expansion toward smart city infrastructure.

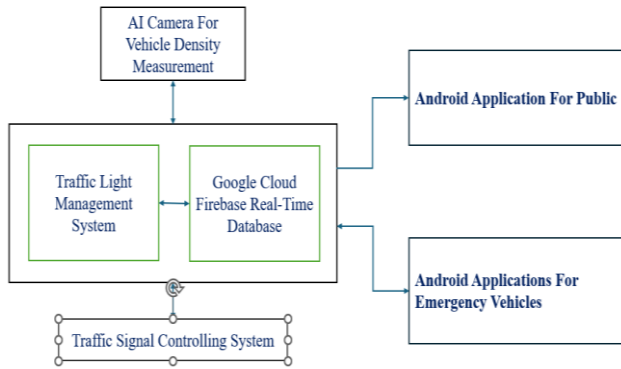


Fig 3. Traffic Management System

The overall system design emphasizes automation, adaptability, and cost-effectiveness. By combining AI-based vehicle detection, microcontroller-driven signal control, IoT communication, and cloud analytics, the proposed framework reduces traffic congestion, minimizes fuel consumption, lowers carbon emissions, and improves emergency response time. The design ensures scalability and can be extended to multi-intersection traffic networks for large-scale urban deployment.

V. CONCLUSION

The proposed IoT-enabled density based traffic light control system successfully demonstrates an intelligent and adaptive approach to modern traffic management. By integrating AI-based vehicle detection using the YOLO model with real-time IoT communication and microcontroller-based control through the ESP32, the system overcomes the limitations of conventional fixed-time traffic signals. It dynamically adjusts signal timing based on actual vehicle density and provides priority access for emergency vehicles, thereby improving road safety and response efficiency.

The incorporation of cloud services such as Google Cloud Platform and Google Firebase Realtime Database enables real-time monitoring, data storage, and remote accessibility through a mobile application. This enhances transparency, scalability, and future integration with smart city infrastructure.

Overall, the project offers a cost-effective, scalable, and practical solution for reducing traffic congestion, fuel

consumption, waiting time, and environmental pollution. The system lays a strong foundation for future enhancements such as multi-intersection coordination, predictive traffic analytics, and large-scale smart city deployment.

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