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Design & Implementation of AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection

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Abstract: *Rapid growth in urban traffic has created major challenges such as congestion, long waiting times, and delays for emergency services. To address these issues, an AI-based intelligent traffic signal system with emergency vehicle detection is developed for smarter road management. The system uses a camera to capture live traffic scenes and applies Artificial Intelligence methods to identify vehicles and estimate traffic density on each lane. Based on the detected traffic load, the signal timings are automatically adjusted to improve vehicle movement and reduce unnecessary delays. It also recognizes emergency vehicles like ambulances and instantly provides priority passage by switching the signal to green. The ESP32 microcontroller is used to control the traffic lights through wireless communication. This approach supports efficient traffic flow, reduces fuel wastage, decreases travel time, and enables quicker emergency response in smart city environments.*

Keywords: *Artificial Intelligence, Smart Traffic Control, ESP32, Vehicle Detection, Emergency Vehicle Priority, IoT, Computer Vision, Urban Traffic Management*

I. INTRODUCTION

Rapid urban growth has significantly increased the number of vehicles on roads, creating major traffic management problems in cities around the world. Conventional traffic light systems generally function using fixed time schedules and do not respond to actual traffic conditions in real time. Because of this, vehicles are often forced to wait unnecessarily at signals, even when other roads are clear, resulting in poor road utilization and higher congestion levels [1]. These drawbacks show the importance of developing a smarter and more responsive traffic control system.

Traffic congestion not only increases travel delays but also causes excessive fuel consumption and environmental damage. Vehicles standing idle at signals continue to burn fuel while remaining stationary, which leads to the release of harmful gases into the environment. The problem becomes more severe during rush hours when traffic volume changes rapidly and fixed-time signals cannot handle the varying demand efficiently. For this reason, intelligent traffic systems that can modify signal timings according to real-time vehicle density are necessary for sustainable urban growth [2].

A further issue with traditional traffic systems is the delay experienced by emergency vehicles such as ambulances, fire engines, and police vehicles. During emergencies, even a short delay can lead to serious outcomes, including loss of life or heavy property damage. Existing signal systems usually do not have the ability to recognize and prioritize such vehicles. Therefore, there is a strong need for an automated solution that can identify emergency vehicles and provide them immediate access through intersections [3].

Recent technological developments in Artificial Intelligence and Computer Vision have created effective solutions for complex real-world challenges. AI-powered object detection models such as YOLO can process live video streams to detect, classify, and count vehicles with high accuracy [7][8]. These technologies allow continuous traffic monitoring

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and support intelligent decision-making based on real-time information, reducing dependence on manual control and fixed signal timing methods [4].

The use of the Internet of Things further strengthens intelligent traffic management systems. IoT enables communication between cameras, processors, sensors, and controllers in an efficient manner. In this project, the ESP32 microcontroller performs an important function by receiving commands from the AI processing unit and operating the traffic lights accordingly. Its inbuilt Wi-Fi and Bluetooth features provide quick and dependable wireless connectivity, ensuring timely responses to changing road conditions [5].

The proposed AI-Based Intelligent Traffic Signal System integrates Artificial Intelligence, IoT, and embedded technology to develop an advanced traffic management model. A camera captures live road footage, which is analyzed using AI algorithms on a computer system. The processed results are then transmitted to the ESP32, which controls the traffic lights. According to traffic density and emergency vehicle presence, the system automatically adjusts signal timings. This method improves traffic movement and also ensures balanced green signal allocation for all lanes [6].

Apart from improving traffic flow, the system also supports public safety and environmental protection. By decreasing waiting time at intersections, it reduces unnecessary fuel usage and lowers carbon emissions. The emergency vehicle priority feature helps ambulances and other rescue vehicles reach destinations faster, which can be life-saving in urgent cases. Overall, this project represents an important step toward smart city development, where intelligent technologies improve transportation systems, safety standards, and efficient resource utilization [9][10].

II. PROBLEM STATEMENT

Rapid urbanization and the continuous rise in vehicle numbers have created major challenges for modern transportation systems, leading to heavy traffic congestion, long waiting times, and inefficient road usage. Conventional traffic signals operate on fixed time intervals without considering real-time traffic density, causing unnecessary delays on empty roads while crowded lanes do not receive enough green signal time. This poor traffic management increases fuel consumption, travel time, driver frustration, and air pollution due to vehicles remaining idle at intersections. In addition, existing systems are unable to detect and prioritize emergency vehicles such as ambulances, fire trucks, and police vehicles, resulting in dangerous delays during critical situations where every second is important. The lack of automation, real-time monitoring, and adaptive signal control in traditional systems highlights the urgent need for an intelligent traffic management solution that can dynamically respond to changing traffic conditions, improve traffic flow, reduce pollution, and ensure safer transportation.

III. OBJECTIVES

- To develop an AI-based intelligent traffic signal system for efficient traffic management
- To detect and count vehicles in real-time using a camera and computer vision techniques
- To classify traffic density as low, medium, or high based on vehicle count
- To dynamically control traffic signal timings according to real-time traffic conditions
- To identify emergency vehicles such as ambulances, fire trucks, and police vehicles
- To give priority to emergency vehicles by automatically turning the signal green

IV. LITERATURE SURVEY

1. R. Sharma et al. (2024), "AI-Driven Emergency Vehicle Detection for Signal Optimization," published in the International Journal of Intelligent Transportation Systems, proposed a vision-based traffic control system that uses YOLOv8 for real-time detection of normal and emergency vehicles. The system captures live traffic footage from road intersections and applies deep learning techniques to classify traffic density and identify emergency vehicles. Once an emergency vehicle is detected, the signal timing is automatically modified to provide priority passage.

2. P. Kumar and S. Verma (2022), "Smart Emergency Vehicle Management at Signalized Intersection Using Machine Learning," published in the Indian Journal of Science and Technology, focused on predicting ideal green signal

duration using machine learning methods. The proposed system used Convolutional Neural Networks (CNN) to examine traffic volume and determine optimized signal timing.

3. A. Patel et al. (2024), "Traffic Management in India Using YOLOv9 for Emergency Vehicle Detection," published in IEEE Access, introduced an advanced object detection model specially designed for Indian road conditions. By using the India Driving Dataset (IDD), the system successfully recognized different categories of vehicles and detected emergency vehicles even in difficult situations such as irregular lane discipline, dense traffic, and poor lighting conditions.

4. Abhirami J.S. et al. (2024), "Smart Traffic Management System with Emergency Vehicle Prioritization and Stolen Vehicle Detection Using Arduino Technology," published in the International Journal of Engineering Research & Technology (IJERT), presented a low-cost embedded traffic management solution. The system used sensors and an Arduino controller to manage traffic lights and identify emergency vehicles. In addition, it incorporated a stolen vehicle detection module, adding a security advantage to the traffic system.

5. S. Masanta et al. (2023), "An Edge-Assisted Robust Smart Traffic Management and Signalling System for Guiding Emergency Vehicles During Peak Hours," published on arXiv, proposed an edge-computing-based traffic management framework. The system processed live video data locally at road intersections, which minimized latency and enabled faster decision-making. It dynamically controlled signal timings according to congestion levels while also giving priority access to emergency vehicles. The study highlighted low deployment cost, easy scalability, and strong performance for smart city applications.

V. WORKING OF SYSTEM

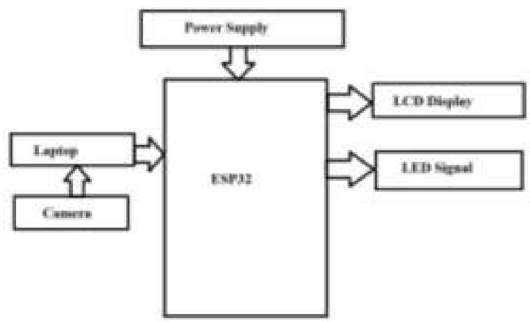

Fig 1: Design of the system

A. Input Data Acquisition

The intelligent traffic signal system starts with a camera module placed at the road intersection to capture live traffic video continuously. It monitors vehicle movement from different lanes and sends the real-time video feed to the computer system for further processing. The camera provides the visual input required for traffic analysis.

B. AI-Based Traffic Analysis

The laptop or computer works as the processing unit of the system. It analyzes the captured video using Artificial Intelligence and Computer Vision tools such as YOLO and OpenCV. The system detects vehicles such as cars, bikes, buses, and trucks, and counts them in each lane. Based on vehicle count, traffic density is identified as low, medium, or high. It also recognizes emergency vehicles like ambulances, fire trucks, and police vehicles.

C. Wireless Data Communication

After processing, the analyzed traffic information is sent wirelessly to the ESP32 microcontroller using Wi-Fi or Bluetooth communication. This ensures fast and real-time transfer of commands for traffic control.

D. Traffic Signal Control

The ESP32 acts as the central controller of the system. It receives commands and controls the traffic signals accordingly. If a lane has high traffic density, the green signal time is increased. If traffic is low, the green time is

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reduced. When an emergency vehicle is detected, the controller immediately turns the signal green for that lane to provide quick passage.

E. Output Display Section

The output unit consists of LED traffic lights and an optional LCD display. The LEDs represent Red for Stop, Yellow for Wait, and Green for Go. These lights are controlled through the GPIO pins of the ESP32. The LCD screen displays traffic density status, active lane signal, and emergency alerts for monitoring purposes.

F. Power Supply Unit

A regulated power supply is used to provide stable electrical power to the controller, LEDs, and other components. In some cases, battery backup can also be included for uninterrupted operation during power failure.

G. Continuous System Operation

The complete system works in a continuous loop where the camera captures traffic data, AI analyzes it, the ESP32 receives commands, and traffic signals are updated automatically. If communication fails, the controller can switch to default timing mode to maintain basic traffic control.

VI. SYSTEM DESIGN

The system design of the AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection is based on the integration of Artificial Intelligence (AI), Internet of Things (IoT), and embedded systems.

1. Camera (Input Unit)

The camera acts as the primary sensing device of the system. It continuously captures live video from the traffic intersection and sends frames to the processing unit.

Fig 2: camera

Specifications:

• Type: USB HD/Full HD Camera
• Resolution: 720p (minimum), 1080p (recommended)
• Frame Rate: 30–60 fps
• Interface: USB 2.0 / USB 3.0
• Field of View: 90°–120° wide angle
• Power Supply: 5V via USB
• Features: Auto-focus, low-light support

2. Laptop / Computer (AI Processing Unit)

The laptop functions as the brain of the system where all AI-based computations take place.

Specifications:

• Processor: Intel i5 or higher
• RAM: Minimum 8 GB
• Storage: 256 GB SSD or higher

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• Operating System: Windows/Linux
• Software: Python, OpenCV, YOLO, TensorFlow/PyTorch
• Connectivity: Wi-Fi / Bluetooth

3. AI Algorithm (Software Component)

The AI model is responsible for analyzing video frames and making intelligent decisions.

Specifications:
• Algorithm: YOLO (You Only Look Once)
• Frameworks: TensorFlow / PyTorch
• Detection Type: Real-time object detection
• Accuracy: High accuracy with low latency
• Output: Vehicle count, class labels, bounding boxes

4. Communication Module (Wi-Fi / Bluetooth)

The communication layer enables data transfer between the laptop and ESP32 microcontroller. It ensures real-time transmission of traffic data and emergency signals.

Specifications:
• Type: Built-in Wi-Fi & Bluetooth (ESP32)
• Protocol: IEEE 802.11 b/g/n, BLE 4.2
• Range: Up to 100 meters
• Data Transfer: Wireless (TCP/IP, Serial, MQTT optional)
• Speed: High-speed, low-latency communication

5. ESP32 Microcontroller (Control Unit)

Fig 3: ESP32

The ESP32 is the core controller that receives commands from the AI system and controls traffic signals accordingly. It executes the logic for signal switching, timing adjustment, and emergency override.

Specifications:
• Processor: Dual-core 32-bit (up to 240 MHz)
• Memory: 520 KB SRAM, 4 MB Flash
• Operating Voltage: 3.3V
• GPIO Pins: 30+
• Connectivity: Wi-Fi + Bluetooth
• Interfaces: ADC, PWM, UART, SPI, I2C
• Power Consumption: Low power, supports sleep modes

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6. Traffic Signal LEDs (Output Unit)

Fig 4: LEDs

LEDs are used to represent traffic signals (Red, Yellow, Green). They visually indicate the system's decisions based on traffic conditions and emergency detection.

Specifications:

- Type: RGB LED / Separate LEDs
- Voltage: 2V–3.3V per LED
- Current: ~20mA
- Colors: Red, Yellow, Green
- Control: GPIO pins via resistors
- Response Time: Instant switching

7. LCD Display (Monitoring Unit)

The LCD display is used to show real-time system information such as traffic density, signal status, and emergency alerts. It improves user interaction and monitoring.

Specifications:

- Type: 16x2 or 20x4 LCD
- Operating Voltage: 5V
- Interface: I2C / Parallel
- Display: Alphanumeric
- Function: Real-time status display

Fig 5: LCD display

8. Power Supply Unit

Fig 6: power supply

The power supply provides stable voltage and current to all components. It ensures continuous and safe operation of the system.

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Specifications:
• Input: 110–240V AC
• Output: 5V / 3.3V DC
• Current Rating: 2–5A
• Efficiency: 80–90%
• Protection: Overvoltage, overcurrent, short circuit

9. Connecting Components (Wires, Breadboard, PCB)

These components are used to establish electrical connections between different modules. They ensure proper circuit formation and system integration.

Specifications:
• Type: Jumper wires (Male-Male, Male-Female)
• Platform: Breadboard / PCB
• Purpose: Circuit connections and prototyping

VII. RESULTS

The developed prototype of the AI-Based Intelligent Traffic Signal System was successfully implemented and tested on a four-road intersection model. The system demonstrated effective traffic signal control by operating multiple LED traffic lights according to programmed logic through the ESP32 controller. The prototype accurately simulated real-time junction management by controlling red, yellow, and green signals for different lanes in sequence. The model structure clearly represents a smart traffic intersection with proper lane division and signal placement. During testing, the controller responded efficiently to timing changes and lane switching, showing reliable performance for adaptive traffic management. The successful hardware implementation confirms that the proposed system can reduce manual traffic control efforts, improve signal coordination, and serve as a cost-effective solution for future intelligent transportation systems.

Fig 7: Model prototype

IX. CONCLUSION

The AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection provides an effective solution for modern traffic management problems such as congestion, unnecessary delays, and poor emergency response. By combining Artificial Intelligence, Computer Vision, IoT, and the ESP32 controller, the system can monitor traffic density in real time and automatically adjust signal timings for smoother vehicle movement. The emergency vehicle priority feature ensures faster and safer passage for ambulances, fire trucks, and police vehicles during critical situations. The developed prototype successfully demonstrated reliable traffic light control and smart intersection management. Overall, the project offers a low-cost, scalable, and efficient approach toward smart city transportation systems with improved safety, reduced fuel consumption, and lower traffic congestion.

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