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# AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection

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**Abstract:** *This project presents an AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection designed to improve traffic management in urban areas. The system uses a camera to capture real-time traffic data, which is processed using Artificial Intelligence algorithms to detect and count vehicles. Based on traffic density, the system dynamically adjusts signal timings to reduce congestion and waiting time. Additionally, it identifies emergency vehicles such as ambulances and gives them priority by automatically turning the signal green. The ESP32 microcontroller is used to control traffic lights through wireless communication. This smart system enhances traffic efficiency, reduces fuel consumption, and improves emergency response time.*

**Keywords:** *Artificial Intelligence, Traffic Signal System, ESP32, Vehicle Detection, Emergency Vehicle Priority, IoT, Smart Traffic Management, Computer Vision.*

## I. INTRODUCTION

Urbanization has led to a rapid increase in the number of vehicles on roads, creating serious challenges in traffic management across cities worldwide. Traditional traffic signal systems operate on fixed-time intervals, which do not adapt to real-time traffic conditions. As a result, vehicles often experience unnecessary delays, even when other lanes are empty, leading to inefficient road utilization and increased congestion [1]. These limitations highlight the need for a smarter and more adaptive traffic control mechanism.

Traffic congestion not only affects travel time but also contributes significantly to fuel wastage and environmental pollution. Vehicles idling at traffic signals consume fuel without productive movement, releasing harmful emissions into the atmosphere. This situation worsens during peak hours, where fixed-time signals fail to manage fluctuating traffic volumes effectively. Therefore, intelligent systems that can dynamically adjust signal timings based on actual traffic density are essential for sustainable urban development [2].

Another major concern in existing traffic systems is the delay faced by emergency vehicles such as ambulances, fire trucks, and police vehicles. In critical situations, even a small delay can result in severe consequences, including loss of life or property. However, traditional systems lack the capability to identify and prioritize such vehicles. This creates an urgent need for a system that can automatically detect emergency vehicles and provide them with a clear path through intersections [3].

With the advancement of technology, Artificial Intelligence (AI) and Computer Vision have emerged as powerful tools for solving complex real-world problems. AI-based object detection algorithms, such as YOLO (You Only Look Once), can analyze real-time video feeds to identify and classify vehicles accurately[7][8]. These technologies enable the system to monitor traffic continuously and make intelligent decisions based on live data, eliminating the dependency on manual intervention or static timing mechanisms [4].

The integration of Internet of Things (IoT) further enhances the capabilities of intelligent traffic systems. IoT allows seamless communication between different components, such as cameras, processing units, and microcontrollers. In

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this project, the ESP32 microcontroller plays a vital role by receiving processed data from the AI system and controlling traffic signals accordingly. Its built-in Wi-Fi and Bluetooth features ensure fast and reliable communication, enabling real-time response to changing traffic conditions [5].

The proposed AI-Based Intelligent Traffic Signal System combines AI, IoT, and embedded systems to create a dynamic and efficient traffic management solution. The system captures live traffic data using a camera, processes it using AI algorithms on a laptop, and sends control signals to the ESP32 microcontroller. Based on traffic density and emergency detection, the system adjusts signal timings automatically. This approach not only improves traffic flow but also ensures fair distribution of green signal time among all lanes [6].

In addition to improving traffic efficiency, the system also contributes to public safety and environmental sustainability. By reducing waiting time at signals, it minimizes fuel consumption and lowers carbon emissions. The emergency vehicle detection feature ensures faster response times, which can save lives in critical situations. Overall, this project represents a step towards the development of smart city infrastructure, where intelligent systems enhance transportation, safety, and resource management [9][10].

## II. PROBLEM STATEMENT

Modern urban transportation systems are facing severe challenges due to the continuous growth in vehicle population and limited road infrastructure, resulting in frequent traffic congestion, long waiting times, and inefficient signal management. Conventional traffic signals operate on fixed time intervals without considering real-time traffic conditions, which leads to unnecessary delays when vehicles are forced to stop even on empty roads, while heavily congested lanes do not receive sufficient green time. This inefficiency increases fuel consumption, travel time, and air pollution, negatively impacting both the environment and commuters. Moreover, existing systems lack the intelligence to identify and prioritize emergency vehicles such as ambulances and fire trucks, causing critical delays during emergencies where every second is crucial. The absence of automation, real-time monitoring, and adaptive control in traditional systems highlights the need for a smart, intelligent traffic management solution that can dynamically respond to traffic conditions and ensure efficient and safe road usage.

## 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

The paper titled **"AI-Driven Emergency Vehicle Detection for Signal Optimization" (2024)** by R. Sharma et al., published in the International Journal of Intelligent Transportation Systems, presents a vision-based traffic control system using YOLOv8 for real-time vehicle and emergency vehicle detection. The system captures live video from road intersections and processes it using deep learning models to classify traffic density and detect emergency vehicles. When an emergency vehicle is identified, the system dynamically adjusts signal timing to prioritize its movement. The study highlights improved traffic flow efficiency and reduced waiting time, especially in congested urban environments, demonstrating the effectiveness of AI-driven adaptive traffic systems.

Another important study, **"Smart Emergency Vehicle Management at Signalized Intersection Using Machine Learning" (2022)** by P. Kumar and S. Verma, published in the Indian Journal of Science and Technology, focuses on machine learning-based prediction of optimal green signal timing. The system uses Convolutional Neural

Networks (CNN) to analyze traffic volume and predict signal durations. It also includes an emergency vehicle prioritization mechanism that significantly reduces delay time. Experimental results show a drastic reduction in emergency vehicle waiting time from several seconds to minimal delay, proving the reliability of machine learning models in real-time traffic applications.

The research work **"Traffic Management in India Using YOLOv9 for Emergency Vehicle Detection" (2024)** by A. Patel et al., published in IEEE Access, introduces an advanced object detection framework tailored for Indian traffic conditions. Using the India Driving Dataset (IDD), the system effectively detects multiple vehicle types and identifies emergency vehicles under complex conditions such as poor lane discipline and varying lighting. The system enables automatic signal override to create a green corridor for emergency vehicles. The results indicate improved detection accuracy and reduced congestion, making it suitable for deployment in developing countries.

A study titled **"Smart Traffic Management System with Emergency Vehicle Prioritization and Stolen Vehicle Detection Using Arduino Technology" (2024)** by Abhirami J.S. et al., published in the International Journal of Engineering Research & Technology (IJERT), proposes a cost-effective embedded system for traffic management. The system uses sensors and microcontrollers to control traffic signals and detect emergency vehicles. Additionally, it integrates a stolen vehicle detection feature, enhancing security. The research demonstrates improved traffic flow and reduced delays, especially for emergency vehicles, while maintaining low implementation cost suitable for small-scale applications.

Finally, the paper **"An Edge-Assisted Robust Smart Traffic Management and Signalling System for Guiding Emergency Vehicles During Peak Hours" (2023)** by S. Masanta et al., published on arXiv, presents an edge-computing-based traffic control system. The system processes video data locally at intersections to reduce latency and improve response time. It dynamically adjusts signal timing based on congestion levels and prioritizes emergency vehicles. The study emphasizes low-cost deployment and scalability for smart cities. Results show enhanced performance during peak hours and faster emergency vehicle movement, highlighting the importance of edge computing in intelligent traffic systems.

## V. WORKING OF SYSTEM

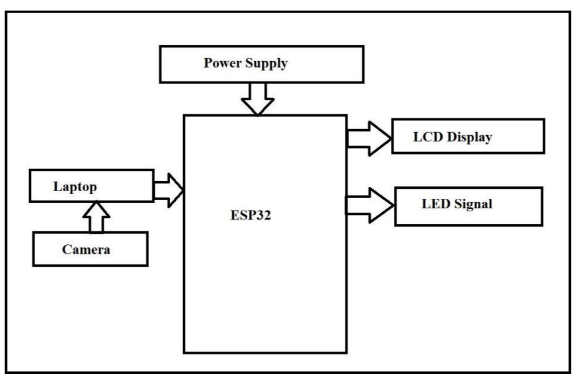


Fig 1: Design of the system

The block diagram represents the complete working structure of the intelligent traffic signal system. It shows how different hardware and software components are interconnected to perform real-time traffic monitoring, analysis, and control.

At the input stage, a camera module is used to capture live video of the traffic at the intersection. This camera continuously records the movement of vehicles from different lanes and sends the video feed to a laptop or computer system. The camera acts as the "eyes" of the system, providing real-time visual data required for processing.

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The laptop (AI processing unit) is the most important component, acting as the "brain" of the system. It processes the incoming video using advanced computer vision and deep learning algorithms such as YOLO and OpenCV. The system detects different types of vehicles like cars, bikes, buses, and trucks, and counts them in each lane. Based on this count, the system classifies traffic density into categories such as low, medium, and high. Additionally, the AI model is trained to identify emergency vehicles like ambulances, fire trucks, and police vehicles by recognizing their unique features. If an emergency vehicle is detected, a priority signal is generated immediately.

After processing, the analyzed data (traffic density level or emergency alert) is sent to the ESP32 microcontroller through wireless communication (Wi-Fi or Bluetooth). This communication is fast and ensures real-time response. The ESP32 acts as the central control unit of the system, receiving commands and executing them accordingly.

The ESP32 microcontroller processes the received data and controls the traffic signals. It is programmed using embedded C/C++ through the Arduino IDE. When the system detects high traffic in a particular lane, the ESP32 increases the green signal duration for that lane. Similarly, for low traffic, the green time is reduced to avoid unnecessary waiting in other lanes. In the case of an emergency vehicle, the ESP32 immediately overrides normal operation and turns the signal green for the respective lane, ensuring quick and safe passage.

The output section consists of LED traffic signals and an optional LCD display. The LED lights represent real-world traffic signals—Red (Stop), Yellow (Wait), and Green (Go). These LEDs are controlled by the ESP32 through its GPIO pins. The LCD display shows important system information such as traffic density status, current signal, and emergency alerts, providing a visual interface for monitoring.

A power supply unit is connected to provide stable electrical power to all components, especially the ESP32 and LEDs. It ensures uninterrupted operation of the system. In some setups, a battery backup may also be used for reliability.

The system operates in a continuous loop. The camera captures data, the AI processes it, the ESP32 receives commands, and the traffic lights are updated accordingly. This cycle repeats in real-time, making the system adaptive and efficient. If any failure occurs, such as loss of communication, the ESP32 can switch to a 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. The architecture is divided into input, processing, communication, control, and output layers. Each component plays a crucial role in ensuring real-time traffic monitoring, intelligent decision-making, and adaptive signal control.

### 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. The effectiveness of the system largely depends on the quality and positioning of the camera. It enables detection of vehicle movement, counting, and classification.


Fig 2: camera

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**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. It receives video input from the camera and processes it using computer vision and deep learning algorithms like YOLO and OpenCV. It detects vehicles, counts them, classifies traffic density, and identifies emergency vehicles.

**Specifications:**

- Processor: Intel i5 or higher
- RAM: Minimum 8 GB
- Storage: 256 GB SSD or higher
- 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. It detects objects (vehicles), classifies them, and determines traffic density levels. It also identifies emergency vehicles based on trained datasets.

**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)**

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

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- GPIO Pins: 30+
- Connectivity: Wi-Fi + Bluetooth
- Interfaces: ADC, PWM, UART, SPI, I2C
- Power Consumption: Low power, supports sleep modes

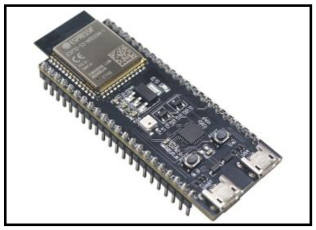

Fig 3: ESP32

**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.

**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 AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection was successfully implemented and tested in a prototype setup, demonstrating effective integration of camera input, AI processing, and ESP32-based signal control. The system was able to capture real-time traffic video and process it using computer vision algorithms to detect and count vehicles accurately. The communication between the laptop and ESP32 through Wi-Fi/Bluetooth worked efficiently, ensuring smooth data transfer and real-time response. The overall system operated in a synchronized manner with minimal delay, proving its capability for real-time traffic management.

The vehicle detection performance of the system was found to be highly reliable under normal lighting conditions. The AI model successfully identified multiple vehicle types such as cars, bikes, buses, and trucks using object detection techniques. It generated accurate bounding boxes and classifications, which helped in precise vehicle counting. However, slight inaccuracies were observed in challenging conditions such as low light, shadows, or partial occlusion of vehicles. Despite these minor limitations, the system maintained consistent performance suitable for practical applications.

The system effectively classified traffic density into low, medium, and high categories based on the number of detected vehicles in each lane. This classification enabled dynamic adjustment of signal timings, which is a major improvement over traditional fixed-time systems. In high-density conditions, the system extended the green signal duration, while in low-density conditions, it reduced the time to avoid unnecessary waiting. This adaptive behavior resulted in smoother traffic flow and better utilization of road space.

The dynamic signal control implemented through the ESP32 microcontroller showed excellent performance. The controller received real-time data from the AI system and adjusted the traffic signals accordingly. The green signal duration varied depending on traffic conditions, ensuring that heavily congested lanes were cleared efficiently while maintaining balance across all directions. This intelligent control significantly reduced waiting time and minimized traffic congestion at intersections.

One of the most significant outcomes of the system was the successful detection and prioritization of emergency vehicles. The AI model was trained to recognize emergency vehicles such as ambulances and fire trucks, and upon detection, the system immediately triggered an override mechanism. The ESP32 switched the corresponding lane to green, allowing the emergency vehicle to pass without delay. Once the vehicle cleared the intersection, the system automatically resumed normal operation. This feature highlights the system's potential to improve emergency response time and save lives.

The overall response time of the system was observed to be very low, making it suitable for real-time applications. The time taken from vehicle detection to signal switching was minimal, ensuring that the system could react quickly to dynamic traffic conditions. This fast response is particularly important for handling emergency situations and sudden traffic changes.

When compared to traditional traffic signal systems, the proposed system showed clear advantages. Unlike fixed-time systems, it adapts to real-time traffic conditions, reduces unnecessary delays, and improves overall traffic efficiency. Additionally, the ability to detect and prioritize emergency vehicles provides a significant improvement in safety and functionality.

Overall, the results confirm that the proposed system is efficient, reliable, and capable of intelligent traffic management. It successfully reduces congestion, optimizes signal timing, and enhances emergency vehicle movement. The integration of AI, IoT, and embedded systems makes it a promising solution for future smart city applications.

## IX. CONCLUSION

The AI-Based Intelligent Traffic Signal System with Emergency Vehicle Detection provides an effective solution to the limitations of traditional traffic control systems. By integrating Artificial Intelligence, Computer Vision, and IoT technologies, the system is capable of analyzing real-time traffic conditions and dynamically adjusting signal timings. This ensures efficient traffic flow, reduces congestion, and minimizes unnecessary waiting time at intersections.

The system successfully demonstrates accurate vehicle detection, traffic density classification, and adaptive signal control using the ESP32 microcontroller. One of its most significant contributions is the ability to detect and prioritize emergency vehicles, allowing them to pass through intersections without delay. This feature enhances public safety and can play a critical role in saving lives during emergency situations.

In conclusion, the proposed system represents a modern, intelligent, and practical approach to traffic management. It has strong potential for real-world implementation and can significantly improve urban transportation systems by making them smarter, safer, and more responsive.

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