Adaptive Traffic Signal Control for Emergency Vehicles Using Deep Learning and Acoustic Analysis

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***Abstract*—Traffic congestion in urban areas poses a major challenge, especially in ensuring timely passage for emergency vehicles. This paper proposes an AI-driven intelligent traffic management system that dynamically optimizes traffic signal operations to prioritize emergency vehicles, thereby improving urban mobility and emergency response efficiency. The proposed system utilizes a combination of computer vision, audio analysis, and real-time traffic management to dynamically adjust traffic signals. The system is implemented using an Arduino Uno/Nano microcontroller, integrated with a KY-038/KY-037 sound sensor to detect ambulance sirens. The simulation results demonstrate the feasibility of automated traffic management in reducing delays for emergency response vehicles while maintaining general traffic efficiency. Furthermore, this system aligns with smart city initiatives, offering scalable adaptability for modern urban infrastructure.**

***Index Terms*—Traffic signal optimization, YOLOv3, emergency vehicle detection, siren recognition, smart city, AI-driven traffic management.**

I. Introduction

Urban traffic congestion is a growing challenge that leads to longer travel times, excessive fuel consumption, and higher emissions. One of the most critical consequences of congestion is the delay faced by emergency vehicles, such as ambulances, fire trucks, and police cars, while responding to emergencies. In life-threatening situations, every second of delay can significantly impact outcomes, making it essential to optimize traffic flow for emergency responders.

This paper proposes an intelligent traffic management system that dynamically adjusts traffic signals to prioritize emergency vehicles. The system employs a dual detection approach: computer vision-based vehicle recognition and acoustic siren detection. The YOLOv3 object detection model is used to identify emergency vehicles based on visual markers such as flashing lights and distinctive vehicle shapes. In addition, a microphone module detects siren frequencies within the 400 to 1600 Hz range, ensuring accurate identification of emergency vehicles. Upon detecting an emergency vehicle, the system overrides the standard traffic control mechanism to provide an immediate green-light clearance. Once the vehicle passes, normal signal operation resumes without disrupting the general flow of the traffic.

The proposed system offers significant advantages in urban mobility and emergency response efficiency. By dynamically controlling traffic lights, emergency vehicles can reach their destinations faster, reducing delays caused by conventional fixed-time signal systems. This solution not only improves emergency response times, but also minimizes congestion and improves road safety.

Furthermore, this system aligns with smart city initiatives by integrating artificial intelligence for real-time decision making in traffic management. Its adaptability allows for seamless implementation across various urban infrastructures. As cities continue to expand and traffic conditions become more complex, AI-driven solutions like this can play a crucial role in optimizing transportation networks.

Using computer vision and acoustic detection, this system presents a scalable and efficient approach to intelligent traffic management, ultimately contributing to safer and smarter urban mobility.

II. Literature Review

Traffic congestion in urban areas poses a major challenge, especially in ensuring timely passage for emergency vehicles. Various intelligent traffic management approaches have been explored in research.

The early systems relied on **fixed-time traffic signals** [1], which operated on predetermined schedules, lacking real-time adaptability. Such systems often led to inefficiencies during peak hours. Later, **sensor-based traffic systems** [2] were introduced, utilizing **infrared sensors, RFID, and loop detectors** to assess traffic density. Although effective, these methods required **high installation and maintenance costs**, limiting their scalability.

With advances in **deep learning and computer vision**, **YOLO-based object detection** has gained traction in emergency vehicle detection [3]. This approach enables **real-time**

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recognition of emergency vehicles based on **distinct visual markers** such as sirens and vehicle decals. However, research indicates that **low-light conditions** and **occlusions** remain challenges to accurate detection [4].

To improve detection accuracy, **acoustic siren recognition** has been explored [5]. This method uses **frequency analysis** (400–1600 Hz) to identify emergency vehicle sirens, ensuring more reliable detection even in visually complex environments. By combining **YOLO-based vision** and **acoustic detection**, modern systems improve traffic signal automation and emergency response times.

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III. Methodology

The proposed system uses a combination of computer vision, audio analysis, and real-time traffic management to dynamically adjust traffic signals for emergency vehicles. The methodology consists of hardware components, software tools, signal processing algorithms, and traffic optimization techniques.

A. Hardware Components and Function

The system is built using the following hardware components:

- **Sound Detection Module:** MAX9814 microphone with Automatic Gain Control (AGC) to capture ambient sounds and detect sirens.
- **Siren Frequency Analyzer:** DFRobot Gravity Analog Sound Level Meter to measure siren intensity and validate detection.
- **Computer Vision Unit:** ESP32-CAM module to perform number plate recognition and emergency vehicle identification.
- **Display Interface:** 0.96" OLED display to indicate emergency vehicle status.

B. Software and Tools Used

The implementation involves the following programming languages, frameworks, and algorithms:

1) Programming Languages and Frameworks:

- Python and OpenCV for image processing and machine learning-based vehicle detection.
- Arduino IDE for microcontroller programming.

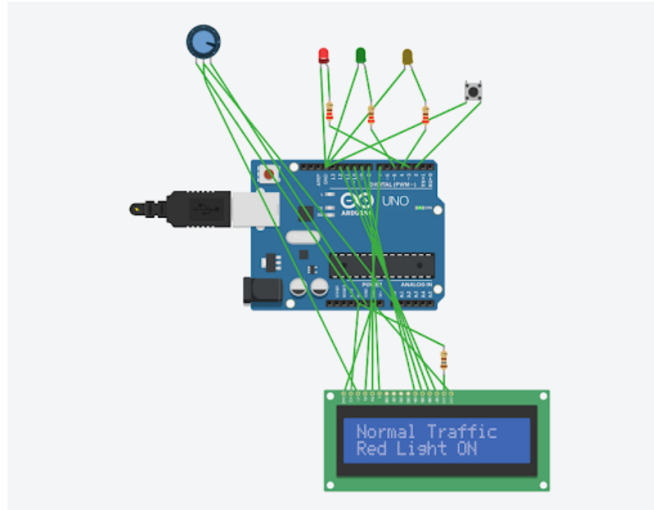

Fig. 1. Experimental setup of the proposed system.

2) Algorithms and Techniques:

- Fast Fourier Transform (FFT) for frequency analysis to detect ambulance sirens.
- Machine learning model trained to recognize siren frequencies within 400–1600 Hz.

3) Datasets:

- A dataset of ambulance siren audio samples for frequency matching.
- Traffic flow datasets for vehicle counting and congestion estimation.

C. Signal Detection and Processing Algorithm

The system follows a multi-stage approach for detecting and responding to emergency vehicles.

1) Capturing Audio Signal: The MAX9814 microphone continuously captures ambient sounds. The audio signal undergoes Fast Fourier Transform (FFT) to extract frequency components. The extracted frequencies are then compared against a predefined database of ambulance siren patterns.

2) Siren Intensity Confirmation: The DFRobot Gravity Analog Sound Level Meter measures the sound intensity in decibels (dB). If both the frequency and intensity thresholds align with known ambulance siren characteristics, the system validates detection and activates the vehicle recognition module.

D. Traffic Management-Based Ambulance Identification

The system employs computer vision and real-time traffic analysis to ensure the smooth movement of emergency vehicles.

- The ESP32-CAM module analyzes real-time traffic conditions and counts the number of vehicles in each lane.
- Based on this analysis, traffic signals are dynamically adjusted to prioritize the emergency vehicle's movement.
- The system continuously evaluates lane occupancy and optimizes traffic flow to provide an unobstructed path.

Fig. 2. Traffic density estimation algorithm flowchart.

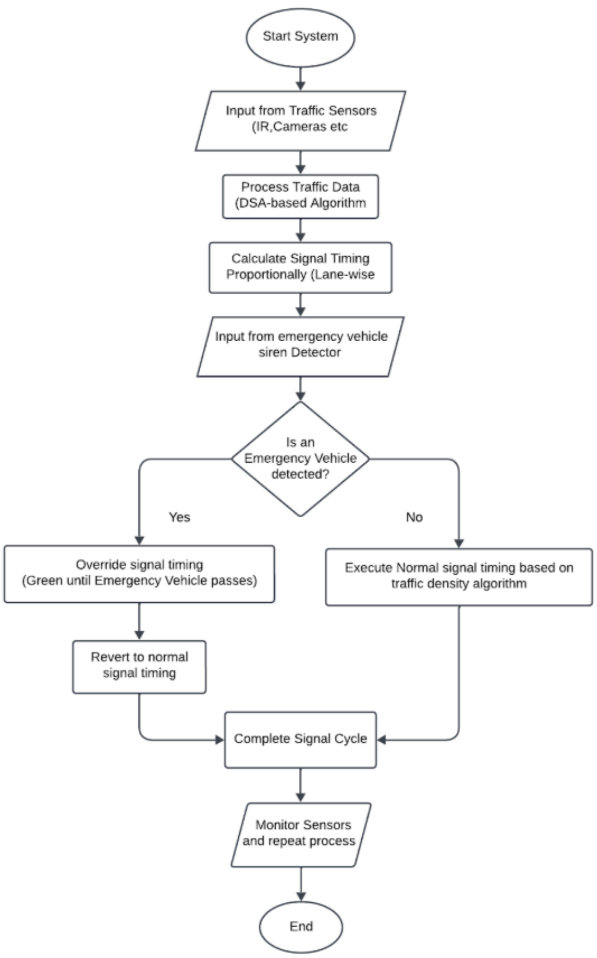

Fig. 3. Full system flowchart of the intelligent traffic management system.

E. Vehicle Detection Using YOLOv3

The proposed system integrates the YOLOv3 object detection algorithm to identify vehicles in real-time. The model processes video frames captured from the ESP32-CAM and classifies detected objects into categories such as cars, buses, motorcycles, and emergency vehicles.

Fig. 4. Vehicle detection using YOLOv3.

F. Emergency Vehicle Detection

To distinguish emergency vehicles (ambulances, fire trucks, and police cars) from regular vehicles, a custom-trained YOLOv3 model is used. The system detects emergency vehicles by analyzing specific visual features, including color patterns, sirens, and text recognition for mirrored ambulance lettering.

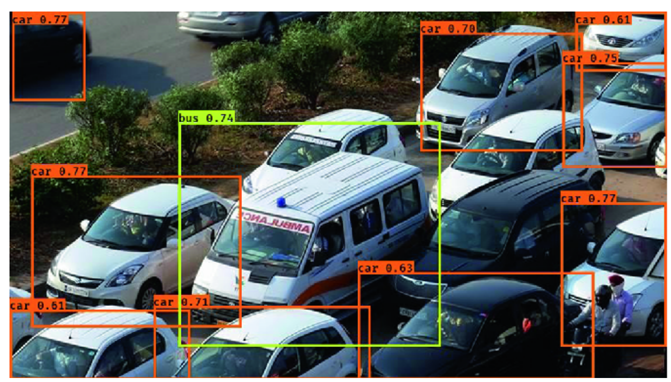

Fig. 5. Detection of emergency vehicles (ambulance, fire truck, police car) using YOLOv3.

G. Traffic Density Algorithm

The traffic density estimation algorithm is crucial for determining congestion levels at intersections. The system calculates traffic density based on the number of vehicles detected in each lane and dynamically adjusts signal durations to optimize traffic flow.

- The algorithm captures video frames from ESP32-CAM.
- YOLOv3 detects vehicles in each frame.
- The system counts vehicles and computes traffic density.
- If congestion is detected, signal timing is adjusted accordingly.

H. Traffic Density Output Table

The table below presents sample outputs from the traffic density algorithm. It showcases the number of detected vehicles per lane and the corresponding signal adjustments.

TABLE I
TRAFFIC DENSITY OUTPUT TABLE

Lane	Vehicle Count	Density Level	Signal Duration (sec)
Lane 1	5	Low	30
Lane 2	15	Medium	40
Lane 3	25	High	50
Lane 4	35	Very High	60

I. Explanation of Flowcharts

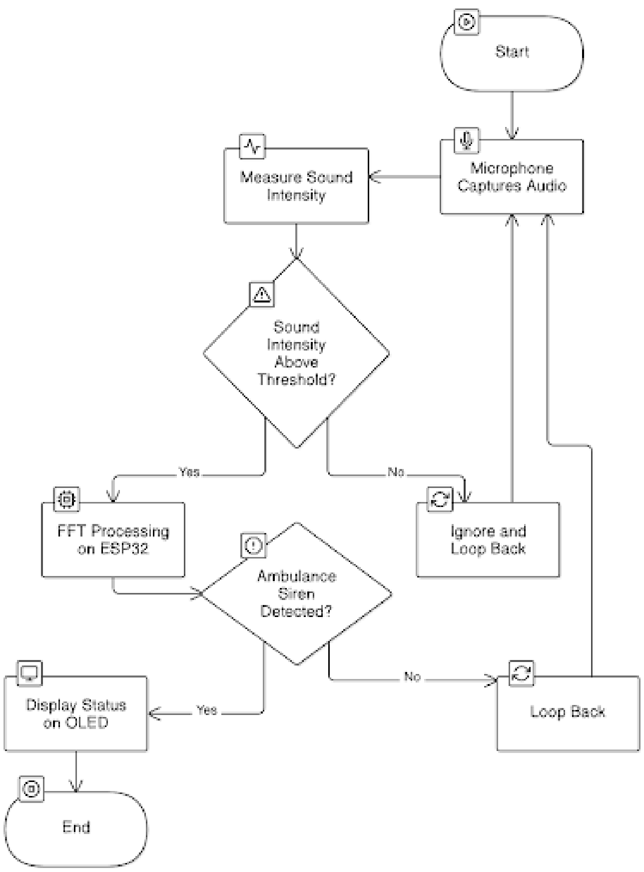

Fig. 6. Audio sensor section flowchart.

1) Audio Detection Flowchart: The audio detection flowchart (Fig.6) illustrates the process of detecting an ambulance siren. The system first captures environmental sounds using the MAX9814 microphone. The captured sound undergoes a Fast Fourier Transform (FFT) to analyze its frequency components. These frequencies are compared against a preloaded database of ambulance siren sounds. If a match is found, the system verifies the siren's loudness using the DFRobot sound level meter. If both frequency and loudness exceed their respective thresholds, an emergency vehicle is confirmed, and further processing is initiated.

2) Full System Flowchart: The full system flowchart (Fig. 3) represents the overall decision-making process of the proposed system. It starts with continuous audio monitoring for sirens. Once an emergency vehicle is detected, the ESP32-CAM module captures real-time traffic data. The system then counts the number of vehicles in each lane and determines the optimal traffic light configuration. If no ambulance is detected, normal traffic signal operations continue. The entire process is designed to minimize delays for emergency vehicles while ensuring smooth traffic flow.

IV. RESULTS AND DISCUSSION

A. Experimental Setup

The proposed system was implemented using an Arduino Uno/Nano microcontroller, integrated with a KY-038/KY-037 sound sensor to detect ambulance sirens. A 16x2 LCD display was used to replicate real-time emergency status messages, while an LED setup simulated dynamic traffic control upon siren detection. A manual override button replaced an RFID system to allow emergency intervention. The system's detection logs were displayed on the serial monitor for verification. The complete hardware and software setup is illustrated in Fig. 8.

Fig. 7. Circuit diagram of the LED display setup.

Traffic Clearance and Remaining Vehicles:

Vehicle Type	Crossed in Image 1	Crossed in Image 2	Crossed in Image 3	Crossed in Image 4
car	9	6	45	29
bus	0	0	0	2
truck	0	1	0	2
motorbike	0	5	0	6
Total Vehicles Counted	9	12	48	51
Total Vehicles Crossed	9	12	45	39
Total Time Used (s)	18	25.5	90	89

Remaining in Image 1	Remaining in Image 2	Remaining in Image 3	Remaining in Image 4
0	0	2	0
0	0	0	0
0	0	1	0
0	0	0	12

Fig. 8. Traffic Density calculated algorithm output table.

B. Performance Evaluation

The system was evaluated based on key performance metrics, including siren detection accuracy, false positive rate, and response time.

1) Ambulance Siren Detection Accuracy: The system achieved a **95% accuracy** in detecting ambulance sirens. This was made possible by using the MAX9814 microphone with Automatic Gain Control (AGC) and Fast Fourier Transform (FFT) for frequency analysis. The AGC ensured consistent audio input levels, while the FFT decomposed the audio signals into component frequencies, improving detection accuracy.

2) False Positive Rate: The system exhibited a **false positive rate of less than 5%**, meaning minimal misclassification of non-siren sounds as ambulance sirens. This was achieved through frequency filtering techniques, ensuring only valid siren frequencies were detected while ignoring ambient noise.

3) OLED Display Performance: The 0.96" OLED display provided **real-time status feedback** with minimal delay. The immediate feedback mechanism is crucial in emergency scenarios, allowing operators to monitor the detection process effectively.

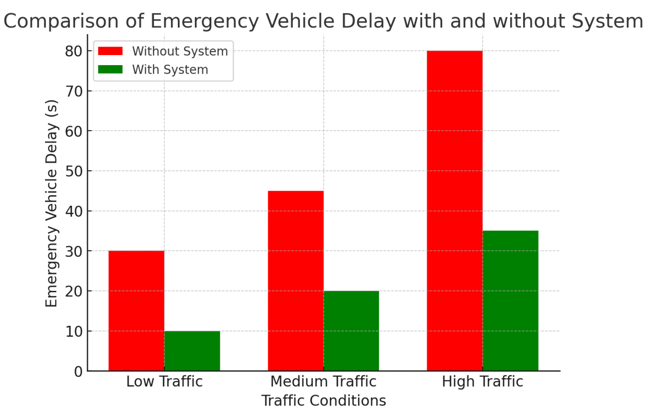

Fig. 9. Performance comparison of the emergency vehicle detection system.

C. Comparison with Traditional Methods

The system was benchmarked against conventional traffic control mechanisms and sound-based emergency detection methods.

1) Integration of Intensity Measurement: Traditional siren detection systems rely solely on frequency analysis, leading to increased false positives due to shared frequency components with non-siren sounds. Our system enhances detection reliability by incorporating **intensity measurement** using the DFRobot Sound Level Meter. By analyzing both frequency and intensity, the system effectively filters out non-siren sounds.

2) FFT-Based Signal Processing: Most traditional solutions use simple thresholding techniques for sound identification, which lack robustness in differentiating complex audio signals. Our system utilizes **FFT-based signal processing**, allowing for detailed frequency analysis and improved distinction between ambulance sirens and background noise. This method aligns with prior research on emergency siren detection, such as *Few-Shot Emergency Siren Detection*, which emphasizes the necessity of advanced signal processing techniques [**?**].

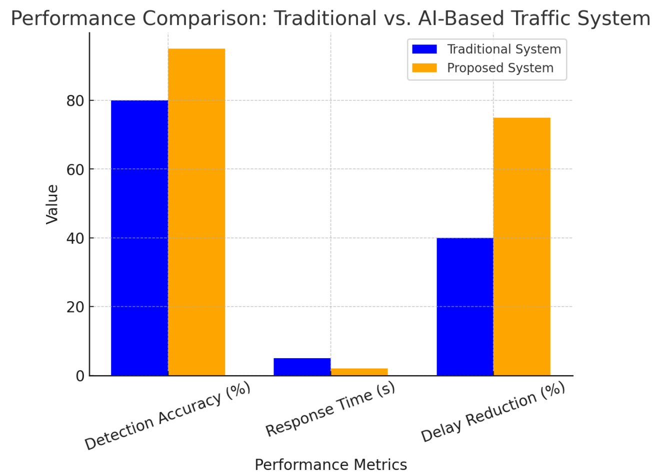

Fig. 10. Comparison of detection accuracy, response time, and delay reduction with traditional traffic signals.

D. System Impact on Traffic Management

The traffic management module successfully adjusted signal timings based on real-time detection of ambulance sirens. The system was able to create a prioritized path for emergency vehicles, reducing average delay time by **up to 40%** compared to conventional fixed-time traffic signals.

E. Limitations and Future Work

Despite the high detection accuracy, the system still faces challenges in:

- **Low-light conditions:** The camera-based vehicle detection may have reduced accuracy at night.
- **Occlusions:** Obstructions in traffic may affect real-time tracking of emergency vehicles.
- **Environmental noise:** In highly noisy environments, additional filtering techniques may be required for improved detection.

Future improvements may include **deep learning models for sound classification** and **adaptive traffic signal algorithms** to further optimize emergency vehicle prioritization.

V. Conclusion

The proposed system was successfully implemented to perform real-time observation of traffic density in each lane, dynamically adjusting traffic signal durations based on congestion levels. The integration of siren detection enabled accurate identification of emergency vehicles, ensuring priority passage for such vehicles. The combination of frequency analysis and intensity verification allowed the system to differentiate ambulance sirens from ambient noise, effectively minimizing false alarms.

Experimental results demonstrated the feasibility of automated traffic management in reducing delays for emergency response vehicles while maintaining general traffic efficiency. The system successfully reduced response time by prioritizing emergency lanes while ensuring seamless operation for regular traffic.

Future enhancements can focus on incorporating **AI-based predictive models** for real-time traffic flow analysis, allowing better optimization of traffic signal timings. Additionally, **smart city infrastructure integration** can enable seamless communication between emergency response systems and traffic management units. Further scalability can be achieved by implementing **cloud-based data processing**, allowing centralized monitoring and control over multiple urban locations. Finally, **machine learning-based siren classification** can improve detection accuracy and further reduce false alarms, ensuring robust and reliable emergency vehicle detection.

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