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AI-Driven Emergency Vehicle Detection for Signal Optimization Using YOLOv8

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Abstract: Traffic congestion in urban environments presents a persistent challenge, resulting in increased travel time, fuel consumption, and environmental degradation. Conventional traffic signal systems rely on fixed-time operations, which are often inadequate in responding to fluctuating traffic densities and emergencies. This study proposes an Intelligent Traffic Signal Optimization System leveraging YOLOv8, an advanced deep learning-based object detection algorithm, to enhance traffic management and emergency response. The system captures real-time traffic video footage and processes individual frames using OpenCV to improve the detection of emergency vehicles such as ambulances, fire engines, and police cars. YOLOv8 is employed to accurately identify these vehicles, enabling the dynamic adjustment of traffic signal durations based on real-time data. In emergency scenarios, the signal duration is extended automatically, ensuring the priority passage of essential services. This adaptive approach not only improves traffic flow efficiency but also reduces overall congestion. Integrating computer vision and artificial intelligence in this context highlights its potential contribution to sustainable urban planning.
Keywords: Emergency Vehicle Detection, YOLOv8, Intelligent Traffic Management, Deep Learning, Real-Time Video Processing.

I. INTRODUCTION

Urban traffic congestion remains a significant challenge, leading to increased travel times, fuel consumption, and environmental pollution. Traditional traffic signal systems, which operate on fixed-time schedules, often fail to adapt to real-time traffic fluctuations and emergencies, resulting in inefficiencies and delays. This study proposes an Intelligent Traffic Signal Optimization System that integrates computer vision and deep learning to improve urban traffic management. Using YOLOv8, a state-of-the-art object detection algorithm, and OpenCV for frame processing, the system analyzes real-time traffic footage to detect vehicles, focusing on identifying emergency responders such as ambulances, fire trucks, and police cars. Upon detection, the system dynamically adjusts traffic signal timings, prioritizing emergency vehicles by extending green light durations, thereby enabling quicker response times. This adaptive, AI-driven solution aims to optimize traffic. flow, reduce congestion, and contribute to sustainable urban development through smarter infrastructure.

II. RELATED WORK

fixed-time schedules and often fail to adapt to real-time traffic fluctuations or emergency scenarios, leading to increased congestion and delays. Recent computer vision and deep learning advancements have enabled more dynamic and intelligent traffic management solutions. Object detection models such as YOLO have demonstrated high accuracy and speed in identifying vehicles from real-time video feeds, including emergency vehicles like ambulances, fire trucks, and police cars. These AI-based approaches eliminate the need for additional hardware by directly analyzing video frames, allowing traffic signal control systems to respond more effectively to on-road conditions. Unlike existing systems that rely on external sensors or GPS for environmental awareness, our approach uses OCR techniques to extract temperature data from video frames, enabling automatic weather classification and corresponding signal time adjustments. While several studies focus either on traffic flow optimization or emergency vehicle prioritization, few integrate both aspects with environmental adaptation in a unified, real-time system, an area our proposed solution aims to address.

A. System Architecture and Methodology

The Emergency Vehicle Detection and Signal Time Management System is designed for real-time operation using computer vision and deep learning. It features an easy-to-use Tkinter-based graphical interface where users can upload datasets, train a YOLOv8 object detection model, and perform detection on images and videos. OpenCV processes each video frame, with the YOLOv8 model detecting emergency vehicles like ambulances, fire trucks, and police cars.

The system adjusts traffic signal durations based on these detections. It also estimates weather conditions using random temperature values, classifying them as foggy, rainy, or normal, each linked to a specific signal duration. If an emergency vehicle is detected, the system automatically extends the green light by 15 seconds. The system displays real-time video frames with bounding boxes and updated signal timings, providing an efficient, adaptive traffic management solution without relying on sensors.

B. System Workflow

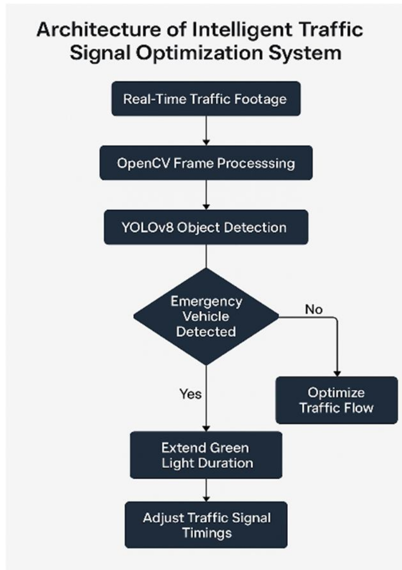

Figure 1. System Architecture

The Intelligent Traffic Signal Optimization System improves traffic flow using real-time video and deep learning. It captures live footage via surveillance cameras, processes each frame with OpenCV, and uses YOLOv8 to detect vehicles, especially emergency ones like ambulances and fire trucks. If an emergency vehicle is detected, the system extends the green light for its lane and adjusts other signals to maintain traffic balance. If not, it optimizes signal timings based on traffic density. This dynamic system enhances overall efficiency and speeds up emergency response.

III. METHODOLOGY

1) Real-Time Traffic Footage: The system captures live video feeds from traffic surveillance cameras at intersections, providing continuous real-time monitoring of traffic conditions. These feeds serve as the primary data source for detecting vehicles, including emergency vehicles. The footage is streamed to a processing unit for analysis and object detection.
2) OpenCV Frame Processing: The incoming video feed is divided into individual frames using OpenCV, an open-source computer vision library. These frames are preprocessed to enhance their quality for object detection. Preprocessing steps include resizing, color space conversion (from BGR to RGB), noise reduction, and image normalization. This ensures that the frames are consistent and clear for accurate analysis.
3) YOLOv8 Object Detection: Each processed frame is passed through a YOLOv8 (You Only Look Once, version 8) object detection model. This deep learning model is trained to detect and classify various objects, including ambulances, fire trucks, and police vehicles. YOLOv8 provides fast and accurate detection, making it suitable for dynamic traffic environments. It outputs bounding boxes, class labels, and confidence scores for detected objects.
4) Emergency Vehicle Detection: After object detection, a decision block evaluates whether an emergency vehicle is present in the current frame. If an emergency vehicle is detected, the system triggers an emergency response workflow. If no emergency vehicle is found, the system defaults to its standard operation mode, optimizing traffic flow based on predefined logic or adaptive control systems.
5) Extend Green Light Duration: When an emergency vehicle is detected, the system immediately extends the green light duration in the direction of the vehicle’s approach. This extension ensures the vehicle can pass through the intersection without delay. The system may also preemptively turn red signals green along the vehicle’s path, creating a 'green corridor' to prioritize its passage.

6) Adjust Traffic Signal Timings: The updated green light duration is sent to the traffic signal controller, adjusting the current signal cycle to accommodate the emergency vehicle. This may involve software-level communication with smart traffic light systems or hardware-level GPIO interfacing, depending on the system's setup. The goal is to adjust signal timings in real-time, without manual intervention, enhancing safety and reducing emergency response times.
7) Optimize Traffic Flow (No Emergency Vehicle): In the absence of emergency vehicles, the system continues with its standard traffic management logic. This includes optimizing signal timings based on real-time traffic data, such as congestion levels and vehicle density. Machine learning algorithms or rule-based methods are used to minimize waiting times and improve traffic flow across all directions.

IV. RESULT AND METRICS

```
Validating runs/detect/train/weights/best.pt...
Ultralytics 8.3.86 🚀 Python-3.11.11 torch-2.5.1+cu124 CUDA:0 (Tesla T4, 15095MiB)
Model summary (fused): 92 layers, 25,841,497 parameters, 0 gradients, 78.7 GFLOPs
                 Class     Images  Instances      Box(P          R      mAP50  mAP50-95): 100%|
                   all        160        147      0.766      0.739      0.781      0.657
             ambulance         36         38      0.937      0.921      0.968      0.834
           fire-engine         56         56      0.712      0.768      0.792      0.673
                police         39         53      0.648      0.528      0.582      0.465
Speed: 0.4ms preprocess, 10.3ms inference, 0.0ms loss, 4.7ms postprocess per image
Results saved to runs/detect/train
```

Figure 2. Accuracy

The emergency vehicle detection system is built using the YOLOv8 object detection model, which is trained to identify specific emergency vehicles such as ambulances, fire engines, and police cars. The model was trained over 30 epochs and demonstrated high detection accuracy, especially for ambulances. Performance metrics such as precision, recall, and mean Average Precision (mAP50) were consistently strong.

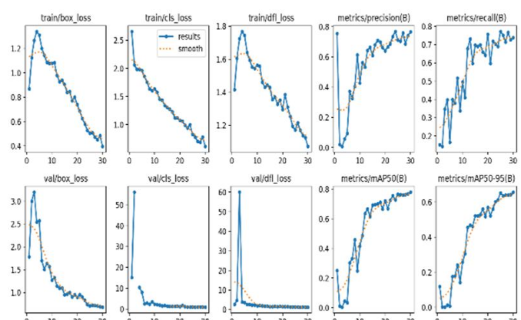

Figure 3. Training Graph

During training, key loss metrics—box loss, classification loss, and distribution focal loss—gradually decreased, indicating effective model learning and convergence. Validation losses showed a similar trend, confirming the model's ability to generalize well on unseen data. The evaluation metrics, including precision, recall, and mAP, improved steadily, with mAP50-95 exceeding 0.6 by the end of the training phase. This demonstrates the model's robustness in detecting emergency vehicles under varied conditions.

V. DISCUSSIONS

The experimental results demonstrate that emergency vehicle detection can effectively prioritize such vehicles in real time, particularly in traffic-congested areas. This is achieved through appropriate preprocessing and model training. In this subsection, we discuss the system's performance, as well as its advantages and disadvantages, based on empirical results.

A. *Merits of the Suggested System*

1) Real-Time Emergency Vehicle Prioritization: The system promptly identifies emergency vehicles and modifies traffic light timings to prioritize their passage, thereby reducing response times.

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2) Dynamic Signal Control: Traffic signals are continuously adjusted based on real-time traffic density, ensuring smoother traffic flow and alleviating congestion.
3) Sensor-Free Automation: By using video analysis powered by computer vision, the system removes the need for expensive physical sensors or road-installed hardware.
4) Adaptive Timing for Weather Conditions: The system adjusts signal durations in response to weather conditions, enhancing safety and traffic efficiency during fog, rain, or clear weather.
5) Enhanced Public Safety: By reducing delays for emergency vehicles, the system enables faster responses in critical situations
6) Cost-Efficient Infrastructure: Leveraging existing CCTV systems and software-driven processing makes the solution both affordable and scalable.

VI. FUTURE IMPROVEMENTS

Integrating GPS modules will enable accurate location tracking of detected emergency vehicles, improving response times and precision. Coordinating multiple cameras can expand the system's coverage. Linking with mobile apps or connected car systems can enhance automated detection by providing human reports for verification or early alerts.

VII. CONCLUSION

This project presents a real-time system that utilizes the YOLOv8 model to detect vehicles from CCTV footage. It also simulates different weather conditions, such as fog, rain, and clear weather, by generating random temperature values to replicate these environments. The system enhances traffic management by adjusting traffic signal timings to prioritize emergency vehicles, ensuring quicker response times. This functionality improves road safety, raises awareness, and promotes smoother traffic flow. YOLOv8 provides fast and accurate vehicle detection, making the system particularly effective for highway monitoring. With further advancements, this system holds the potential to significantly lower response times, save lives, and improve road safety overall.

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