JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Project Prometheus: Illuminating the Path to Efficient Traffic Flow

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Abstract– Urban environments face substantial challenges in managing traffic congestion, particularly in ensuring the swift transit of emergency vehicles such as ambulances. Traffic-induced delays can severely impede emergency response times, potentially resulting in fatal outcomes. Conventional traffic management systems often lack the necessary adaptability and real-time responsiveness to address these critical issues effectively. This paper introduces an innovative adaptive traffic signal control system designed to prioritize emergency vehicles and dynamically manage traffic congestion. Our system employs advanced detection methods to identify emergency vehicles with active sirens, subsequently adjusting traffic signals to create an unobstructed passage, thereby ensuring expedited transit. Furthermore, the system continuously monitors vehicle density at intersections, modifying signal timings to mitigate congestion. By leveraging IoT technology and sophisticated communication protocols, our approach significantly enhances emergency response times and optimizes overall traffic flow. Experimental results reveal notable improvements, establishing this system as a pivotal component of smart city infrastructure. This study advances the development of intelligent transportation systems, providing a robust solution to contemporary urban traffic challenges.

Keywords- IoT, Emergency Vehicles, Adaptive Traffic Signal Control, Raspberry pi, Smart City Infrastructure, Real-Time Traffic Management.

I. INTRODUCTION

Urbanization and the rapid rise in vehicular populations have intensified traffic congestion, posing critical challenges to urban mobility. A key issue is the delay experienced by emergency vehicles, such as ambulances and fire trucks, at signalized intersections. These delays can be life-threatening, as timely response is essential for saving lives. Traditional traffic systems, reliant on fixed-time signals, fail to adapt to real-time conditions or prioritize emergency vehicles, resulting in inefficiencies and dangerous delays. To address these challenges, modern cities require adaptive traffic management systems that integrate advanced technologies.

The Internet of Things (IoT) and machine learning present promising solutions for smart traffic control. IoT-enabled signals can communicate with vehicles and other intersections, optimizing traffic flow. Machine learning models like YOLOv8, known for high-precision object detection, can detect emergency vehicles in real-time. When integrated with IoT systems, this technology allows traffic signals to dynamically adjust, turning green for emergency vehicles and clearing their path.

Beyond emergency response, traffic density management is essential for reducing congestion. Dynamic signal timings based on real-time traffic data outperform static systems, helping alleviate bottlenecks. By combining emergency vehicle prioritization with traffic density management, cities can enhance both safety and efficiency.

This project proposes an adaptive traffic signal control system using IoT devices, such as Raspberry Pi controllers and cameras, along with YOLOv8 for vehicle detection. When an emergency vehicle is detected, the corresponding signal turns green, and others switch to red, ensuring an uninterrupted path. Simultaneously, traffic density is monitored to optimize flow and minimize congestion.

By integrating advanced technologies, the system offers a comprehensive solution to urban traffic management, promoting smarter cities. This approach not only ensures timely emergency response but also improves overall traffic efficiency, ultimately saving lives and enhancing urban living standards.

II. Literature review

In recent years, the development of smart traffic signal systems that cater to emergency vehicles has gained significant traction due to the increasing need for efficient traffic management in urban areas. Many studies have explored innovative technologies and methods to address traffic congestion while ensuring the rapid movement of emergency vehicles. One such study by [1] highlights a system that optimizes traffic signals for emergency vehicles in resource-constrained environments. Their approach uses real-time traffic data to detect congestion and prioritize emergency vehicles by adjusting traffic lights accordingly. This method helps reduce response times for ambulances, police vehicles, and fire trucks, thereby improving safety in urban areas. The researchers focused on low-cost hardware solutions to ensure scalability and affordability, making it viable for deployment in developing countries.

Similarly, [2] propose a smart traffic signal system for emergency vehicles that utilizes RFID tags and Arduino-based microcontrollers. Their solution allows emergency vehicles to communicate with traffic signals, ensuring that the lights turn green as the vehicle approaches. By integrating signal processing and electromagnetic induction, their system ensures smooth and uninterrupted movement of emergency vehicles through crowded intersections. The use of low-cost components like RFID tags makes this solution highly feasible for real-world implementation, especially in areas with constrained financial resources. The study successfully demonstrates how even basic technological components can be combined to create an effective traffic management solution.

TABLE I. OVERVIEW OF PREVIOS TECHNOLOGIES

Technology	Description	Application
RFID-based Smart Traffic Signals	Use of RFID technology to detect emergency vehicles and change traffic signals accordingly.	Improves traffic management efficiency by prioritizing emergency vehicles, particularly in developing countries.
Microcontroller-based Systems	Microcontrollers integrated with sensors and RFID to automate traffic signals for emergency vehicle detection.	Cost-effective and efficient in managing traffic signals, particularly in urban settings with limited resources.
Raspberry Pi & Image Processing	Raspberry Pi used as the main controller for adaptive traffic signal systems, utilizing image processing for vehicle detection.	Provides a scalable and flexible solution for traffic management, adapting in real-time to vehicle density and emergency scenarios.
Predictive Models & Queueing Analysis	Utilizes predictive modelling and queuing analysis for traffic condition prediction and signal control.	Improves traffic safety and efficiency by anticipating and managing congestion before it occurs.

Another notable contribution comes from [5], who developed a machine learning-based traffic congestion detection and control system. Their system incorporates artificial intelligence to predict traffic patterns and manage signal timings accordingly. By using historical traffic data, the model can learn and adapt to changing traffic conditions, ensuring that signals operate efficiently in both normal and emergency situations. This approach not only reduces congestion but also helps in the rapid clearance of pathways for emergency vehicles. The authors emphasize the importance of data analytics in optimizing traffic flow, making their system highly adaptive to real-world conditions.

The IoT-based traffic signal management system proposed by [7] further enhances the scope of smart traffic systems. By leveraging IoT devices, their system collects real-time data from traffic sensors and sends it to a centralized system for analysis. The system can adjust traffic signals dynamically based on the current flow of traffic and detect emergency vehicles to give them priority. This centralized control architecture, combined with cloud-based analytics, offers a scalable solution that can be deployed in large urban environments, ensuring seamless traffic management.

[10] extend this concept by incorporating big data analytics into smart traffic signal control. Their study highlights how large datasets collected from multiple traffic sensors can be used to train machine learning models that predict traffic congestion. The system also includes provisions for detecting emergency vehicles and clearing their pathways by adjusting signal timings. By utilizing big data, their system becomes more accurate and responsive, enabling real-time traffic management.

In a more advanced implementation, [12] present an AI-driven traffic congestion control system that uses Convolutional Neural Networks (CNNs) to analyse traffic data. The system can detect emergency vehicles using camera footage and adjust traffic signals accordingly. This deep learning-based approach offers a high level of accuracy in detecting traffic patterns and emergency vehicles, making it ideal for use in complex urban traffic environments.

[15] explored the communication between emergency vehicles and traffic lights through a dedicated communication system. Their study demonstrates how emergency vehicles can transmit signals to traffic lights, instructing them to change to green, allowing the vehicle to pass through intersections without delay. This system effectively reduces the time spent at traffic lights, enhancing the overall efficiency of emergency service.

Further progress has been made through the application of machine learning and predictive modelling in traffic management. By incorporating machine learning algorithms and image processing techniques, traffic systems can now dynamically adjust to real-time conditions, such as vehicle density, while also prioritizing emergency vehicles. These adaptive systems, often implemented using devices like Raspberry Pi, are capable of significantly reducing traffic jams and optimizing signal control based on current road conditions. Additionally, predictive models have been used to anticipate traffic congestion, allowing for pre-emptive adjustments to traffic signals, which further enhances the efficiency of traffic management. This hybrid approach, combining real-time data with predictive analytics, offers a robust solution for the complex demands of urban traffic control.

III. Methodology

The system architecture of the adaptive traffic signal control system is designed to ensure efficient traffic management, with a special focus on prioritizing emergency vehicles like ambulances. The architecture is centred around a combination of hardware components, software algorithms, and communication protocols that work together to detect, classify, and respond to traffic situations in real-time.

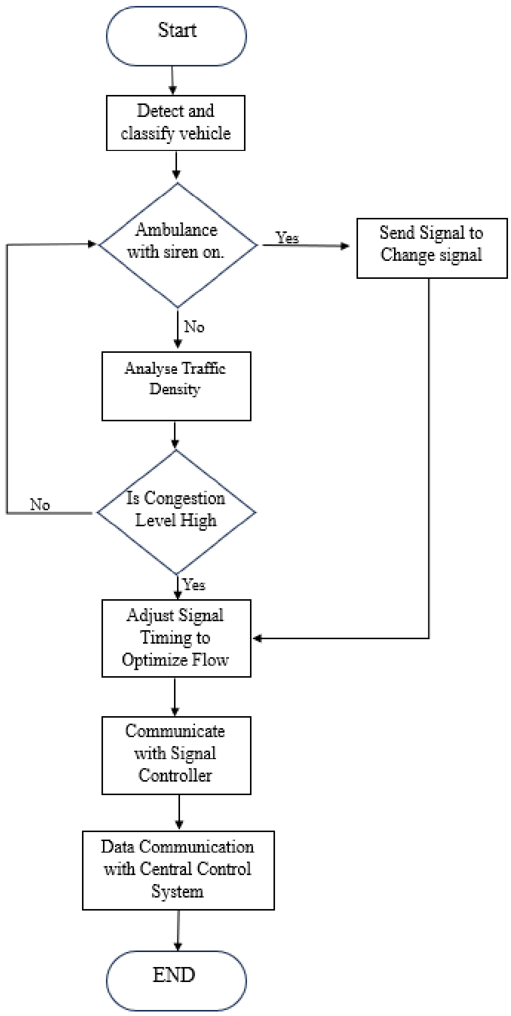

Fig 1. flowchart

A. *Hardware Components*

The core of the system is a Raspberry Pi, chosen for its balance of processing power, size, and cost-effectiveness. The Raspberry Pi acts as the main controller, orchestrating the various tasks within the system. It interfaces with cameras installed at strategic locations around the intersection. These cameras are the primary source of data, capturing live video feeds of the traffic situation. The video feeds are then processed in real-time to detect vehicles and identify emergency vehicles, particularly ambulances.

Additionally, the system includes the traffic signal controllers, which are responsible for changing the lights based on the decisions made by the Raspberry Pi. The Raspberry Pi communicates with these controllers to adjust the timing of traffic signals, ensuring that emergency vehicles are given priority.

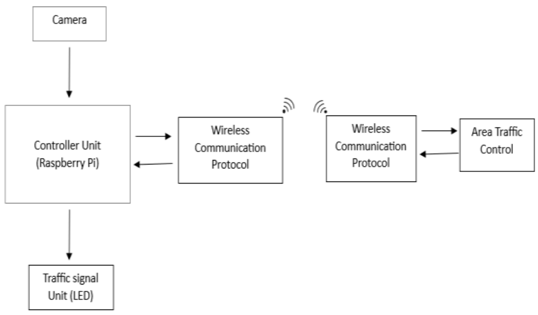

Fig 1. Block diagram for EV system.

B. Software Architecture

The software architecture is primarily built around the YOLOv8 object detection model, which is optimized for real-time performance. YOLOv8 has been trained with a custom dataset that includes various types of vehicles, specifically focusing on ambulances with different states (siren-on and siren-off). The model processes the video frames captured by the cameras, identifying and classifying vehicles within the field of view.

Once a vehicle is detected, the software checks the classification results. If an ambulance is detected with its siren on, the system immediately prioritizes this vehicle, triggering an adaptive control flow. This involves pre-empting the regular traffic signal cycle to allow the emergency vehicle to pass through the intersection as quickly as possible. If an ambulance is detected but with its siren off, the system may treat it as a regular vehicle, depending on the overall traffic density.

For other vehicles, the system assesses the traffic density by counting the number of vehicles in each lane. Based on the density, the system dynamically adjusts the timing of green, yellow, and red lights to optimize traffic flow. This dynamic adjustment helps in reducing congestion, especially during peak hours.

C. Communication Protocols

The communication between the Raspberry Pi, the cameras, and the traffic signal controllers is handled using secure and low-latency communication protocols. These protocols ensure that the system can operate in real-time, with minimal delays between detection and action. The Raspberry Pi continuously receives video feeds, processes the data, and sends control signals to the traffic light controllers.

In the future, this architecture can be extended to include, where equipped vehicles can directly communicate with the traffic signal system. This would allow for even faster response times and better coordination between different elements of the traffic management system.

D. Communication Between Single Traffic Junction and Central Control System

In the proposed Area Traffic Control (ATC) system, communication between individual traffic junctions and the central control system is crucial for coordinated traffic management. Each traffic junction is equipped with a communication module that allows it to send real-time data to the central control system. This data includes information on traffic density, the presence of emergency vehicles, and the current status of traffic signals. The central control system processes this data and can send override commands to individual junctions if needed, ensuring that traffic flow is optimized across the entire area.

The communication system is designed to be robust and scalable, using wireless communication protocols such as LoRa or 5G to ensure reliable data transmission even in dense urban environments. The central control system also includes a user interface that allows traffic operators to monitor traffic conditions in real-time and make manual adjustments if necessary. This centralized control ensures that traffic management is efficient and responsive to changing conditions.

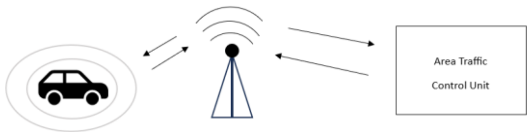

Fig 2 Vehicle to Infrastructure Communication

IV. Future scope

In the future, the project can be expanded by integrating each traffic signal junction pole with a central control unit. This centralized system will dynamically manage traffic signals across multiple junctions to create an optimized passage for emergency vehicles. By leveraging real-time data from sensors and cameras installed at each junction, the central control unit will analyse traffic conditions and vehicle density, enabling coordinated control of multiple signals. This will ensure that an uninterrupted, green corridor is provided to emergency vehicles, significantly reducing their response time. Furthermore, the system can incorporate predictive algorithms to anticipate the movement of emergency vehicles, allowing pre-emptive traffic clearance across the city. This integration will not only enhance the efficiency of emergency response but also improve overall traffic management by reducing congestion and minimizing delays.

V. Result

The results of this project underscore the effectiveness of utilizing advanced computer vision techniques, specifically the YOLOv8 model, in enhancing urban traffic management, particularly for prioritizing emergency vehicles. The model, trained on a custom dataset, achieved a notable accuracy of 81% in detecting emergency vehicles, which is reflected in the confusion matrix where most vehicles were correctly classified. However, the system did encounter challenges with certain misclassifications, particularly between categories like siren-off and background, indicating potential areas for improvement. The precision-recall analysis further illustrates this, with the "Ambulance" class achieving a strong precision score of 0.714, while the "Siren-On" class lagged with a precision of 0.534, suggesting that specific detection scenarios could benefit from additional refinement.

Fig 3. Detection of ambulance with or without siren on.

1. Confusion Matrix:

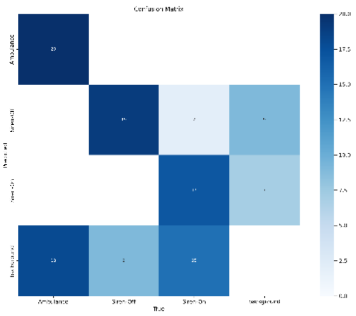

Fig 4. Confusion Matrix

Above confusion matrix provides a detailed view of the model's classification performance across the four classes: Ambulance, Siren-Off, Siren-On, and Background. It highlights the number of correct and incorrect predictions, where values along the diagonal represent successful classifications. The model demonstrates strong performance in identifying ambulances, with 20 correct predictions, but encounters challenges in differentiating between Siren-Off and Background, as indicated by multiple off-diagonal misclassifications. The overlap between Siren-On and Siren-Off categories reflects difficulties in distinguishing these subtle variations, hinting at potential areas for model improvement through further fine-tuning or enhanced feature extraction.

2. Precision-Recall Curve

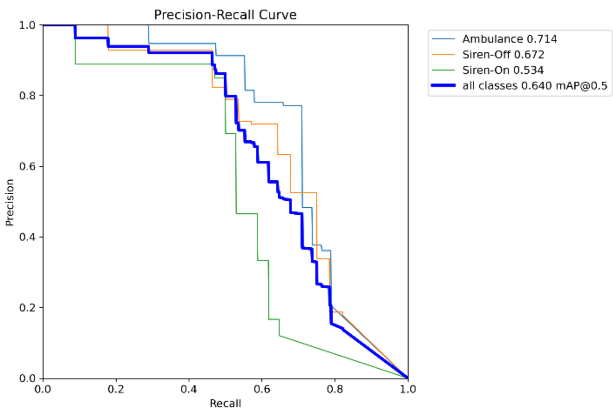

Fig 5. Precision-Recall Curve

The above precision-recall (PR) curve evaluates the model's performance by illustrating the balance between precision and recall across different thresholds. Ambulance detection shows superior performance with a PR score of 0.714, reflecting high confidence and accuracy. However, Siren-Off and Siren-On classes exhibit lower PR scores, 0.672 and 0.534 respectively, indicating the model's relative difficulty in handling siren-related classes.

VI. Conclusion

this project successfully developed an adaptive traffic control system that prioritizes emergency vehicles using advanced object detection techniques with YOLOv8 and a custom dataset. The integration of real-time vehicle density analysis and emergency vehicle detection ensures efficient traffic management, reducing response times for ambulances. Despite achieving significant accuracy, further improvements, such as enhancing siren detection and optimizing performance in complex urban scenarios, could enhance system reliability. This innovative solution addresses critical challenges in urban traffic management, demonstrating its potential for practical implementation in smart cities to improve emergency response and traffic flow.

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