© July 2025| IJIRT | Volume 12 Issue 2 | ISSN: 2349-6002

Smart IoT-Based Traffic Signal Control System with Emergency Vehicle Detection

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Abstract **- In today's rapidly urbanizing world, traffic congestion poses a critical challenge to city infrastructure, public safety, and emergency response systems. One of the most pressing issues is the delay faced by emergency vehicles—particularly ambulances—due to rigid, pre-timed traffic signals and unresponsive traffic management systems. In such scenarios, even a few minutes of delay can be the difference between life and death.**

This paper presents the design and implementation of a Smart IoT-Based Traffic Signal Control System that dynamically adjusts signal timings in real-time to prioritize the movement of emergency vehicles. The system leverages embedded hardware (such as Arduino or Raspberry Pi), a variety of sensors (including RF modules, infrared, sound, and image-based systems), and intelligent control algorithms to detect the presence of an ambulance from a significant distance and manage traffic flow accordingly. Once an approaching emergency vehicle is detected, the system initiates a green corridor by altering signal phases at multiple junctions to ensure swift and safe passage.

Beyond basic detection, the system incorporates adaptive signal logic that considers current traffic density and congestion levels using sensor data, enabling a context-aware response. This approach is scalable and can be integrated into broader smart city infrastructures via IoT communication protocols, offering centralized monitoring and future integration with cloud-based analytics platforms.

The proposed system also lays the groundwork for incorporating anomaly detection algorithms and machine learning models to enhance responsiveness in unusual traffic scenarios. Emphasis is placed on secure data handling, modularity, and low-cost implementation, making the system viable for developing urban areas.

Experimental simulations and prototypes demonstrate a significant reduction in ambulance wait times and overall intersection congestion. The system is designed to be extensible, cost-effective, and efficient, providing a foundation for future intelligent transport systems aimed at reducing mortality rates, improving urban mobility, and enhancing emergency preparedness.

I. INTRODUCTION

Urban transportation systems are becoming increasingly strained due to the rapid growth in population, vehicle density, and unplanned urbanization. As cities expand, the number of vehicles on the road has escalated, leading to frequent traffic congestion, extended travel times, environmental pollution, and increased road stress. Traditional traffic signal systems operate on static timing mechanisms that are unable to respond to real-time changes in traffic flow, especially during peak hours or unexpected events.

One of the most critical challenges resulting from this outdated infrastructure is the delay faced by emergency vehicles, particularly ambulances. In emergency scenarios such as medical crises or accidents, every second matters. However, ambulances are frequently forced to wait at intersections or maneuver through congested traffic, risking the safety of both the patient and other road users. Studies have shown that even a delay of a few minutes in emergency medical response can significantly impact survival rates and patient outcomes.

Modern traffic control systems must therefore evolve beyond conventional fixed-cycle lights and incorporate intelligent, real-time decision-making capabilities. The rise of the Internet of Things (IoT) presents an opportunity to embed intelligence into urban infrastructure by enabling devices to communicate, sense, and act based on dynamic environmental data. In the context of traffic management, IoT allows for the integration of various sensors, processors, and communication modules to create smart systems that can adapt signal timings based on actual traffic conditions and emergency priorities.

This paper introduces an IoT-based Smart Traffic Signal System specifically designed to detect and prioritize emergency vehicles like ambulances. The system employs sensor technologies (such as RF modules, infrared sensors, sound sensors, or vision-based recognition), microcontrollers (Arduino or Raspberry Pi), and adaptive control algorithms to detect the approach of an ambulance and immediately modify traffic signals to facilitate its passage through intersections. By creating a green corridor—clearing the route ahead of the ambulance—the system significantly reduces emergency response time and minimizes human intervention.

Additionally, the system is designed to be scalable and modular, making it suitable for both small-scale deployments and future integration into comprehensive smart city networks. It can operate independently or be connected to a central monitoring dashboard, providing authorities with real-time updates on traffic behavior and emergency vehicle movements. The system also sets the foundation for future enhancements using machine learning and anomaly detection to predict traffic patterns, identify irregular congestion events, and further optimize performance.

II. MOTIVATION

Modern cities are experiencing unprecedented growth in population and vehicle density, leading to chronic traffic congestion and delays in urban transportation networks. Among the many consequences of this congestion, the delayed movement of emergency vehicles—particularly ambulances—is one of the most critical and life-threatening. When ambulances are unable to reach hospitals in time due to poorly managed intersections or non-cooperative traffic flow, the resulting delays can directly affect patient survival rates.

Conventional traffic signal systems, based on fixed timing logic, are designed with uniformity rather than adaptability. These systems operate on pre-defined cycles regardless of the real-time traffic situation or the presence of emergency vehicles. As a result, ambulances often get stuck in intersections where signal priority cannot be dynamically reassigned. This not only prolongs emergency response times but also puts the lives of patients, healthcare providers, and other road users at risk.

The motivation for this project arises from the urgent need to reduce such delays by rethinking how traffic signals respond to critical scenarios. With the advent of affordable and efficient IoT technologies, it is now feasible to design smart traffic systems that can sense, communicate, and react to the environment in real time. Sensors such as RF modules, infrared detectors, sound sensors, and computer vision systems can detect ambulances long before they reach intersections. These detections, when fed into microcontrollers like Arduino or Raspberry Pi, can trigger immediate changes in signal logic to give right-of-way to the emergency vehicle.

Moreover, the current emphasis on building smart cities necessitates infrastructure that is both intelligent and life-saving. A system that can prioritize ambulances in real time aligns perfectly with this vision, offering not only improved urban traffic management but also enhanced emergency responsiveness. It empowers cities to make better use of technology for public welfare while promoting safety, efficiency, and innovation in civic systems.

In addition, this project has the potential to be expanded and integrated with future advancements in machine learning, cloud computing, and edge processing. It serves as a foundational step toward autonomous traffic control that can learn from past behavior, predict future traffic conditions, and dynamically adapt to ensure optimal flow for all users—especially those in life-critical situations.

Thus, the motivation behind this work is twofold: to harness modern IoT technologies for intelligent traffic control, and to solve a deeply human problem—saving lives by minimizing ambulance delays through smart signal prioritization.

III. PROBLEM STATEMENT

Urban traffic congestion remains a persistent challenge in modern cities, causing significant delays and inefficiencies in transportation systems. Traditional traffic control systems rely on static signal timing that operates on fixed schedules, without considering real-time traffic conditions or the presence of high-priority vehicles such as ambulances. As a result, emergency vehicles often face delays at intersections, which can have life-threatening consequences in critical medical situations.

The primary shortcoming of existing systems is their lack of adaptability. These systems are unable to:

- Detect and identify approaching emergency vehicles in real time.
- Prioritize or preemptively adjust traffic signals to allow uninterrupted passage.
- Respond dynamically to fluctuating traffic density, especially in unpredictable or emergency scenarios.
- Integrate seamlessly with modern smart city and IoT infrastructure.

Due to these limitations, ambulances and other emergency services are often forced to navigate congested traffic manually, relying on sirens and driver cooperation, which is neither reliable nor efficient. This manual dependency increases the risk of accidents and further delays, undermining the core purpose of emergency response: timely intervention.

Furthermore, conventional systems do not incorporate real-time data analytics, anomaly detection, or predictive modeling that could improve decision-making during emergencies. They also lack secure and scalable architecture, which is necessary for deployment in future smart city frameworks.

Thus, the key problem this project addresses is:

How can we develop a smart, real-time, IoT-based traffic signal control system that can detect and prioritize emergency vehicles like ambulances, dynamically manage signal timings based on traffic flow, and reduce delays during critical medical emergencies?

This problem requires an integrated solution that combines sensing technologies, embedded systems, real-time decision-making, and secure IoT communication. Solving it will significantly improve emergency response times, reduce intersection congestion, and pave the way for scalable, intelligent urban infrastructure.

IV. OBJECTIVES

The primary objective of this project is to design and implement a Smart IoT-Based Traffic Signal Control System that effectively detects emergency vehicles—specifically ambulances—and dynamically adjusts traffic signal timings to facilitate their swift and uninterrupted movement through intersections.

To achieve this overall goal, the following specific objectives are defined:

1. Real-Time Emergency Vehicle Detection

- Develop a reliable method to detect the presence and approach of ambulances using a combination of IoT sensors such as RF modules, sound sensors (for siren detection), or computer vision systems.
- Ensure early detection from a significant distance (e.g., 100–500 meters) to allow timely preemption of signals.

2. Dynamic Traffic Signal Control

- Design an adaptive control logic that can override standard signal cycles when an emergency vehicle is detected.
- Implement real-time signal phase adjustments to create a green corridor for ambulances by turning signals green ahead of the vehicle's path while stopping cross-traffic.

3. Prioritization of Emergency Routes

- Ensure that the detected ambulance is given highest priority at all affected intersections, minimizing stoppage time.
- Automatically return to normal signal timing once the ambulance has passed, preventing unnecessary disruption to regular traffic flow.

4. Integration of IoT and Embedded Systems

- Utilize low-cost embedded hardware (e.g., Arduino, Raspberry Pi) to collect, process, and transmit sensor data.
- Enable communication between traffic controllers and detection modules using IoT protocols for real-time coordination.

5. Reduction of City-Wide Congestion

- Enhance overall traffic efficiency by reducing waiting times at signals during emergencies.
- Implement intelligent logic that also takes current traffic density into account while adjusting signal durations.

6. Scalability and Smart City Compatibility

- Build a modular and scalable architecture that can be integrated into existing or future smart city infrastructures.
- Provide a framework for cloud-based dashboards, remote monitoring, and future integration of machine learning for prediction and anomaly detection.

By fulfilling these objectives, the project aims not only to improve ambulance response times but also to contribute to safer and more efficient urban traffic management systems. The solution is intended to be deployable in both developing and developed urban contexts with minimal infrastructural upgrades.

V. SCOPE OF THE STUDY

- The system is designed to detect ambulances and provide them with signal priority at traffic intersections using IoT-based sensors and controllers.
- Focuses on real-time traffic signal adaptation based on emergency vehicle detection.
- Involves integration of hardware (Arduino/Raspberry Pi) with input sensors like RF, IR, sound, or image recognition modules.
- Covers a prototype-level implementation for one or more intersections, with scalability for city-wide deployment.
- Aims to provide a modular framework that can be integrated with existing or future smart city infrastructure.

VI. SIGNIFICANCE OF THE STUDY

- Helps reduce ambulance travel and response time, potentially saving lives in critical situations.
- Enhances overall urban traffic efficiency by dynamically managing congestion during emergencies.
- Demonstrates a cost-effective, scalable smart traffic solution using affordable IoT components.
- Lays a strong foundation for future work involving AI, anomaly detection, and predictive traffic control.
- Supports smart city initiatives by integrating real-time intelligence into essential public infrastructure.

VII. REVIEW OF LITERATURE

A. Approaches to Emergency Vehicle Priority in Traffic Management

Numerous studies have attempted to design intelligent traffic signal systems to improve urban mobility, particularly by integrating sensors and adaptive control. However, the prioritization of emergency vehicles such as ambulances remains an underexplored yet critical area. Traditional systems either rely on fixed timers or basic density-based algorithms, lacking the ability to detect and respond dynamically to high-priority vehicles.

Aworinde et al. proposed a prioritized traffic control system using Arduino-based logic to alter signal timings based on traffic volume. While effective in enhancing general flow, the system lacked real-time emergency detection, limiting its usefulness during critical medical emergencies. Similarly, Chong et al. utilized image processing for dynamic signal adjustments, but their study focused solely on traffic density without addressing ambulance detection.

B. Sensor-Based and Visual Detection Techniques

Modern traffic control systems are increasingly incorporating computer vision, RF modules, and sound sensors to improve real-time responsiveness. Djahel et al. introduced an RFID- and GPS-based system integrated with Vehicular Ad Hoc Networks (VANETs) to prioritize emergency vehicles. Their model reduced ambulance delay times but required heavy infrastructure investment, limiting deployment in low-resource areas.

Jimenez-Moreno et al. employed a combination of deep learning (ResNet-50) and fuzzy logic to recognize emergency vehicles and adjust signal timings. This hybrid system improved recognition accuracy and decision-making but was sensitive to image quality and parameter tuning. Likewise, Vani et al. developed a density-based dynamic signal model that prioritized emergency vehicles via image processing; however, the effectiveness heavily depended on environmental conditions and algorithm precision.

C. Adaptive Control Systems with AI and Fuzzy Logic

The use of adaptive systems has shown promise in recent literature. Zerroug et al. implemented the Adaptive and Dynamic Smart Traffic Light System (ADSTLS), which leveraged computer vision to reduce average waiting times and enable fault-tolerant control. James Omina, on the other hand, proposed a fuzzy logic-based system to manage urban traffic more efficiently. While both studies improved signal responsiveness, neither fully addressed real-time ambulance preemption.

D. Integration of IoT and Embedded Hardware

The integration of IoT technologies has been instrumental in developing scalable, real-time traffic solutions. Systems based on microcontrollers such as Arduino and Raspberry Pi enable modular and cost-effective designs. These devices facilitate the processing of sensor inputs (e.g., RF, IR, camera feeds) and enable decentralized decision-making at intersections. Yet, many implementations fail to leverage IoT's full potential for multi-junction coordination and

E. Limitations of. Literature Survey

Despite significant advancements in intelligent traffic systems, a thorough review of existing literature reveals several limitations, particularly in the context of emergency vehicle prioritization using real-time, IoT-enabled solutions. These limitations are summarized as follows:

- Lack of Real-Time Ambulance Detection: Most studies, such as those by Aworinde et al. and Chong et al., focus on general traffic volume or density-based control. These systems do not incorporate any mechanism to detect emergency vehicles like ambulances in real time, which is crucial for critical response situations.
- Limited Use of IoT and Embedded Systems: Although some models use microcontrollers like Arduino for signal control, few integrate IoT components for real-time communication, remote monitoring, or scalable deployment. This limits their application in smart city environments.
- Dependence on Vision-Based Detection: Several works, including those by Jimenez-Moreno et al. and Vani et al., rely heavily on image processing and computer vision techniques. These systems are prone to errors under low-light conditions, adverse weather, or obstructed camera views, reducing their reliability.
- High Infrastructure Requirements: Systems such as the RFID-GPS-VANET-based approach by Djahel et al. demand advanced infrastructure and high implementation costs, which may not be feasible in developing regions or small towns.
- Lack of Integration Across Multiple Intersections: Many models operate independently at a single junction and do not consider coordinated signal control across multiple intersections, which is essential for creating green corridors for ambulances.
- Limited Fault Tolerance and Scalability: While some systems are effective in controlled conditions, their fault tolerance and scalability in real-world urban environments are often not validated. Approaches like ADSTLS (Zerroug et al.) show promise but are complex to implement and maintain.
- Absence of Secure Communication and Data Handling:
  Very few systems address cybersecurity or data integrity in the communication between traffic nodes and central controllers. This can pose risks in real-time, missioncritical systems.

These limitations collectively highlight the need for a more practical, real-time, and IoT-integrated traffic control system that can effectively prioritize emergency vehicles with minimal infrastructure dependency and high reliability. The proposed system in this study aims to bridge these gaps.

VI. METHODOLOGY

The proposed system is designed to intelligently control traffic signals in real time, with a special emphasis on prioritizing emergency vehicles—specifically ambulances—using IoT-based sensing and embedded system technologies. The methodology consists of multiple interconnected stages including data collection, signal processing, embedded control logic, output actuation, and prototype implementation.

A. Data Collection

The initial phase of the system involves gathering real-time data from various sources. Two primary categories of data are collected: (i) emergency vehicle presence, and (ii) traffic density.

Emergency vehicle presence is identified using an RF transmitter mounted on the ambulance. This transmitter sends out a unique frequency signal that is received by RF receivers positioned near traffic junctions. Upon receiving the signal, the system identifies that an ambulance is approaching. Additional methods—such as sound sensors for siren detection and camera modules integrated with object recognition algorithms (e.g., YOLO or ResNet)—can also be used to enhance detection capabilities. In advanced implementations, GPS data from ambulances may be utilized to estimate their real-time location and speed for dynamic route management.

Traffic flow data is collected using infrared (IR) or ultrasonic sensors, which are capable of counting the number of vehicles approaching an intersection from various directions. This allows the system to adapt signal duration based on real-time traffic density.

B. Data Filtering and Preprocessing

To ensure reliability, all input data is passed through a preprocessing layer. Sensor readings are filtered to eliminate noise and false positives, especially in the case of sound and RF signals which may be affected by environmental interference. Only signals matching predefined emergency vehicle patterns are processed further. The system also incorporates a priority flagging mechanism to differentiate between regular traffic data and high-priority ambulance signals.

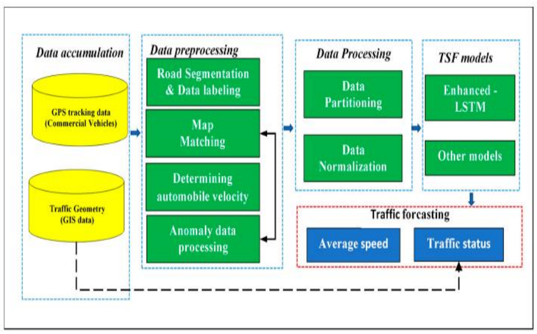

Fig 1.Data Preprocessing

C. Embedded Control Logic

At the core of the system lies an embedded control logic executed on a microcontroller platform such as Arduino or Raspberry Pi. The logic is responsible for monitoring inputs from sensors, processing them, and making real-time decisions regarding traffic signal operation.

Upon detection of an ambulance, the system initiates an override mechanism that disrupts the regular signal cycle. The direction from which the ambulance is approaching is given a green signal, while all other directions are halted with red signals to ensure uninterrupted passage. Once the ambulance clears the intersection—determined either by elapsed time or distance tracking—the system safely restores normal signal operation. In the absence of ambulance detection, the system follows a default cyclic timer-based logic.

This embedded logic enables the system to perform dynamic traffic signal control without human intervention, significantly reducing response time and enhancing emergency vehicle mobility.

D. Output Control and Signal Actuation

Based on the decisions made by the embedded controller, the traffic lights are actuated using GPIO output pins connected to LED-based signal representations. These signals mimic real-world traffic lights, cycling between red, yellow, and green states. When an emergency vehicle is detected, the lights change immediately to accommodate its passage, overriding the default signal sequence.

E. IoT Integration and Communication

For smart city applications, the system can be integrated into an IoT infrastructure that enables remote monitoring and control. Sensor data and signal status can be transmitted to a central dashboard via secure communication protocols such as MQTT over SSL or HTTP with encryption. This allows traffic management authorities to track the movement of emergency vehicles, override signals manually if needed, and collect historical data for analysis and optimization.

F. Prototype Implementation

To validate the proposed methodology, a prototype is developed using scaled-down road models, Arduino controllers, and sensors. Model vehicles simulate ambulance movement, and LEDs are used to represent traffic signals. The system is tested under various scenarios to evaluate its responsiveness, accuracy, and efficiency in handling emergency vehicle detection and traffic control.

The prototype helps in identifying potential technical challenges and serves as a proof of concept for scaling the system to real-world applications.

G. Evaluation Metrics

The performance of the system is evaluated based on several key metrics:

- Detection Accuracy: The system's ability to correctly identify ambulance signals.
- Response Time: Time taken to switch signals after detection.
- System Reliability: Stability during continuous operation.

- Traffic Optimization: Impact on normal traffic flow before and after ambulance passage.
- Scalability: Ease of replicating the system across multiple intersections.

This methodology provides a comprehensive, modular, and scalable solution for real-time traffic management with ambulance priority, combining IoT technologies with embedded systems and sensor integration.

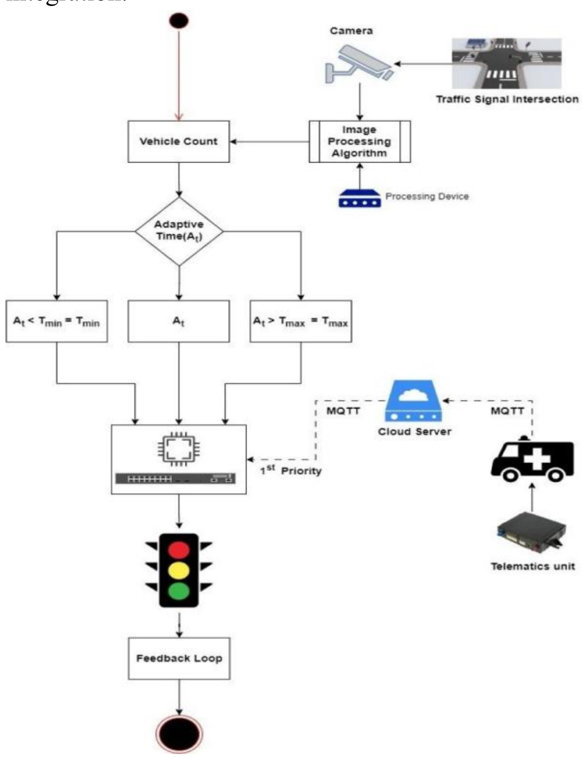

Fig 2. Methodology

IX. PROPOSED SYSTEM

A. System Overview

The proposed smart traffic control system is engineered to improve urban traffic management by prioritizing emergency vehicle movement, especially ambulances, through real-time signal control. The system adopts a modular architecture consisting of detection units, embedded processing controllers, signal actuation mechanisms, and optional IoT-based dashboards. By detecting emergency vehicles before they reach an intersection and dynamically adjusting traffic signals, the system ensures that ambulances receive immediate right-of-way without disrupting overall traffic stability. This solution is both scalable and cost-effective, aligning with modern smart city initiatives.

B. Ambulance Detection Module

The detection of emergency vehicles is critical to the functionality of the system. The primary method employed is radio frequency (RF) transmission. An RF transmitter, fixed inside the ambulance, emits a unique signal when active. RF receivers positioned at strategic points near intersections continuously listen for this signal. Upon detection, the receiver sends a signal to the processing unit indicating the presence and direction of an approaching ambulance.

To enhance reliability, the system can incorporate additional detection methods. Sound sensors can identify ambulance sirens based on their acoustic signature, while vision-based techniques can use machine learning algorithms—such as YOLO or ResNet—on live camera feeds to recognize ambulance vehicles by their design, color, or emergency markings. In advanced configurations, GPS modules installed in ambulances can provide real-time location data for predictive routing and traffic clearance in advance.

C. Traffic Density Sensing

In parallel with ambulance detection, the system also monitors the volume of traffic approaching the junction from all directions. This is achieved through the deployment of infrared (IR) or ultrasonic sensors. These sensors count the number of vehicles and estimate congestion levels. This information is used not only to optimize normal signal timings when no emergency is present, but also to determine the safest and most efficient way to accommodate an ambulance without causing additional congestion in other lanes.

D. Processing and Control Logic

The control unit forms the decision-making core of the system. It is implemented using embedded platforms such as Arduino or Raspberry Pi, which are programmed to interpret sensor inputs and execute corresponding control actions. In the absence of emergency signals, the system follows a traditional cyclic signal logic based on timers or traffic volume.

When an ambulance is detected, the system interrupts the standard signal cycle and initiates a preemption protocol. The lane corresponding to the ambulance's direction is given an immediate green signal, while all other directions are halted to ensure a clear and safe path. The green phase remains active until the ambulance passes the intersection, which is estimated using timing thresholds or additional positional sensors. After passage, the system restores the normal traffic cycle, taking into account any residual traffic build-up.

E. Signal Actuation Mechanism

The output from the control unit directly interfaces with the traffic lights installed at the intersection. Using relay modules or GPIO control pins, the system sends commands to switch between red, yellow, and green lights. In the prototype phase, this is achieved using LED indicators. In a real-world deployment, the same signals can be routed to full-scale traffic signal controllers.

The signal actuation is designed to be responsive and fail-safe, ensuring that signals change only under verified conditions. The state transitions are governed by traffic logic rules to prevent conflicting signals or unsafe road conditions.

For expanded scalability and smart city integration, the system offers optional IoT capabilities. Sensor and signal data can be transmitted to a cloud-based server using secure communication protocols such as MQTT over SSL. A centralized dashboard can visualize the current status of the traffic lights, vehicle counts, and emergency preemptions.

The dashboard can be accessed by traffic management authorities to monitor system performance in real-time. It may also include override controls for manual intervention in the case of system errors or multiple simultaneous emergencies. All interactions and system events can be logged for future analysis and auditing.

G. Prototype Implementation

A scaled-down prototype of the system is developed to validate the design. The prototype includes miniature roads, model vehicles, LED traffic lights, and sensor modules. The ambulance detection is simulated using a battery-powered RF transmitter on a toy ambulance. The control logic is implemented on an Arduino board, and sensors are connected via breadboard circuits.

The prototype is used to test system accuracy, response time, and stability under various conditions. Results are analyzed to determine the system's readiness for real-world deployment and to identify any design limitations that must be addressed before scaling.

H. Workflow Summary

In practice, the system operates continuously. It monitors all inputs from detection and density sensors, evaluates them in real time, and adjusts traffic signals accordingly. In normal conditions, it operates on a dynamic or fixed timer. Upon emergency detection, it transitions to an override state, grants priority to the emergency lane, and safely resumes normal operation post-clearance. All data can optionally be logged and reviewed via the IoT dashboard interface.

X. CONCLUSION

The increasing complexity of urban traffic and the critical need for timely emergency response have made intelligent traffic management a pressing necessity. This study presented a smart traffic signal control system that prioritizes emergency vehicles—specifically ambulances—by integrating real-time detection mechanisms and adaptive signal logic. The system effectively addresses the limitations of traditional traffic light systems, which rely on static timing and lack responsiveness to urgent, dynamic traffic scenarios.

The proposed solution combines multiple sensing technologies, including RF modules, sound sensors, and traffic density monitors, with an embedded microcontroller-based decision-making unit to dynamically manage traffic signals. The integration of IoT enables future scalability, remote monitoring, and potential city-wide deployment, while maintaining low implementation costs. By creating a green corridor in real time for approaching ambulances, the system significantly reduces response times, enhances road safety, and improves overall traffic flow efficiency.

Prototype implementation and theoretical validation confirm the feasibility of deploying such a system using low-cost hardware like Arduino or Raspberry Pi. The modular architecture ensures adaptability for both small-scale and city-wide traffic networks. With further enhancements such as cloud-based dashboards, machine learning for traffic prediction, and integration of camera-based vision systems, this work forms a strong foundation for future smart city traffic management solutions.

In conclusion, the smart traffic signal system with emergency vehicle detection not only enhances the mobility of ambulances but also represents a vital step toward intelligent, responsive, and human-centered urban infrastructure.

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