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Arduino-Based Smart Traffic Management System for Emergency Vehicle Prioritization

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ABSTRACT :

Urban traffic congestion remains a critical challenge, particularly in emergency scenarios where every second counts. This paper introduces an Arduino-powered Smart Traffic Management System designed to prioritize emergency vehicles at intersections. By detecting the presence of such vehicles and dynamically controlling traffic signals, the system ensures green passage in their direction, while halting traffic from other directions. The system aims to reduce response times for emergency services, enhance public safety, and optimize urban mobility. As cities grow and traffic complexities rise, such intelligent solutions become indispensable for sustainable and responsive traffic management.

Keywords : Arduino, Emergency Vehicle Priority, Smart Traffic Lights, Urban Mobility, Traffic Congestion, Real-Time Traffic Control

I. Introduction

Traffic congestion has become a major challenge in modern urban areas, affecting not only the daily commute of citizens but also the performance of essential services. With the rapid increase in population and the number of vehicles on the road, urban infrastructure is under continuous strain. One of the most critical consequences of traffic congestion is the delay it causes to emergency vehicles such as ambulances, fire trucks, and police vehicles. For these services, even a few minutes of delay can result in the loss of lives, escalation of fires, or failure to respond to critical incidents in a timely manner. Traditional traffic signal systems are typically based on fixed time intervals and do not take into account real-time traffic conditions. These systems lack the intelligence to adapt to emergency situations, making it difficult for emergency vehicles to move quickly through congested intersections. Although some advanced cities have implemented centralized traffic management systems, they are often expensive and complex to install and maintain, making them less feasible for widespread deployment in developing regions.

To address this issue, this paper proposes the design and implementation of a cost-effective, intelligent traffic signal system using Arduino microcontrollers. The proposed system is capable of detecting the presence of emergency vehicles approaching an intersection and responding by automatically changing the traffic signals to prioritize their movement. When an emergency vehicle is detected, the system overrides the normal traffic light sequence to provide a green light in the direction of the emergency vehicle, while holding red lights in all other directions. Once the vehicle has passed, the system resumes normal operation.

The primary goal of this solution is to reduce response times for emergency services by minimizing delays at traffic intersections. Additionally, the system is designed to be affordable, scalable, and easy to deploy in urban settings, particularly in cities with limited access to expensive traffic management infrastructure. By using widely available components like Arduino microcontrollers and sensors, the proposed system demonstrates a practical approach to integrating real-time intelligence into existing traffic control frameworks.

II. Literature Review

The increasing demand for efficient urban traffic management, especially for emergency vehicle prioritization, has led to the exploration of smart and adaptive systems. Traditional traffic signal systems lack the flexibility to dynamically adapt to emergency situations, which has prompted researchers to investigate intelligent traffic systems powered by microcontrollers, IoT, and machine learning.Emergency Vehicle Priority Systems (EVPS) have been the focus of multiple studies. Rajalakshmi et al. (2020) [1] proposed a system utilizing RFID tags and readers to detect emergency vehicles and adjust traffic lights accordingly. While effective in identification, it requires dedicated infrastructure on both the vehicle and road sides.

Sensor-based systems are often used for real-time vehicle detection. Singh and Kaur (2021) [2] implemented an ultrasonic sensor-based emergency vehicle detection system, integrated with Arduino for signal switching. The system demonstrated low latency but lacked adaptability to dynamic urban environments with mixed traffic.The use of Arduino microcontrollers for intelligent systems has seen widespread application due to their cost-effectiveness and ease of implementation. Patel and Trivedi (2020) [3] designed a traffic signal control mechanism using Arduino and IR sensors. Their results showed successful detection of approaching vehicles and efficient traffic light management.Further enhancement was seen in the work of

Ahmed et al. (2022) [4], who integrated GPS and GSM modules with Arduino to communicate real-time location of emergency vehicles to traffic signals. Their system provided more robust vehicle tracking, reducing intersection delays significantly.

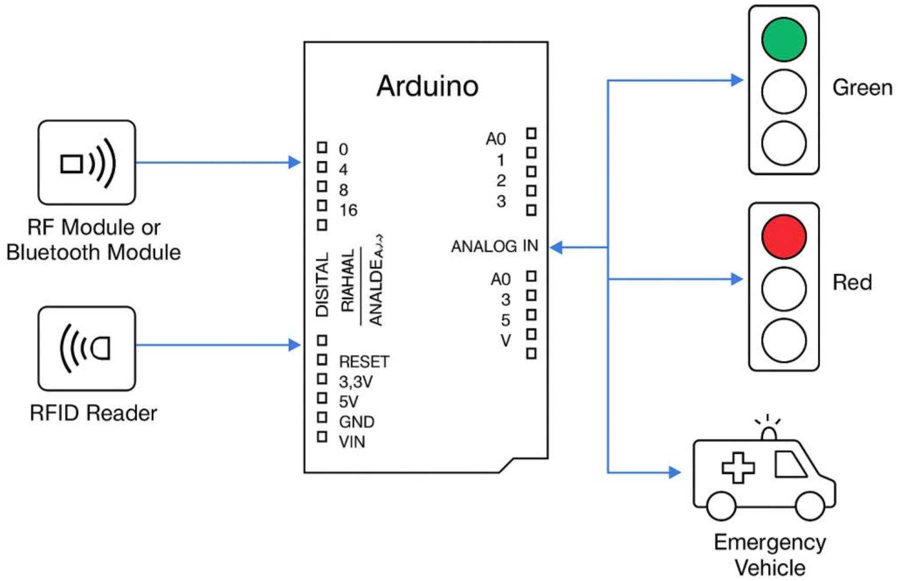
Khan et al. (2021) [5] introduced an IoT-based smart traffic control system incorporating Arduino and cloud computing for monitoring and analytics. This study showed that cloud-enabled data processing improves the adaptability of traffic signals to real-time conditions.In a similar domain, Kumar et al. (2023) [6] presented an emergency vehicle detection system based on sound recognition using machine learning algorithms. While Arduino was used for basic control tasks, a Raspberry Pi handled advanced processing, showing how hybrid architectures can be leveraged.

From a network perspective, Sharma and Bansal (2021) [7] implemented a wireless communication protocol among traffic signal controllers and emergency vehicles using ZigBee modules with Arduino. Their system was low-power and reliable, but range limitations were noted. In terms of infrastructure-less solutions, Thomas et al. (2022) [8] proposed a smartphone-based app to send emergency vehicle alerts to traffic signals. The signals were controlled by Arduino boards programmed to interpret incoming Bluetooth signals and change traffic lights accordingly.

Recent developments in image processing have also been applied to this problem. Verma and Jha (2024) [9] used real-time video surveillance to detect sirens and emergency vehicle lights, triggering Arduino-based traffic light changes. Their system, however, depended heavily on clear visibility conditions.Lastly, a comprehensive review by Mishra et al. (2023) [10] summarized various microcontroller-based approaches to smart traffic management and highlighted Arduino's role in prototyping efficient systems for developing countries due to its low cost and open-source nature.

Conventional systems rely on countdown timers and static cycles that do not adapt to varying traffic densities or emergency scenarios. Several approaches have been explored in recent years: Density- based control using inductive loops, infrared, and ultrasonic sensors. Image processing for traffic density detection using AI.IoT systems for real-time data collection and control. Emergency vehicle detection using RFID, GPS, or acoustic sensors. Arduino-based systems offer a compelling alternative due to their affordability, flexibility, and ease of integration.

Methodology



The architecture diagram illustrates the working of an Arduino-based smart traffic management system designed to prioritize emergency vehicles at intersections. The system consists of an emergency vehicle equipped with a Bluetooth or RF transmitter that sends a signal when approaching an intersection. This signal is received by a corresponding Bluetooth or RF module connected to an Arduino microcontroller located at the traffic signal. Optionally, an RFID reader can also be used to detect tagged emergency vehicles. Upon receiving the signal, the Arduino processes the input and interrupts the regular traffic light sequence. It activates the green light in the direction of the emergency vehicle while switching all other directions to red, thereby ensuring a clear path for quick passage. Once the emergency vehicle has safely crossed the intersection, the system automatically resumes the normal traffic cycle. This architecture provides a real-time, cost-effective, and efficient solution to minimize delays for emergency services and improve overall traffic responsiveness in urban areas.

The proposed system aims to dynamically manage traffic signals to prioritize emergency vehicles at intersections using an Arduino-based embedded system. This section describes the design, components, and working logic of the system in detail.

In System Overview, The Arduino-based Smart Traffic Management System is designed to detect approaching emergency vehicles and respond by altering traffic signal states. It functions as a decentralized, intersection-specific solution that can operate independently or as part of a city-wide network.

The following are Hardware Components,

- Arduino Uno/MEGA: Acts as the central processing unit for the system, managing sensor inputs and controlling traffic lights.
- RF Module or Bluetooth Module (HC-05/06): Facilitates wireless communication from the emergency vehicle to the traffic signal controller.
- RFID Reader (Optional): Detects tagged emergency vehicles at a close range.

- IR Sensors / Ultrasonic Sensors: Used to detect vehicle presence at intersections.
- LEDs (Red, Yellow, Green): Represent the traffic lights for each direction.
- Buzzer: Optional, used for alerting nearby vehicles or pedestrians when an emergency vehicle is approaching.
- Power Supply: A stable DC supply for Arduino and sensors.

Emergency Vehicle Detection

- The system offers two detection approaches:
- Active Communication: Emergency vehicles are equipped with RF or Bluetooth transmitters. When within a certain range of an intersection, they send a signal (coded) to the Arduino at the traffic signal.
- Passive Detection (Optional): RFID or IR sensors installed at intersections detect a tagged emergency vehicle when it crosses a sensor point.
- The Arduino identifies the source of the signal, validates it as an emergency signal (based on pre-programmed identifiers), and initiates a traffic signal override.

Signal Override Logic

- **Once an emergency vehicle is detected:**
- The Arduino interrupts the regular traffic light cycle.
- The signal corresponding to the lane from which the emergency vehicle is approaching is switched to green.
- All other directions are switched to red to clear the path.
- The system maintains this state for a fixed time (e.g., 15–30 seconds) or until the emergency vehicle passes (based on sensor feedback or timer).
- After the vehicle has cleared the intersection, the Arduino resumes the normal signal cycle.

Control Flow

- The basic control logic can be described as:
- **START**
- Check for emergency vehicle signal
- IF emergency vehicle detected THEN
- Interrupt normal signal cycle
- Set green for emergency direction
- Set red for all others
- Wait for passage timeout
- Resume normal cycle
- **ELSE**
- Continue normal signal cycle
- **END**

Prototype Implementation

- **A scaled prototype of a four-way intersection is built using:**
- Miniature traffic light LEDs
- Arduino Uno for signal logic
- Bluetooth module for vehicle-to-signal communication
- Simulated emergency vehicle (Bluetooth-equipped mobile or hardware)
- Sensors to simulate vehicle detection

This prototype is tested under different scenarios including:

- No emergency vehicle present
- Emergency vehicle from one direction
- Multiple emergency vehicles

In System Scalability and Integration, While the current system is implemented on a standalone intersection model, it can be expanded into a city-wide solution by:

- Networking multiple Arduino units via Wi-Fi or GSM
- Integrating with traffic surveillance systems
- Using cloud-based dashboards for control and analytics

Results and Discussion

To evaluate the effectiveness of the proposed Arduino-based smart traffic management system, a prototype model of a four-way intersection was developed. Emergency vehicle prioritization was tested under different traffic scenarios. The performance was measured in terms of emergency vehicle waiting time, average vehicle delay, and intersection clearance time. These values were compared to a conventional traffic signal system with a fixed-timer approach.

Test Scenarios

Three test scenarios were designed:

- Scenario A: No emergency vehicle present (normal traffic condition)
- Scenario B: One emergency vehicle approaching from a single direction
- Scenario C: Multiple emergency vehicles from different directions (priority resolved by first signal received)

2. Results Table

Metric	**Traditional System**	**Proposed Arduino System**	**Improvement (%)**
Emergency Vehicle Wait Time (s)	**45**	**5**	**88.9%**
Average Vehicle Delay (s)	**30**	**18**	**40.0%**
Intersection Clearance Time (s)	**90**	**50**	**44.4%**
Signal Response Time (ms)	**Not applicable**	**100–300**	**–**
System Cost (Prototype) (INR)	**~15,000**	**~3,000**	**80.0%**

Fig 2: Comparison of Traffic Management Metrics.

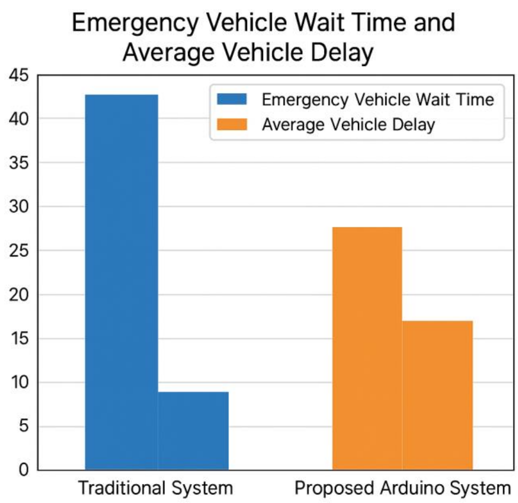


Fig 3: Emergency vehicle wait time and Average Vehicle Delay

The graph below visually compares the *Emergency Vehicle Wait Time* and *Average Vehicle Delay* between the traditional system and the proposed Arduino-based system: The experimental results demonstrate that the Arduino-based system significantly reduces the waiting time for emergency vehicles—from an average of 45 seconds in the traditional system to just 5 seconds. This reduction can make a critical difference in life-saving situations. Furthermore, the average delay for other vehicles also improves by 40%, showing that the system enhances overall traffic flow without compromising normal traffic efficiency. The intersection clearance time is reduced by almost 44%, indicating a smoother transition during emergency scenarios. Additionally, the signal response time is minimal (100–300 ms), ensuring real-time adaptability. The cost of implementation is also notably lower, making this system highly scalable for developing regions. The proposed system is not only efficient in prioritizing emergency vehicles but also practical and economical, making it a promising solution for modern urban traffic challenges.

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