Geofencing-Enabled V2I System for Efficient Emergency Vehicle Traffic Management

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Abstract: *Modern urban settings require intelligent traffic management to ensure efficient emergency vehicle transit. Integrating geofencing within Vehicle-to-Infrastructure (V2I) systems facilitates real-time, automated traffic control through virtual geographic boundaries. This proactive approach enhances roadway safety and reduces congestion by dynamically adjusting infrastructure in response to emergency vehicle proximity.*

The integration of geospatial perimeter-based triggers within V2I systems enables context-aware, autonomous traffic regulation in response to emergency vehicle proximity. This location-sensitive mechanism enhances vehicular mobility, reduces intersection delays, and expedites emergency response times.

By synergizing geofencing with V2I communication protocols, the proposed system ensures continuous traffic flow along critical emergency routes, thereby advancing the operational efficacy of urban traffic networks. This technological convergence not only expedites emergency interventions but also fosters a safer, more adaptive, and intelligent transportation ecosystem.

Keywords: Esp32, Geofencing, Vehicle-to-Infrastructure Communication(V2I), RFID Module, Emergency Vehicle Prioritization, Smart Traffic Management

1. INTRODUCTION

In contemporary rapidly urbanizing environments, traffic congestion presents a critical challenge, particularly in densely populated metropolitan areas. A big problem in these crowded areas is the time it takes for emergency vehicles like ambulances, fire trucks, and police cars to move through. To mitigate this issue, the development and deployment of an advanced, intelligent traffic management system is imperative to facilitate unobstructed passage for emergency vehicles at intersections.

The Emergency Vehicle Traffic Management System (EVTMS) is a new technology that uses Vehicle-to-Infrastructure (V2I) communication to help emergency vehicles and traffic lights work together in real time. When an emergency vehicle approaches an intersection, the system finds out where it is using wireless methods like Radio Frequency (RF) modules, GPS, or IoT sensors. This then starts an automatic process where the traffic light controller gives priority to the emergency vehicle by turning the light green in its direction.

Operating in real time, the system simultaneously restricts opposing traffic flows at the intersection, thereby ensuring a secure and uninterrupted passage for the emergency vehicle. This adaptive signal modulation significantly reduces emergency response latency and enhances the overall operational efficiency of urban emergency services.

2. LITERATURE SURVEY

[1] This study proposes an innovative approach to address the critical issue of emergency vehicles being delayed in congested urban traffic, which can significantly hinder the timely delivery of essential medical services. The proposed system, termed the Real-Time Emergency Vehicle Traffic Signal Management System (EVTMS), leverages Vehicle-to-Infrastructure (V2I) communication in conjunction with real-time location tracking of emergency vehicles to dynamically control traffic signals. By giving priority to emergency vehicles at crossroads, the system helps them move quickly and safely through traffic. This helps cut down the time it takes for emergency services to reach people in need, making their work more efficient and better at helping.

[2] This study looks at how Vehicle-to-Infrastructure (V2I) communication can be used in Intelligent Transportation Systems (ITS) to solve problems like traffic jams, breaking traffic rules, and accidents. It uses Internet of Things (IoT) technology to let vehicles and traffic systems talk to each other in real time. This helps catch speeding and sends information about how people are driving to a main monitoring center. The paper also suggests a model that uses V2I to help emergency vehicles, like ambulances, get through traffic faster. It does this by changing traffic lights based on where the emergency vehicle is. This makes sure there are fewer delays in busy cities, which helps emergency services work better and faster.

[3] This study addresses the increasing incidence of vehicular accidents caused by over speeding and negligent driving, despite existing traffic regulations. It introduces a geofencing-based alert system utilizing RFID and Global Positioning System (GPS) technologies to define virtual geographic boundaries for real-time speed and location monitoring. The system enhances road safety by issuing SMS alerts when vehicles exceed designated speed thresholds or exit predefined zones. While geofencing offers significant safety benefits, usability challenges hinder widespread adoption among non-technical users such as parents and caregivers.

[4] Modern improvements in self-driving cars help make roads safer and ease traffic in cities. One important part of these cars is the ability to detect traffic lights, which helps them respond quickly and correctly to signals. However, even with cameras and other visual tools, self-driving cars still have trouble recognizing traffic lights accurately. This situation shows the need for using Vehicle to Infrastructure (V2I) communication to improve traffic light detection. This research focuses on using V2I technology in decision-making for self-driving cars at traffic lights. The proposed system uses an RF24L01 transmitter and a digital compass to send and receive information, helping self-driving cars reliably detect traffic signals at intersections.

[5] Road traffic congestion is a major issue in cities with high population densities, like Chennai. "Intelligent automatic traffic control for ambulance" is the method that this article suggests using to expedite

ambulance transit. Essentially, the proposed setup uses an RFID placed at the traffic light to track the RFID-tagged ambulance. If, after acknowledgment, a traffic signal causes the ambulance to stop while in motion, the data is transmitted to the cloud.

3. PROBLEM STATEMENT

Emergency vehicles like ambulances, fire trucks, and police cars often face serious delays at crossroads because of heavy traffic and traffic lights that don't adjust properly. Traditional traffic lights operate on fixed-time cycles and lack the capability for real-time emergency vehicle prioritization, compromising public safety in time-sensitive situations.

Furthermore, the lack of real-time communication between cars and traffic infrastructure exacerbates the problem, resulting to longer emergency response times, traffic interruptions, and, in the worst-case scenario, loss of life and property. A smart, automatic system is needed right away to spot emergency vehicles coming in real time. Communicate efficiently with traffic signal infrastructure. Priorities emergency vehicle flow by dynamically managing traffic signals.

The main goal of this project is to create and put into place a Real-Time Emergency Vehicle Traffic Signal Management System (EVTMS) utilizing Vehicle-to-Infrastructure (V2I) communication and Internet of Things (IoT) technologies. The proposed system is engineered to ensure the seamless and continuous movement of emergency vehicles through heavily congested intersections. By allowing emergency vehicles to communicate instantly with traffic control systems, the system facilitates the automated detection and dynamic prioritization of such vehicles. This interaction with traffic signal controllers ensures minimal delay and supports the efficient and safe navigation of emergency vehicles in urban traffic environments.

4. OBJECTIVES

The main purpose of this project is to build a smart traffic signal system that allows emergency vehicles such as ambulances, fire trucks, and police cars to travel through city roads without any delays or obstacles.

- To detect and identify approaching emergency vehicles at traffic intersections using real-time sensing.
- To establish wireless communication between emergency vehicles and traffic signal controllers via advanced technologies (e.g., RF, GPS, or IoT modules).
- To autonomously switch traffic signals to green in the direction of the emergency vehicle, ensuring right-of-way prioritization.
- To cut down on how long it takes for emergency help to arrive and make emergency services work better.
- To mitigate the risk of collisions and alleviate traffic congestion during critical and time-sensitive situations.

5. PROPOSED METHOD

5.1 Design of System

This project introduces a smart traffic management system that uses geofencing and communication between vehicles and road infrastructure to give priority to emergency vehicles at traffic intersections. Virtual geofences, defined by GPS coordinates, enable real-time detection via LoRa-based communication, triggering dynamic signal phase alterations. The system leverages microcontrollers, GPS modules, and communication protocols to ensure reliable and responsive operation in urban settings. Upon validation, the embedded controller overrides the standard traffic signal routine and dynamically alters the signal state to give immediate green-light access to the approaching emergency vehicle. This interaction is managed through a combination of microcontrollers, GPS modules, LoRa transceivers, and communication protocols for robust performance in real-world environments.

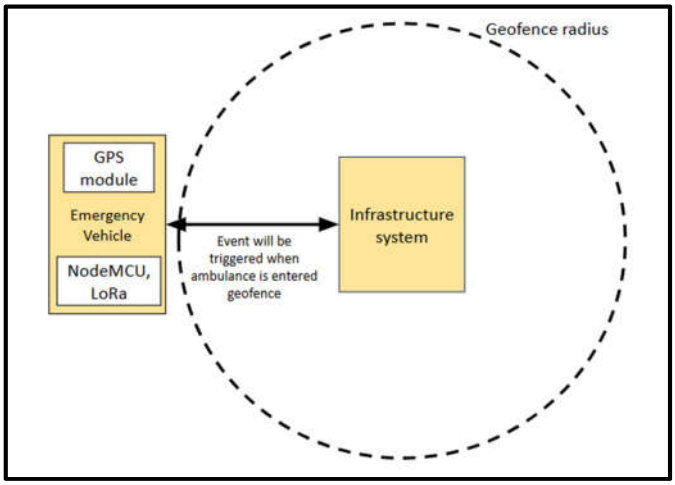

Figure 1. Geofence Area

5.2 Block Diagram

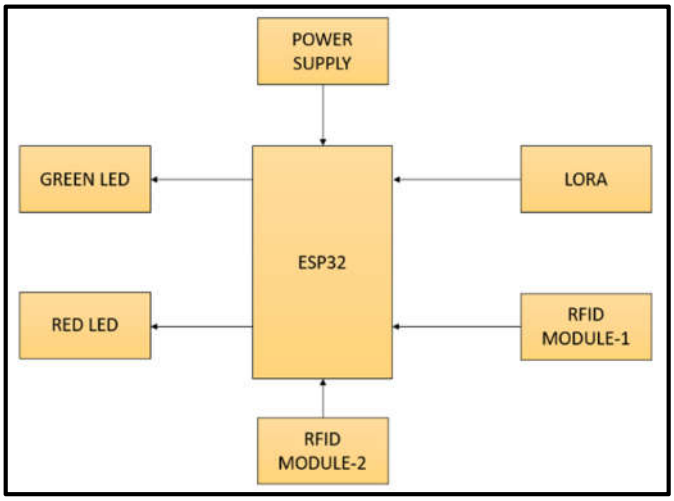

Figure 2. Traffic Controller System

The block diagram of this project comprises of Infrastructure system i.e. Traffic Controller System and Emergency Vehicle Unit.

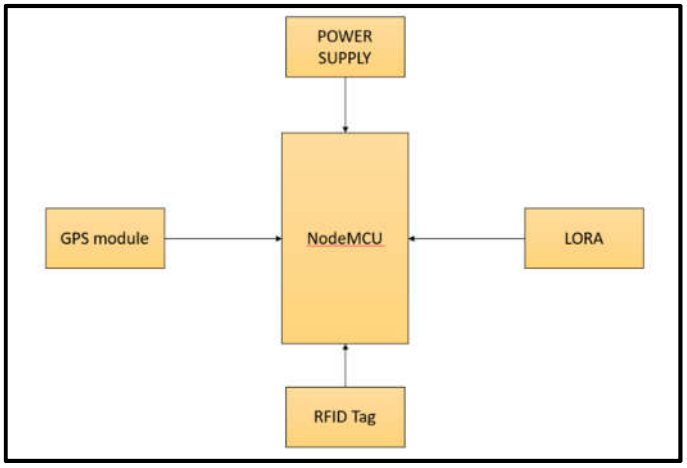

Figure 3. Emergency Vehicle Unit

5.3 Hardware Requirements

5.3.1 ESP32 Microcontroller

The ESP32 is a powerful and energy-saving microcontroller chip made by Espress if Systems. It is designed to work well with smart devices connected to the internet. As the successor to the widely adopted ESP8266, the ESP32 incorporates either a single-core or dual-core Tensilica Xtensa LX6 processor, capable of operating at frequencies up to 240 MHz. The microcontroller features built-in support for Wi-Fi and both Classic Bluetooth and Bluetooth Low Energy (BLE), rendering it an optimal platform for wireless communication systems that demand robust processing capabilities, real-time connectivity, and low power consumption. Serves as the central control unit for managing operations at the traffic signal infrastructure.

5.3.2 LoRa Module

A LoRa (Long Range) module is a compact hardware component designed to enable long-range, low-power wireless communication based on LoRa modulation technology, which is widely utilized in Internet of Things (IoT) systems. These modules typically integrate a radio transceiver, antenna interface, and a microcontroller unit (MCU), allowing for efficient data transmission across extended distances while maintaining minimal energy consumption. This makes LoRa modules highly suitable for applications requiring low-power wide-area network (LPWAN) capabilities in resource-constrained environments.

5.3.3 EM – 18 RFID Module

The EM-18 RFID reader module works at 125 kHz and provides an affordable option for systems that use RFID for identification. It features an integrated antenna, operates on 5V DC, and supports serial communication via its TX pin to a microcontroller's RX pin. Upon detecting an RFID tag within range, it transmits the unique identification number (UID) to the host system. The module also supports Wiegand protocol output, enhancing its applicability in access control and security systems.

5.3.4 GPS Module

The Global Positioning System (GPS) is a satellite-based navigation technology that provides real-time positional and temporal data to receivers across the globe, regardless of weather conditions. A GPS module is an integrated device comprising an antenna, RF receiver, and processing unit, designed to acquire satellite

signals and compute geospatial coordinates such as latitude, longitude, altitude, and velocity. It is widely applied in geolocation, navigation, and real-time tracking systems.

5.3.5 Node MCU

NodeMCU is an open-source development platform that integrates both hardware and software components, built upon the ESP8266 Wi-Fi system-on-chip (SoC). It is widely utilized for rapid prototyping in Internet of Things (IoT) applications due to its cost-effectiveness, scalability, and ease of deployment for wireless communication. The hardware architecture is centred around the ESP-12 module, which encompasses key functionalities such as General-Purpose Input/Output (GPIO) pins, Pulse Width Modulation (PWM), Inter-Integrated Circuit (I^2C), 1-Wire protocol, and an Analog-to-Digital Converter (ADC). These features collectively provide a versatile interface for integrating a wide range of sensors and peripheral devices, thereby enabling efficient development of interconnected smart systems in IoT environments.

5.3.6 LED

A Light-Emitting Diode (LED) is a semiconductor optoelectronic device that emits electromagnetic radiation in the visible spectrum when subjected to an electric current. As a type of unidirectional diode, it permits current flow in only one direction forward bias. Under this condition, electron-hole recombination occurs within the p-n junction of the semiconductor material, resulting in the release of energy in the form of photons, thereby producing light. LEDs are widely recognized for their energy efficiency, longevity, and compact form factor, making them essential components in modern electronic and photonic applications.

5.4 Software Requirements

Arduino IDE:

The Arduino Integrated Development Environment (IDE) is a cross-platform software framework developed to streamline programming, upload and debugging processes for Arduino-based microcontroller platforms. It offers a user-friendly graphical interface for developing embedded applications, wherein programs referred to as "sketches" are written using a simplified variant of C/C++ and saved with the ".ino" file extension. The IDE includes essential features such as syntax highlighting, code compilation, serial communication tools, and library integration, making it well-suited for both novice and experienced developers in embedded system design and prototyping.

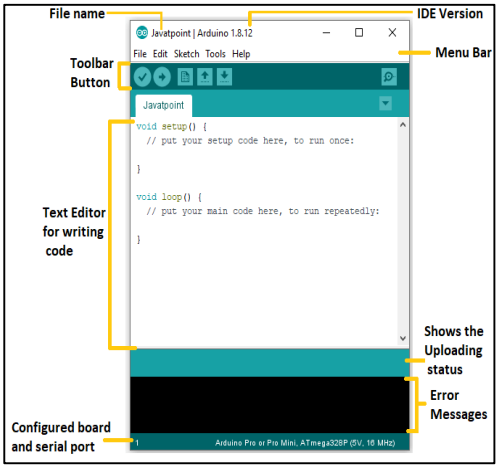

Fig 4: Arduino IDE

The IDE supports serial communication with connected Arduino hardware and enables seamless integration with third-party libraries and board configurations. It is compatible with several operating systems such as Windows, MacOS, Linux, Chromeos, and also offers portable versions for Linux and Windows platforms. The Arduino IDE serves as a comprehensive toolchain for embedded systems development, promoting accessibility and rapid prototyping within the open-source hardware ecosystem.

5.5 Methodology

In the proposed system architecture, emergency vehicles are outfitted with a wireless transmission module, such as Node MCU or an RF transceiver, to facilitate real-time communication. When the vehicle is actively responding to an emergency, it transmits a signal as it approaches an intersection. Each traffic signal is integrated with a wireless receiver and a microcontroller unit (e.g., ESP32) that continuously monitors for incoming signals from authorized emergency vehicles.

Upon detection of the emergency vehicle's signal, the system autonomously identifies the direction of approach and dynamically assigns a green light to the corresponding lane, while simultaneously activating red signals for all other directions to halt cross traffic. This prioritization ensures an unobstructed passage for the emergency vehicle through the intersection. Once the vehicle has safely cleared the junction, the traffic signal control logic automatically reverts to its predefined operational state, thereby restoring standard traffic flow across all lanes.

The software architecture of the proposed emergency vehicle prioritization system is a multi-layered stack that integrates embedded firmware, communication protocols, control logic, and geofencing algorithms. Each software module is developed to operate independently yet collaboratively to ensure modularity, real-time performance, and high system reliability. The system software is implemented using C/C++ for embedded firmware and Arduino IDE as the development platform, ensuring compatibility with ESP32 and NodeMCU hardware.

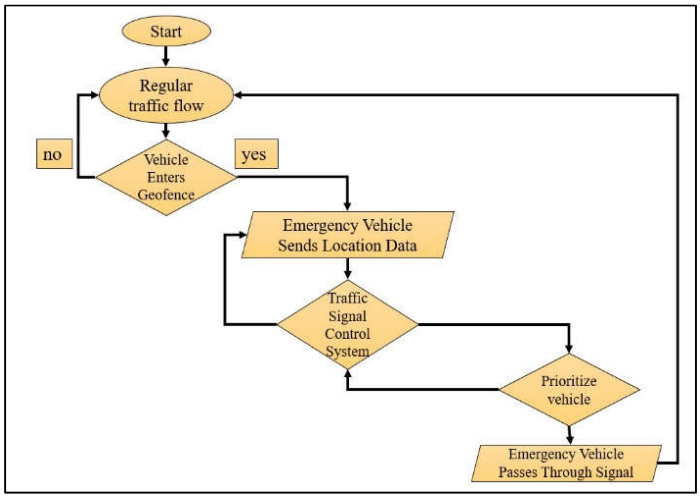

Fig 5: Flow Chart

The integration and testing phase of the emergency vehicle prioritization system represents a critical point in ensuring the seamless interaction between hardware and software components. This stage validates the correct functioning of the overall system through systematic assembly, firmware synchronization, inter-device communication, and real-time performance testing. This mechanism ensures expedited and uninterrupted transit for emergency responders, thereby reducing operational delays and enhancing emergency response efficiency.

6. ADVANTAGES

1. Enhanced Emergency Response: Enables rapid transit of ambulances, fire services, and law enforcement vehicles, improving critical response times.
2. Automated Traffic Signal Control: Eliminates the need for manual intervention by dynamically adjusting signals in real time.
3. Congestion Mitigation: Facilitates smooth vehicle clearance for emergency services without severely disrupting general traffic flow.
4. Real-Time Detection and Operation: Ensures immediate signal activation upon emergency vehicle approach through continuous wireless monitoring.
5. Life-Critical Support: Minimizes response delays, potentially reducing mortality and improving public safety outcomes.

7. RESULT

The main aim of the system is to help identify and give priority to emergency vehicles as they approach traffic lights. Once the system recognizes an emergency vehicle, it will change the light to green in the direction the vehicle is going. This helps the emergency vehicle pass through quickly without stopping. At the same time, the lights in all other directions will turn red to stop other cars. This reduces the chance of accidents and keeps traffic moving smoothly.

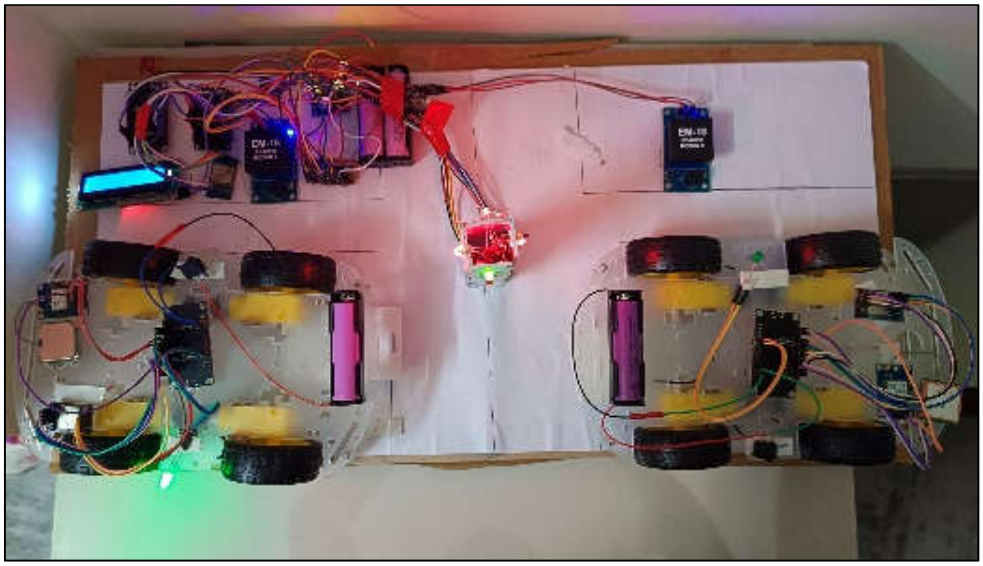

Figure 6. Proto Type

This approach is projected to significantly reduce response times for ambulances, fire services, and law enforcement vehicles, particularly during periods of high traffic density. Furthermore, the system aims to optimize traffic flow, enhance urban mobility, and contribute to the realization of a smart and efficient traffic management ecosystem.

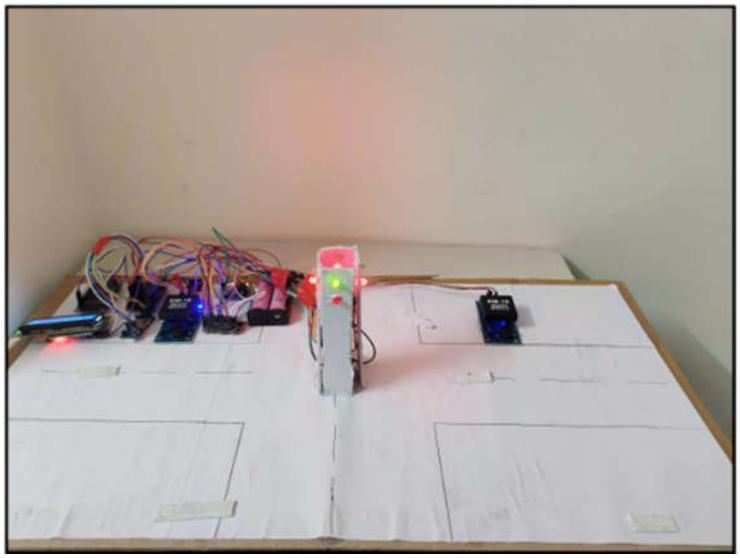

Figure 7. Infrastructure System (Traffic Signal)

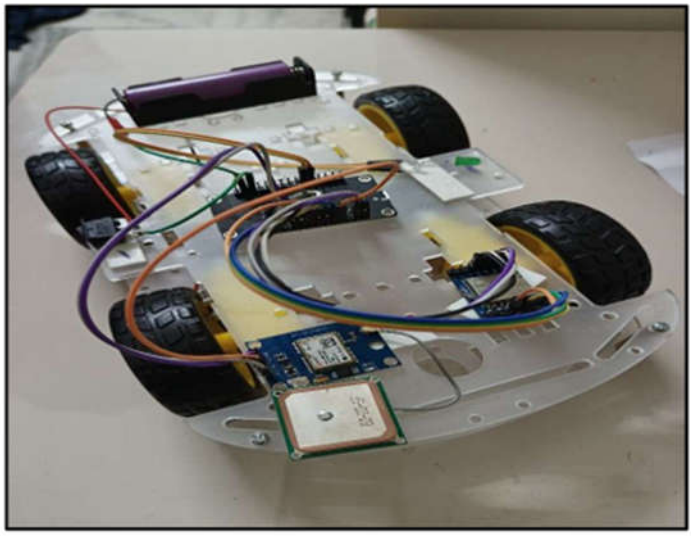

Figure 8. Emergency Vehicle

8. CONCLUSION

The Emergency Vehicle Traffic Signals Management System (EVTMS) offers an efficient and technologically viable solution to mitigate delays encountered by emergency vehicles at signalized intersections. By using real-time communication between vehicles and infrastructure, the system changes traffic light priorities on the fly to give emergency vehicles a green light just in time, helping them move quickly and safely through city traffic.

This approach enhances emergency response efficiency, alleviates traffic congestion, and has the potential to significantly contribute to life-saving outcomes. The system is cost-effective, scalable, and

relatively straightforward to integrate within existing infrastructure, making it a compelling component of smart city traffic management frameworks. With continued advancements, the EVTMS can evolve into a more intelligent, adaptive, and widely deployable solution for urban mobility challenges.

9. FUTURE SCOPE

Future enhancements of the proposed system may involve the integration of GPS-based real-time tracking in conjunction with artificial intelligence (AI) algorithms to optimize route prediction for emergency vehicles based on dynamic traffic conditions. The system can be further extended to interface with smart city infrastructure, enabling centralized management of traffic flow across multiple intersections simultaneously.

Using mobile apps in control centres or healthcare places can help teams work together better and stay more informed. Also, using tech like Automatic Number Plate Recognition and cameras to detect vehicles can make the system more accurate, dependable, and secure.

The adoption of 5G connectivity and cloud-based infrastructure can significantly increase system responsiveness and scalability, making it well-suited for deployment in large-scale, urban intelligent transportation networks.

REFERENCE

[1] Perusomula et al. (2023) developed a Geo-Fencing and Overspeed Alert SMS System, which leverages location-based services to enhance vehicular safety by notifying users of boundary breaches and speed violations. The study highlights the integration of GPS tracking with real-time SMS alerts to ensure timely notifications for enhanced road safety management [1].

[2] Kim et al. (2008) proposed a real-time ambulance tracking system utilizing GPS and Maps Open API. This system effectively monitors ambulance locations, thereby facilitating faster response times in emergency medical scenarios by providing continuous positional updates to control centers [2].

[3] Nalini et al. (2023) introduced a smart traffic control mechanism incorporating ambulance detection using signal processing techniques. The proposed model enables dynamic traffic signal adjustments in response to approaching ambulances, thereby reducing emergency vehicle delay and improving route efficiency [3].

[4] Anushya (2018) presented a system for monitoring traffic violations via Vehicle-to-Infrastructure (V2I) communication. This work underscores the potential of V2I technologies in enforcing traffic rules through automated detection and reporting of vehicular infractions [4].

[5] Saradha et al. (2017) explored an intelligent traffic signal control system that employs RFID-based ambulance identification in conjunction with cloud computing for decision-making. This approach ensures prioritized signal clearance for ambulances, demonstrating the utility of IoT and cloud integration in real-time traffic systems [5].

[6] Kumar and his team in 2023 introduced a real-time system called EVTMS, which uses communication between vehicles and traffic infrastructure to manage traffic for emergency vehicles. The goal is to control traffic signals in a way that helps emergency vehicles move through with as little delay as possible. This system improves how emergency vehicles and roadside equipment work together, making traffic flow better during emergencies.