

Original Article

Adaptive Traffic Management: A Priority - Based Framework for Congestion Control

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Abstract - One of the major urban problems with far-reaching effects is traffic congestion. Traffic congestion in large cities can have dangerous consequences, especially for emergency vehicles, for instance, fire trucks and ambulances. In a fixed, delayed traffic system, under normal conditions, irrespective of the traffic, there are equal delays for all lanes. Such a system does not consider emergency vehicles. This study presents an intelligent traffic control system that prioritizes emergency vehicles according to designated priority indications. The proposed system allows emergency vehicles to drive through high-traffic areas without stopping. Any emergency vehicle that needs to cross the signal beforehand uses a Global Positioning System (GPS) to transmit its location. Traffic control systems are informed of the area and priority of emergency vehicles well in advance via special communication channels. The presented system comprises two sections: a live location transmitter placed in an emergency vehicle and a traffic control unit. The microcontroller module in the traffic control unit determines the vehicle distance and clears the lane for a set amount of time when it gets close to the signaling unit. After a certain amount of time, the specific lane status will turn green and restart regular operations. The suggested system dynamically modifies signal timing according to real-time priority, thus alleviating congestion and minimizing waiting times at junctions. The approach boosts public safety, improves emergency response efficiency, and supports sustainable urban mobility management by allocating distinct priorities to ambulances, police vehicles, and other emergency services.

Keywords - Adaptive traffic control, Emergency vehicle, GPS, Priority traffic, Traffic control.

1. Introduction

The substantial rise in vehicle ownership leads to increased traffic and significant traffic delays, especially in urban areas. A major contributor to traffic congestion is an excess of automobiles on the road, particularly during peak hours [1]. Traffic congestion in metropolitan areas can hinder the movement of emergency vehicles, including fire engines and ambulances, leading to unpleasant situations [2]. Weather, time of day, season, and unforeseen occurrences like construction projects or accidents influence traffic delays [3]. A traffic management system restricts the number of vehicles that can travel through a roadway without causing an accident or obstructing the path [4]. Traditional traffic control systems employ preset schedules and don't account for the dynamic traffic circumstances in real time [5]. Long queues of vehicles at traffic signal points cause air pollution, longer delays, and higher fuel usage. A Density-Based Traffic Control System (DBTCS) is a solution to this problem. A DBTCS measures the traffic in each lane and adjusts the signals accordingly. A traditional traffic control system does not prioritize emergency vehicles like fire engines, ambulances, etc. Human life is

precious. Reaching out to the critical situations at the right time is crucial in emergency situations. To reduce the emergency response time, automatic detection of emergency vehicles and giving priority to them is important. Priority-based traffic management is one of the key IoT components in smart city urban mobility, providing fire engines and ambulances with a green signal [6].

The Sultanate of Oman is always focused on giving its people a good quality of life. Highly commendable highways link each area of this beautiful country. The road quality index in the Sultanate of Oman is 5.7, higher than the global average of 4.07, according to the World Economic Forum (WEF) [7]. In the current road quality ranking, the country came second among Arab states. More individuals commute to work every day in places like Muscat. Traffic is backed up during peak hours because people are committed to arriving at work on schedule.

"Traffic density is defined as the number of vehicles per unit length of a road segment" [8]. Express highways (6-lane



divided) in Oman are designed for high mobility, with a design speed of 120 km/h. During peak hours (7.00 AM-8.00 AM), traffic volume on the expressway reaches 7029, exceeding the designed capacity, and the mean speed drops to 57 km/h. Mahairzi et al. [9] Conducted a study on traffic density in AlHail to Airport Road on Tuesday, 18.04.2017, during peak and non-peak hours. During non-peak hours, 6:00-7:00 AM, the traffic volume-to-capacity ratio (V/C) is 0.55, indicating free flow of traffic and a good Level Of Service (LOS). During the peak hours, 8.00-9.00 AM, the V/C value is 2.16, indicating a descent in the Level Of Service (LOS) to F, forced failure. A similar pattern is observed in the Airport to Al Hail Road during the afternoon. From 2.00-3.00 PM, the ratio (V/C) is 0.55, and from 4.00-5.00 PM, it increases to 2.22, indicating a reduction in LOS. Traffic density varies over time and depends on the number of offices, schools, hospitals, etc., in a particular area.

Most traffic signals in Oman use a fixed-time delay pattern. Light traffic only works well with the fixed delay traffic system, which processes data at a programmed time [10]. A longer green light is needed to reduce traffic congestion in the busier lane. Hence, giving the same amount of time to each route in a roundabout may not be the most effective strategy, especially if there is a significant difference in traffic volume between directions. Systems with large traffic volumes require an adaptive system that can handle traffic density. A general traffic control system may need assistance in detecting high-priority situations and emergency scenarios. This emphasizes the need for an intelligent traffic control system to handle all operations and make choices automatically.

Three widely used real-time traffic density data collection techniques are Wide Sensor Network (WSN), Vehicular Ad-Hoc Network (VANET), and the image-capturing-analysis technique [11]. WSN makes use of a dense network of sensors, including magnetic, infrared, and other types of sensors. A network of sensors, a processing unit, and a communication system are the components that make up a traffic control system that is based on a WSN. In a WSN, the medium of communication might be ZigBee or any other wireless system. Noteworthy research in the field of WSN-based traffic control systems includes Colotta et al. [12], Nellore et al. [13], and Srivastava et al. [14].

VANET uses a network of linked vehicles that exchange data using the IEEE 802.11p standard. Vehicles function as communication nodes in this system and are outfitted with onboard devices to share data, including location and speed. Priemer et al. [15], Rehman et al. [16], Majed et al. [17], and Wongdeethai [18] have conducted noticeable studies on VANET-based traffic control.

In image capture and analysis methodologies, images captured by cameras are processed using advanced algorithms

to estimate traffic statistics. Wang et al. [19] exhibited a traffic monitoring system based on image processing, achieving a high vehicle identification rate. Kanungo et al. [20] introduced a video-based traffic density monitoring system that demonstrates commendable accuracy at a reasonable cost. The research related to image analysis-based traffic monitoring conducted by Maheshwari et al. [21] and Kurniawan et al. [22] are some of the significant works in traffic monitoring systems.

Lots of research has been conducted to reduce traffic in urban areas. In the smart road systems proposed by [9], RFID is used to measure traffic density and vehicle speed. In this system, every vehicle is attached to an RFID module. The sensors and camera modules placed on the roads capture the details and send them to the central processing system.

Baqer et al. [23] described the development and deployment of a vehicle tracking system that integrates General Packet Radio Service (GPRS) and Global Positioning System (GPS) technology. The system is designed to enable real-time vehicle location tracking by transmitting position data over GPRS to a remote sensor, which can then be viewed via a web interface or a mobile application. While GPS integration guarantees precise location data, GPRS permits continuous, affordable communication across cellular networks.

Khin et al. [24] proposed a vehicle tracking system using embedded technology. The proposed system uses GPS to locate the vehicle, and the obtained data is communicated via GSM to a remote server and displayed in real time. The demonstrated system enables users to monitor their vehicle's location remotely. Lee et al. [25] presented a vehicle tracking system using GPS and GSM technologies. They used a GPS for location tracking, a GSM for data communication, and a smartphone application for user interaction. The smartphone application enables a user-friendly, easy-to-use interface for vehicle tracking. Dhakad et al. [26] proposed a system that brings to bear GPS technology to track and report traffic congestion in real time. This research introduces and executes a GPS-based traffic information system. This method uses a smartphone and a GPS receiver to check for traffic jams and an accelerometer to figure out how fast the car is going.

A detailed literature review reveals the importance of a low-cost priority-based traffic management system. The fixed-time-delay traffic system becomes inefficient when traffic volume on one route exceeds that on another [6]. A priority-based traffic management system that adaptively modifies signal duration based on concurrent priorities is a solution for traffic congestion. The mode of communication in a traffic control system plays a significant role. RFID or ZigBee communication is limited to a few meters. To compensate for the distance limitation, we propose a priority-based system using GSM. In general, this kind of system

makes cities safer, speeds up emergency response times, and helps manage urban transportation in a way that is good for the environment. This project, a priority-based traffic management system, prioritizes emergency vehicles within a signal unit and adapts the signal timing based on live traffic.

In this project, traffic density is measured using infrared detectors placed at the roadside. The IR pairs (transmitter and receiver) are mounted on the roadside to detect the vehicle presence by beam interruption. A passing vehicle breaks the IR beam, triggering the sensor. A microcontroller interfaced to the IR pair counts the number of vehicles crossing at a particular location. The controller adjusts traffic light signals automatically, prioritizing lanes with higher density and reducing waiting times, often by increasing green light duration for high-traffic lanes.

An Arduino UNO microcontroller connected to a SIM808 GPS/GSM/GPRS module sends a request containing location (longitude and latitude) to the receiver, the traffic control unit. On the receiver side, an Arduino UNO microcontroller is connected to four mini traffic light modules, each with red, yellow, and green LEDs. Upon receiving a request from the emergency vehicle, the microcontroller unit at the signaling

point determines the vehicle's distance and clears the lane for a set amount of time as the vehicle approaches the signaling unit. Adaptive traffic control is based on traffic density, and both regular and emergency vehicles benefit from the more efficient traffic flow it enables. The major sections of this paper are arranged as follows. Section 2 describes the system model, giving details of system elements and the flow of data. Section 3 evaluates the effectiveness of the system and its output.

2. Proposed System Model

The proposed system prioritizes emergency vehicles at the crossing point and controls traffic signals based on traffic in each direction. A traffic control device and a live location transmitter installed in the emergency vehicle make up the two parts of the priority control system. Figure 1 reveals the block diagram representation of the live location transmitter and receiver installed in the emergency vehicle. On the transmitter side, the SIM808 GSM/GPS module is interfaced with the Arduino UNO microcontroller to send location data. On the receiver side, an Arduino UNO microcontroller is connected to four mini traffic light modules, each with red, yellow, and green LEDs.

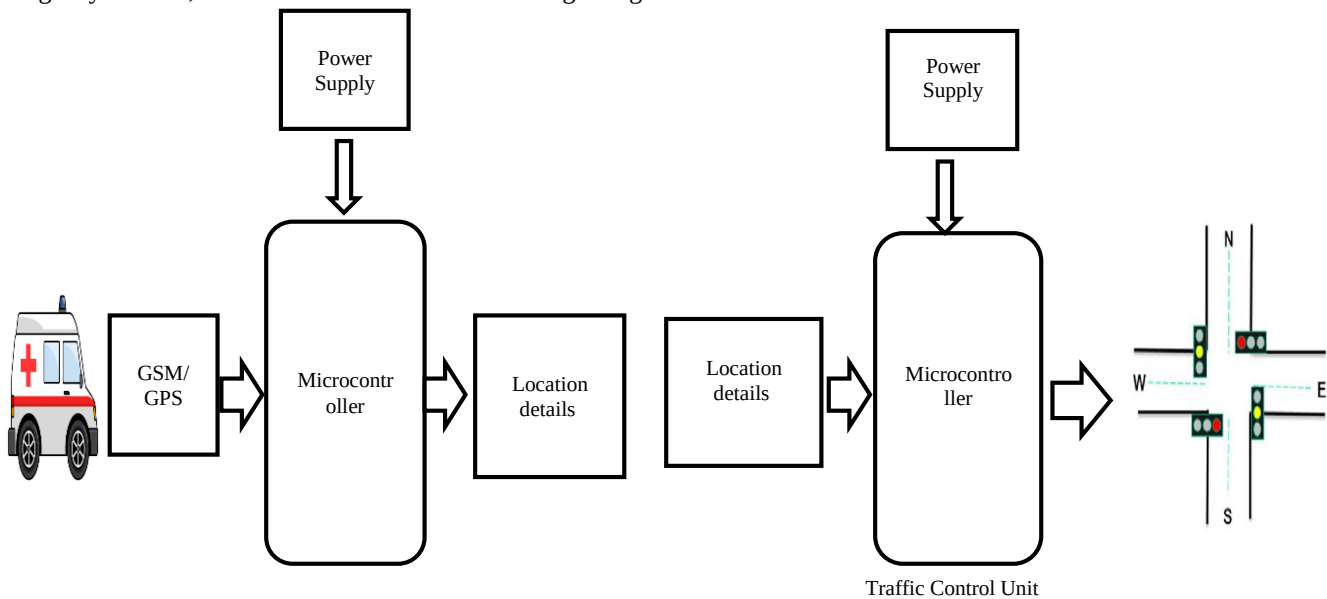


Fig. 1 Priority-based traffic management system block diagram

Infrared pairs interfaced to a microprocessor measure the traffic density at a signal location. An IR sensor system consists of an IR Transmitter (IR LED) that emits infrared light and an IR Receiver (Photodiode/Phototransistor) that detects reflected or interrupted IR light. When a vehicle passes in front of the sensor, the IR beam is interrupted, and this change is detected and counted as one vehicle.

The algorithm for the vehicle count is given below.

Step 1: Initialize the vehicle count = 0.

Step 2: Continuously monitor the IR sensor output

Step 3: If the beam is interrupted, increase the count value.

Step 4: Check that the count is greater than the designated value for a normal delay

If yes, the traffic signal follows the fixed delay

Otherwise, it adapts the green LED duration based on the count value.

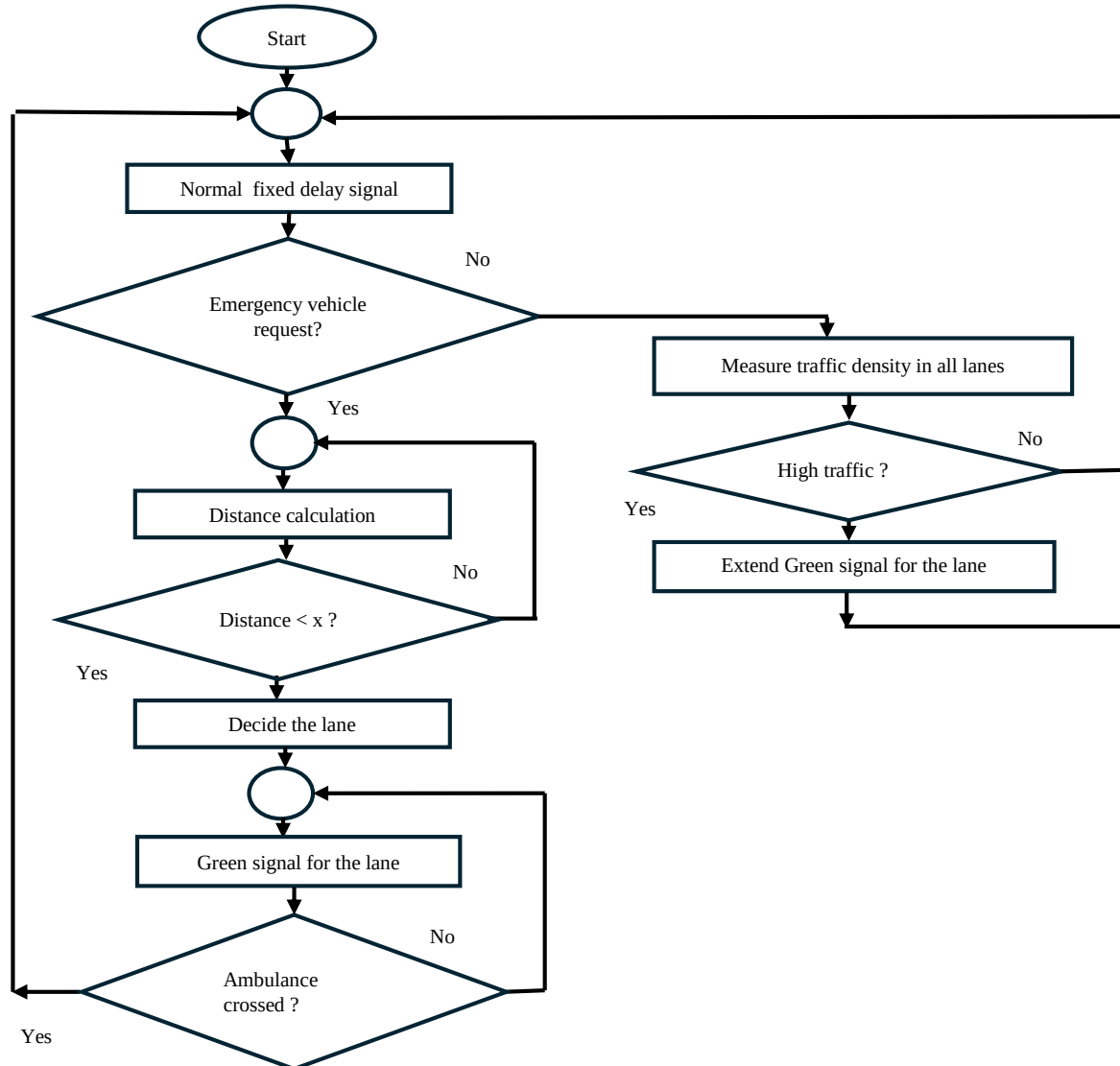


Fig. 2 Priority-based Traffic Management System flow chart

Figure 2 shows the flowchart for the emergency vehicle priority control. Under normal conditions, the system operates in fixed-delay mode. When a priority vehicle needs to cross the signalling unit, it sends its location in advance. The embedded system in the signal control unit receives this signal and calculates the distance to the emergency vehicle from the signal point. The Euclidean distance computation method is utilized to determine the distance between the vehicle and the traffic signal location. If the priority vehicle is within the predefined distance, the control unit clears the lane until the priority vehicle crosses the signal point. The lane status will turn green and resume normal operations after a predetermined period.

Figure 3 shows the circuit diagram on the transmitter side. SIM808 is interfaced with a microcontroller to send the emergency vehicle location details. A powerful GSM/GPRS

engine is included in SIM808. The SIM 808's power supply range is 3.4V to 4.4V. It is advised to use 4 V. It can operate in three different modes: minimum functionality mode, power down mode, and standard operation [27]. The SIM808 module is connected to the Arduino microcontroller. In this connection, it focuses only on three pins, which are (pin11, pin10, Ground) in Arduino and (TX, RX, Ground) in the SIM808 module. First, take a wire from pin 10 of the Arduino and connect it to TX, which is the transmitter part in the GPS-GSM module [28]. Then, another wire from pin 11 of the Arduino is connected to RX, which is a receiver part in the GPS-GSM module. Finally, connect the Ground from the module to the Ground of the Arduino.

A GPS module receives satellite signals and determines the vehicle's geographic coordinates, including latitude, longitude, speed, and time. This data is transmitted to a

microcontroller, which functions as the control unit of the system. The microcontroller acquires the serial data from the GPS module and processes it to extract the required positional information. Once the location data is decoded, the microcontroller forwards it to a monitoring station in the traffic control unit through communication modules. In a vehicle tracking setup, the GPS module continuously updates the real-time position. In short, the GPS module generates the positional data, and the microcontroller manages data processing and transmission, ensuring accurate and efficient vehicle tracking and navigation.

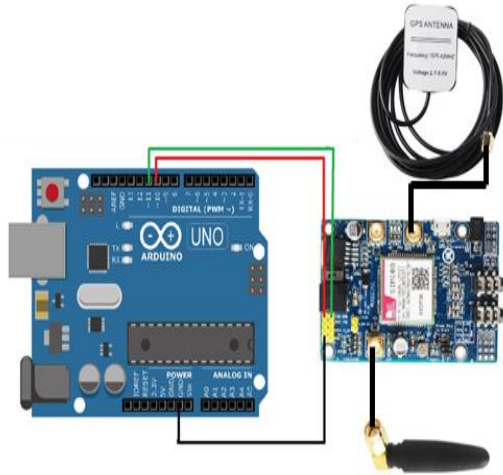


Fig. 3 Microcontroller- GPS-GSM module interfacing diagram

Figure 4 shows the circuit diagram for the 4-way traffic light system on the receiver side, which Uses An Arduino (UNO) Microcontroller. In this project, mini traffic light modules are used to represent the traffic light system. Attach each traffic light cathode to the Arduino's GND pin.

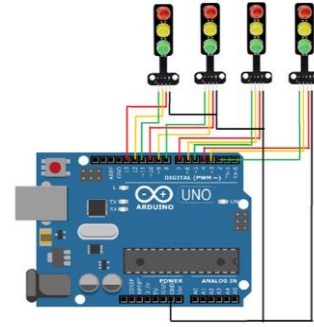


Fig. 4 Circuit diagram for traffic light system

3. Results and Discussion

Figure 5 illustrates the setup where the Arduino UNO microcontroller is interfaced with the traffic light circuit. Specifically, pins 2 through 13 of a microcontroller are connected to the traffic light system.

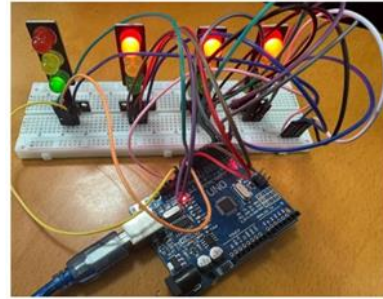


Fig. 5 Mini model of traffic light system

Table 1 outlines the typical 4-way traffic light sequence. During state 1, traffic is allowed on Road 1 by turning on the G1. In all other roads, the RED LED is ON, indicating STOP. In state 2, traffic is allowed in Road 2 and, in state 3, in Road 3, and in state 4, in Road 4.

Table 1. Normal sequence of 4-ways traffic lights

STATES	OUTPUTS											
	Road 1			Road 2			Road 3			Road 4		
	R1	Y1	G1	R2	Y2	G2	R3	Y3	G3	R4	Y4	G4
State 1	0	0	1	1	0	0	1	0	0	1	0	0
State 2	1	0	0	0	0	1	1	0	0	1	0	0
State 3	1	0	0	1	0	0	0	0	1	1	0	0
State 4	1	0	0	1	0	0	1	0	0	0	0	1

Figure 6 shows the connection of the Arduino UNO microcontroller to the SIM808 module. For proper operation, the module requires a 9-volt power supply, and the microcontroller's pins 10 and 11 are used for communication.

Table 2 provides the latitude and longitude coordinates recorded at various test locations. The GPS module in the emergency vehicle sends the latitude and longitude of the vehicle. The embedded system in the signal control unit

calculates the vehicle distance based on these values. Equation (1) indicates the distance formula used [29].

$$\text{distance}, d = A \cos(\sin(\text{lati1}) * \sin(\text{lati2}) + \cos(\text{lati1}) * \cos(\text{lati2}) * \cos(\text{longi2} - \text{longi1})) * 6371 \quad (1)$$

Where 'lati' indicates latitude and 'longi' indicates longitude.

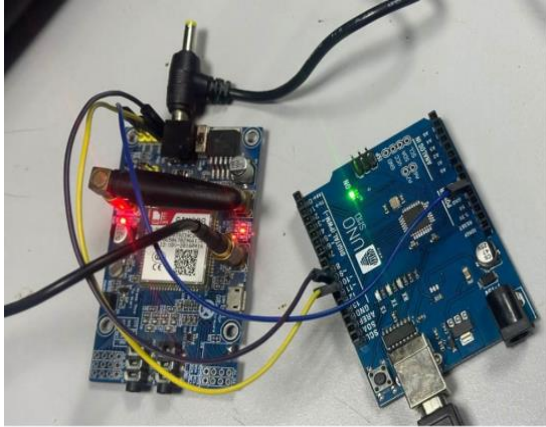


Fig. 6 Connection of Microcontroller and SIM808 module

Table 2. Emergency vehicle location details

Location no.	Latitude	Longitude
Location 1	23.321210	57.506355
Location 2	23.315454	57.504150

Figures 7 and Figure 8 display the latitude and longitude readings obtained from the SIM808 module at different locations, as shown in the serial monitor.

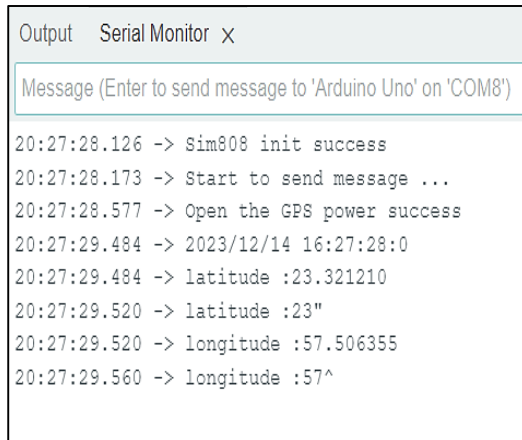


Fig. 7 Location 1 details

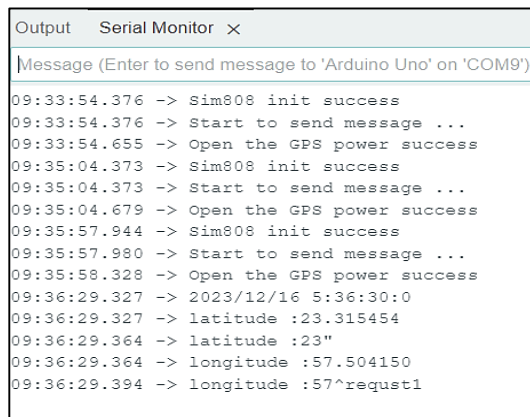


Fig. 8 Location2 details

Figure 9 displays the validation of the proposed system. Position 2 indicates the traffic control unit location. The vehicle begins its journey at position 1. It transmits its position via the embedded system, and the signalling unit's controller unit gets this information and calculates the distance.

This system has set up a one-kilometer buffer to allow the emergency vehicle to pass. At location 1, the distance becomes to 0.6785km, and the required lane will be cleared by putting the green signal ON till the vehicle passes the signalling unit. Once the vehicle passes the unit, the traffic signal resumes its normal operation.

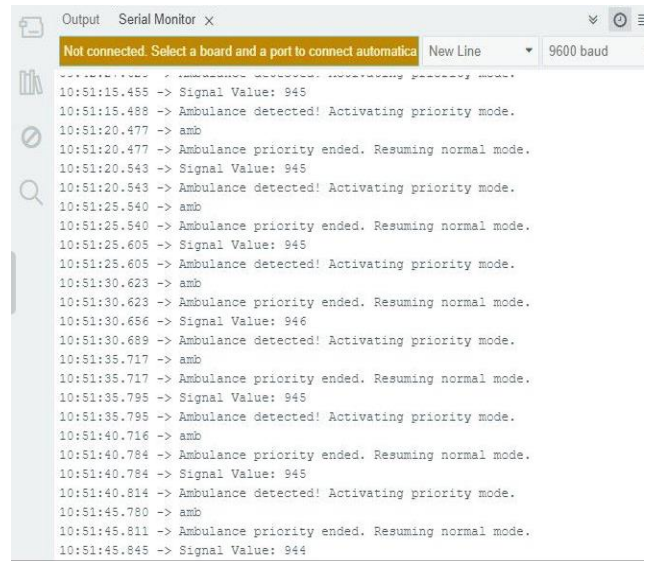


Fig. 9 Outcome of the proposed system on serial monitor

Table 3 shows a comparative analysis of the proposed system with some of the existing traffic control systems.

The suggested adaptive traffic control system employs a combination of GPS, GSM, and infrared sensor pairs to assess traffic density and prioritise emergency vehicles dynamically. Compared to previously reported systems that rely on RFID or basic IR detection, the proposed system computes the closeness of the emergency vehicle to the intersection based on the GPS location updates from the emergency vehicle.

When the emergency vehicle approaches a specified distance, the technology dynamically prolongs the green light duration until the vehicle passes the signal.

The comparative table indicates that the suggested method provides enhanced spatial awareness via GPS and GSM connection, whereas existing methods concentrate on localized detection using only RFID or IR. By assigning unique priorities for ambulances, police vehicles, etc. system enhances public safety, improves emergency response efficiency, and supports sustainable urban transportation management.

Table 3. Comparison of the existing traffic control approaches

Feature/metric	Technique used in research [30]	Technique used in research [31]	Technique used in research [32]	Technique used in Proposed approach
Traffic density measurement	RFID vehicle tag	IR sensor	IR sensor	IR pair
Priority for the emergency vehicle	RFID tag	RFID tag	RFID tag	GSM
Use of GPS	No	No	No	GPS location sent from vehicle to microcontroller extends green signal duration
Use of GSM	Yes	No	No	Yes(for communication and signal updates)
Distance calculation	No	No	No	Yes(GPS based)
Scalability potential	Limited to RFID range	Limited to RFID and sensor range	Limited to sensor range	High (GPS + GSM works across a wide area)
Real-time response	Yes (RFID tag)	Yes (RFID tag)	Yes (RFID tag)	Real-time (distance threshold, and traffic-based)

4. Conclusion

In a fixed-delay traffic system, all lanes have equal delays regardless of traffic volume under normal circumstances, and emergency vehicles are not considered. This study offers an intelligent traffic control system that uses priority indications for emergency vehicles. As a result, emergency vehicles can pass through busy locations without coming to a stop. Any emergency vehicle that must traverse the signal in advance transmits its location via a Global Positioning System (GPS). Special lines of communication are used to notify traffic control systems of the location beforehand. The suggested system is divided into two parts: a traffic control device and a live location transmitter installed in the emergency vehicle. When a vehicle approaches the signalling unit, the microcontroller unit in the signalling point receives a request

from the emergency vehicle, calculates the vehicle's distance, and if it is less than a predetermined value, it clears the lane for a certain period. The lane status will turn green and resume normal operations after a predetermined period. Both ordinary and emergency vehicles benefit from the more efficient traffic flow that this adaptive model ensures, and adaptive traffic control operates based on traffic density. The application of adaptive signalling paradigms and intelligent traffic control systems will significantly increase our capacity to save lives. As an extension of our current work, we plan to integrate artificial intelligence into the proposed system.

Conflicts of Interest

"The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper."

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