

Enhancement of a Real-Time IoT-Based Emergency Vehicle Alert System for Improved Road Safety

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ABSTRACT

Emergency vehicles require effective communication with nearby road users to support timely awareness of their approach, particularly in congested urban environments. This study develops and evaluates an IoT-based emergency vehicle alert system that provides near-real-time location monitoring and proximity-based warnings. The proposed system integrates a NEO-6M GPS module, ESP32 microcontroller, Wi-Fi communication, Firebase Realtime Database, and a web-based monitoring interface. GPS coordinates acquired by the vehicle-side prototype are transmitted through the ESP32 to Firebase and subsequently retrieved by the web interface. The road user's location is obtained through browser-based GPS, while the Haversine formula is used to calculate the separation distance between the two locations.

A predefined 1 km geofence is used as a design and experimental threshold to distinguish between normal monitoring and alert conditions. The system was evaluated through hardware and cloud database integration testing, followed by alert response testing using two vehicles representing the emergency vehicle and road user. The results demonstrated successful GPS data transmission and storage in Firebase, retrieval of the latest vehicle location, and simultaneous visualization of the emergency vehicle and road user locations through the web interface. The system maintained the normal monitoring condition at a separation distance of 1.770 km and activated the alert condition at 0.177 km. Ten experimental trials recorded alert response times ranging from 4.3 to 5.6 seconds, with an average of 4.99 seconds.

A positive relationship was observed between separation distance and alert response time, with Pearson's correlation coefficient of $r = 0.751$ and $R^2 = 0.565$. The findings demonstrate the technical feasibility of the proposed system for near-real-time emergency vehicle monitoring and geofence-based proximity alerting under the tested conditions. However, the 1 km threshold was not evaluated through alternative distance settings and should not be interpreted as an optimal warning distance for all road conditions. The proposed approach extends the previous cloud-based system by providing simultaneous visualization of both locations and an explicit distance-based alert mechanism.

Keywords: Internet of Things (IoT), Emergency Vehicle Alert System, ESP32, Firebase Realtime Database, Haversine Formula

INTRODUCTION

Emergency vehicles, including ambulances, fire engines, and police vehicles, play an important role in providing

rapid response during medical emergencies, fire incidents, and public safety operations. Their effectiveness depends on their ability to reach the incident location as quickly and safely as possible. However, rapid urbanization and the increasing number of vehicles on the road have contributed to traffic congestion, creating a challenge for emergency vehicles. Heavy traffic can delay emergency vehicle arrival at the destination and may also increase the risk of accidents when they navigate through congested roads. These challenges can affect emergency response time and may result in serious consequences, including loss of life, property damage, and reduced effectiveness of emergency response operations. In addition, conventional warning methods such as sirens and flashing emergency lights mainly depend on the awareness and response of nearby drivers. In congested traffic conditions, they may fail to hear the siren due to vehicle sound insulation, loud music, environmental noise, or because the emergency vehicle is outside their field of view. As a result, drivers may not react quickly to provide a clear path, which can further delay the emergency vehicle and increase the risk of accidents. Therefore, there is a need for a more effective warning approach that can provide timely information to drivers and improve their awareness of approaching emergency vehicles.

The rapid advancement of the Internet of Things (IoT), wireless communication technologies, and embedded systems has enabled the development of intelligent transportation solutions capable of improving communication between emergency vehicles and drivers. By integrating sensors, Global Positioning System (GPS) technology, microcontrollers, cloud computing, and web-based interfaces, real-time location information can be transmitted and presented to nearby drivers. Such an approach provides early awareness of approaching emergency vehicles, allowing drivers to take appropriate actions before the emergency vehicle reaches their vicinity. Therefore, this study proposes a real-time emergency vehicle alert system that utilizes IoT technology to enhance communication between emergency vehicles and surrounding drivers. The proposed system continuously tracks the real-time location of emergency vehicles using GPS and transmits the information through a cloud-based platform. A web-based interface retrieves the emergency vehicle location and the road user's current location through browser-based positioning, allowing both locations to be displayed on a map. The system calculates the distance between the emergency vehicle and road user using the Haversine formula and activates a proximity alert when the distance is within the predefined 1 km geofence. This provides drivers with timely information about the proximity of an approaching emergency vehicle and allows them to respond accordingly. The implementation of this system demonstrates a practical approach to improving road-user awareness of approaching emergency vehicles and supports the development of intelligent transportation systems in Malaysia.

LITERATURE REVIEW

The use of Internet of Things (IoT) technologies in transportation has supported the development of real-time vehicle monitoring and emergency alert systems. These systems commonly integrate Global Positioning System (GPS), microcontrollers, wireless communication, and cloud platforms to collect and transmit vehicle location information. Sumathy et al. (2021) developed an IoT-based vehicle accident emergency alert system that used sensors and GPS to transmit the latitude and longitude of a vehicle following an accident. Similarly, Beheramali and Sahoo (2025) developed a GPS/GSM-based system that automatically transmitted vehicle location information to hospitals, police, and registered emergency contacts. Syed et al. (2020) also demonstrated the use of IoT-based communication for emergency vehicles to support the exchange of vehicle information. These studies demonstrate the potential of GPS and IoT technologies for providing location-based information during emergency situations. The cloud-based communication has further improved the ability of IoT systems to provide real-time monitoring and notifications. Pandey et al. (2024) developed an ESP32-based collision alert system connected to the Blynk cloud platform, demonstrating the use of a microcontroller and cloud service for real-time alert communication. Chowdhury et al. (2023) also demonstrated the application of IoT technologies in emergency vehicle services within intelligent transportation systems. More closely related

to emergency vehicle warning, Ali and Nijar (2025) evaluated an IoT-based emergency vehicle alert system using a NodeMCU microcontroller and Firebase Realtime Database to transmit emergency vehicle coordinates. Their system provided notifications to drivers within a predefined 3.0 km radius through a mobile application, with notification times of less than 6 seconds. The study demonstrated the feasibility of using GPS and cloud-based communication for emergency vehicle monitoring and driver notification. However, the system primarily focused on transmitting the emergency vehicle location and did not explicitly integrate the road user's current location into the monitoring interface.

Distance estimation is an important component of emergency vehicle alert systems because it allows the system to determine whether a road user is sufficiently close to an approaching emergency vehicle. Akash et al. (2025) developed an emergency vehicle alert system using Received Signal Strength Indicator (RSSI) path-loss modelling to estimate the distance between an emergency vehicle and nearby users. Their work demonstrates the importance of determining the relative proximity between an emergency vehicle and road users for activating appropriate warnings. In comparison, GPS-based distance calculation can determine the geographical separation between two users directly from their latitude and longitude coordinates. This approach is suitable for a system that continuously obtains the locations of both the emergency vehicle and road user and determines their distance in real time. Meanwhile, geofencing provides a practical method for defining a geographical area in which a warning or system action is activated. Rosayyan et al. (2021) developed a decentralized emergency service vehicle pre-emption system using RF communication and GNSS-based geo-fencing. Their system used the location of an emergency vehicle to identify its proximity to an intersection and initiate an appropriate traffic control response. This demonstrates the use of GNSS-based geofencing for location-dependent emergency vehicle operations. Chavan et al. (2025) further applied geofencing in a real-time ambulance booking and tracking system to support location-based ambulance management. These studies demonstrate that geofencing can link real-time emergency vehicle location with predefined geographical conditions. More directly related to road-user warnings, Weibull et al. (2024) investigated geofencing to support warnings when drivers interact with approaching emergency vehicles. Their findings indicate that early emergency vehicle warnings can influence driver behaviour and support earlier responses. Therefore, geofencing can provide a defined warning area while helping to limit alerts to road users within a relevant geographical range.

Driver notification is another important consideration because the effectiveness of an emergency vehicle warning depends on whether the driver receives sufficient information and time to respond. Weibull et al. (2024) showed the importance of early warnings in supporting driver responses to approaching emergency vehicles. Petrov et al. (2020) investigated the feasibility of an emergency vehicle approaching warning system and highlighted the importance of communication performance, message delivery, and the time available for drivers to react to an approaching emergency vehicle. These findings suggest that an emergency vehicle alert system should not only identify the vehicle location but also deliver the warning in a timely manner. Consequently, the selection of a suitable proximity condition is important for providing drivers with an appropriate warning before the emergency vehicle reaches their immediate vicinity.

Besides, real-time communication performance is also important because delays in transmitting, receiving, and processing location information can affect the timeliness of emergency alerts. Kumar et al. (2023) demonstrated a V2X-enabled emergency vehicle alert system that transmitted real-time vehicle information, including GPS coordinates, to support emergency vehicle warnings. Pawar et al. (2024) reviewed V2X technologies for intelligent transportation systems and highlighted the potential of advanced communication technologies for supporting low-latency vehicle communication. However, V2X-based approaches may require dedicated communication infrastructure and interoperability between connected vehicles and transportation systems.

Alabdouli et al. (2025) highlighted that communication performance in connected transportation systems can be affected by network conditions, including packet delays and reduced data distribution during high-density traffic conditions. Osman et al. (2021) also investigated V2V communication for emergency vehicle route management, demonstrating the role of real-time communication in supporting emergency vehicle operations. Talukder et al. (2022) examined VANET-based V2V and V2I communication for vehicle collision detection

and prevention, further demonstrating the use of connected vehicle communication for timely safety warnings. These studies indicate that communication performance should be considered when evaluating the response time of real-time emergency vehicle alert systems.

Other studies have examined emergency vehicle priority and warning using different communication and transportation approaches. Shruthi et al. (2019) developed an IoT-based smart ambulance system using GPS and RFID to provide priority at traffic intersections. Patel et al. (2022) investigated an AI-based emergency vehicle priority system, demonstrating another approach to supporting emergency vehicle movement and detection.

Humagain et al. (2020) reviewed route optimisation and pre-emption methods for emergency vehicles, highlighting the importance of reducing delays during emergency operations. These approaches demonstrate that emergency vehicle response can be supported through different technologies. However, they mainly focus on traffic priority, route management, or vehicle detection rather than a location-based proximity warning for road users. Thus, an IoT-based GPS and cloud approach remains relevant for developing a practical warning system that can operate through commonly available connected devices.

Based on the reviewed literature, several research gaps remain in the development of practical real-time emergency vehicle alert systems. Existing studies have demonstrated the use of GPS and IoT technologies for emergency vehicle monitoring, while cloud platforms can support the transmission and visualization of real-time vehicle information. However, some systems primarily provide the emergency vehicle location without explicitly integrating the current location of the road user into the warning process.

Other studies have applied distance estimation, GNSS-based geofencing, or driver warning mechanisms, but these approaches differ in their communication technologies, system architecture, and notification methods. In addition, communication delays caused by network conditions, data transmission, cloud synchronization, and processing can influence the timeliness of emergency warnings.

Although geofencing has been applied in emergency vehicle operations, further practical implementation is needed to integrate emergency vehicle and road-user locations with a predefined proximity condition and real-time driver notification through a lightweight web-based system. These gaps highlight the need for a system that combines accurate location monitoring, cloud-based communication, geographical distance calculation, geofencing, and timely driver alerts in a single practical framework.

To address these gaps, this study presents an enhanced IoT-based emergency vehicle alert system building upon the work of Ali and Nijar (2025). The previous system demonstrated the feasibility of transmitting emergency vehicle coordinates through a cloud-based database and providing location information to road users. However, its monitoring interface primarily focused on the emergency vehicle location and did not explicitly visualize the road user's position or provide a distance-based alert condition for a defined proximity threshold.

The proposed system therefore extends this approach by integrating the emergency vehicle location retrieved from Firebase with the road user's current location obtained through browser-based GPS. The geographical distance between the two locations is calculated using the Haversine formula, and a predefined 1 km geofence is used to determine when the proximity alert should be activated. The system provides a web-based map interface for visualizing the emergency vehicle and road-user locations and provides a proximity warning when the road user is within the defined alert area.

METHODOLOGY

System Architecture

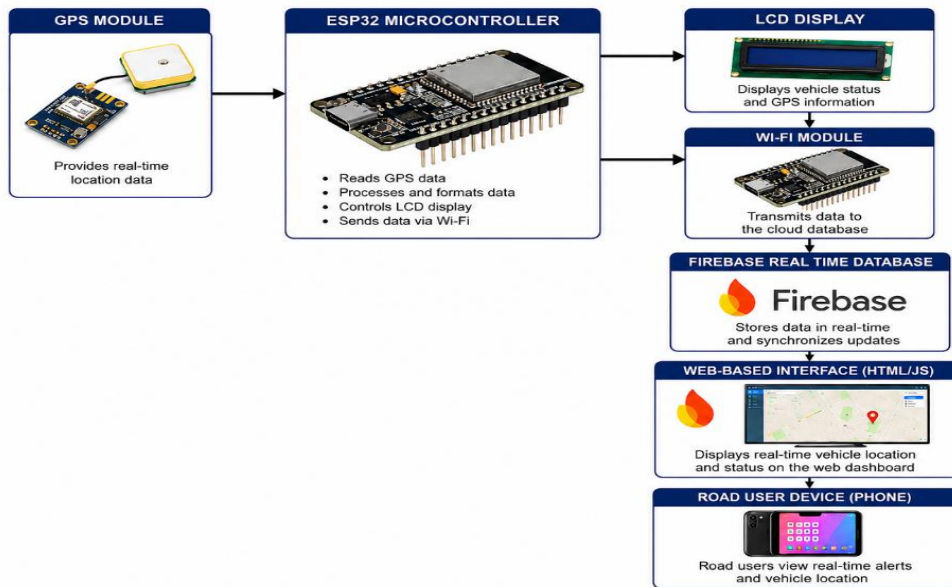


Fig. 1 System Architecture

The proposed IoT-based emergency vehicle alert system is designed to provide real-time communication between an emergency vehicle and nearby road users. As shown in Fig. 1, the system has three main stages which are GPS data acquisition, data processing and communication and alert dissemination. The system consists of a GPS module, ESP32 microcontroller, LCD display, Wi-Fi communication, Firebase Realtime Database, web-based interface and road user device. The GPS module continuously obtains the location of the emergency vehicle in the form of latitude and longitude coordinates and sends the data to the ESP32 microcontroller. The ESP32 acts as the main controller by reading and processing the GPS data. It also displays the vehicle status and GPS information on the LCD display for local monitoring. At the same time, the ESP32 uses its Wi-Fi capability to transmit the processed location data to the Firebase Realtime Database through a wireless network. This allows the emergency vehicle location to be updated and stored in the cloud in real time. The data stored in Firebase is then accessed by the web-based interface, which provides real-time information about the emergency vehicle to road users. The interface displays the vehicle location and status on a dashboard, allowing road users to monitor the approaching emergency vehicle through a web browser on their mobile devices.

The Haversine formula is applied in the proposed IoT-based emergency vehicle alert system to calculate the geographical distance between the emergency vehicle and the road user based on their respective latitude and longitude coordinates. The latitude and longitude values are converted from degrees to radians before the calculation. The Haversine formula is expressed as follows:

$$a = \sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right) \quad (1)$$

The angular distance between the two locations is then calculated as:

$$c = 2 \operatorname{atan2}(\sqrt{a}, \sqrt{1-a}) \quad (2)$$

Therefore, the geographical distance is obtained using:

$$d = Rc \quad (3)$$

Where:

d = geographical distance between the emergency vehicle and road user (km)

R = mean radius of the Earth which is 6371 km

ϕ_1 = latitude of the road user in radians

ϕ_2 = latitude of the emergency vehicle in radians

λ_1 = longitude of the road user in radians

λ_2 = longitude of the emergency vehicle in radians

$\Delta\phi = \phi_2 - \phi_1$ = difference in latitude

$\Delta\lambda = \lambda_2 - \lambda_1$ = difference in longitude

a = intermediate Haversine value

c = angular distance between the two locations

In the proposed system, ϕ_1 and λ_1 represent the latitude and longitude of the road user, respectively, while ϕ_2 and λ_2 represent the latitude and longitude of the emergency vehicle. The differences in latitude and longitude are represented by $\Delta\phi = \phi_2 - \phi_1$ and $\Delta\lambda = \lambda_2 - \lambda_1$, respectively. All latitude and longitude values are converted from degrees to radians before being used in the trigonometric functions. The resulting distance d is then compared with the predefined 1 km geofence threshold. If $d \leq 1$ km, the system activates the visual and audible alert to notify the road user of the approaching emergency vehicle.

System Operation

The system flowchart as shown in Fig. 2 illustrates the overall operation of the proposed emergency vehicle alert system. The system begins when the emergency vehicle activates the system, allowing the ESP32 microcontroller to retrieve real-time location data from the GPS module. The ESP32 processes the received GPS data and performs two main functions which are displaying the vehicle status and GPS information on the LCD display and transmitting the processed GPS data to the Firebase Realtime Database through Wi-Fi. On the road user side, the web-based interface continuously retrieves the latest emergency vehicle coordinates from Firebase and updates the real-time map display.

The system then obtains the road user's current coordinates and calculates the distance between the road user and the emergency vehicle. This distance calculation is used to determine whether the emergency vehicle is within the predefined 1 km alert range. If the calculated distance is 1 km or less, the system triggers both a visual and audible alert to inform the road user of the approaching emergency vehicle. If the distance is greater than 1 km, the system remains in the normal monitoring state without activating the alert. After the alert or normal monitoring process, the real-time map is updated again to reflect the latest vehicle position.

The system then checks whether the emergency vehicle alert system is still active. If the system remains active, the monitoring process continues by updating the vehicle location, obtaining the latest road user position, recalculating the distance, and evaluating the 1 km alert condition. This continuous process enables the system to provide real-time monitoring and timely warnings to road users as the emergency vehicle moves along its route. If the system is deactivated, the process is terminated. Overall, the flowchart represents a continuous monitoring cycle that integrates GPS positioning, ESP32 processing, Wi-Fi communication, cloud data storage, web-based visualization, distance calculation, and proximity-based alert generation.

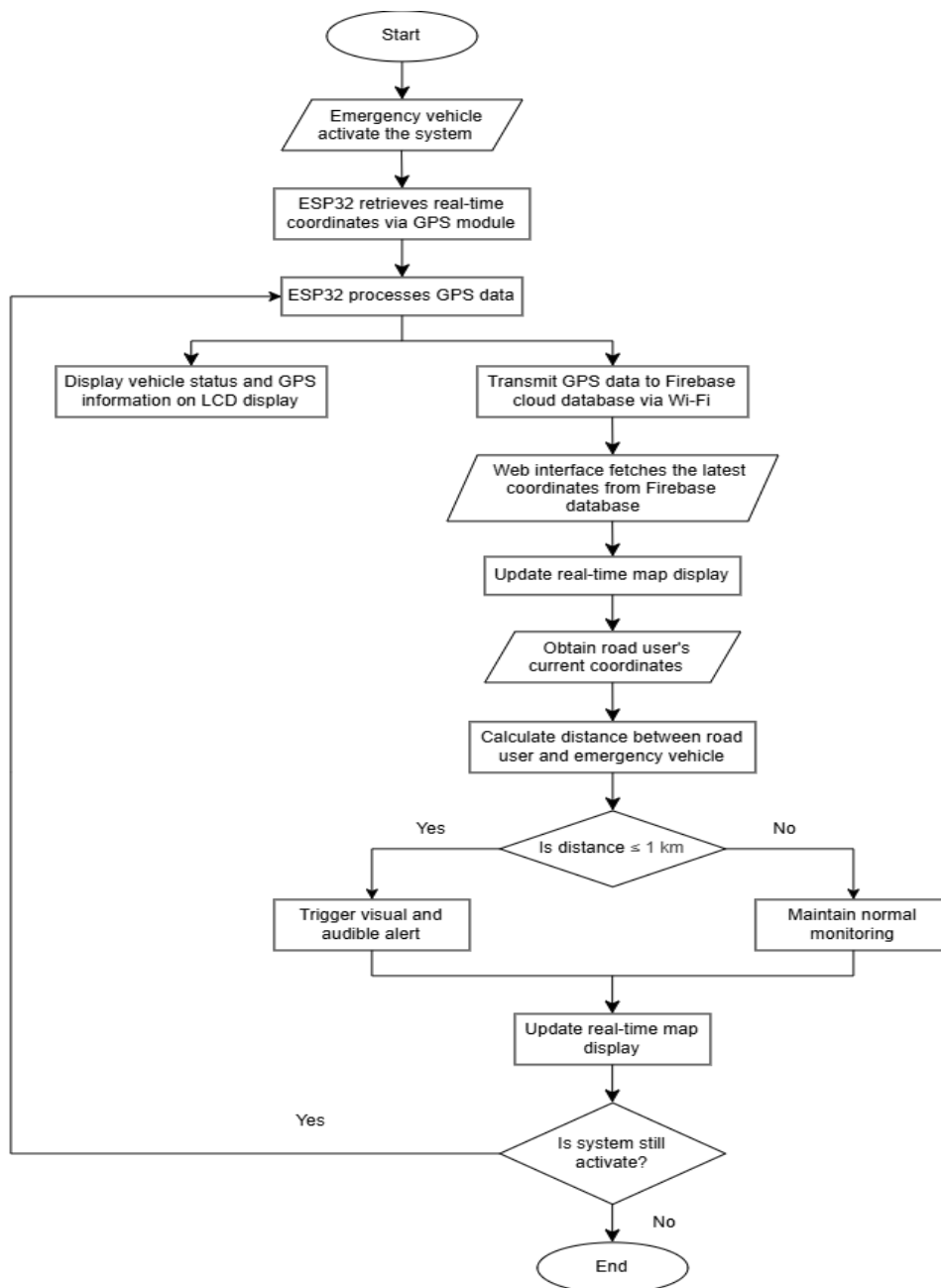


Fig. 2 System Flowchart

RESULTS AND DISCUSSION

Fig. 3 presents the prototype of the proposed IoT-based emergency vehicle alert system, which was developed as a compact vehicle-side unit for GPS data acquisition, local monitoring, and wireless data transmission. The prototype was assembled in a PVC casing to provide physical protection and to organize the main components, including the LCD display, GPS module, external GPS antenna, and USB power connection. During the experimental evaluation, the prototype was placed in one of two test vehicles, which represented the emergency vehicle, while a second vehicle was used to represent the road user. The LCD integrated into the front panel displays the acquired latitude and longitude coordinates, allowing the GPS information to be observed locally during system operation. An external GPS antenna was connected to the GPS module through a cable and positioned outside the enclosure to support GPS signal reception during the vehicle-based tests. The prototype was powered through the USB port, which provided the electrical connection required for operation during the experiments. The arrangement integrates the GPS positioning, local display, antenna connection, and power interface into a single prototype unit. The hardware configuration was designed to support the functional evaluation of the proposed system rather than to represent a final vehicle-ready

installation. In the experimental setup, the prototype acquired the position of the vehicle representing the emergency vehicle and transmitted the location data through the ESP32 and Wi-Fi connection to the Firebase Realtime Database. The prototype therefore served as the vehicle-side sensing and communication unit for subsequent web-based monitoring and proximity-based alert evaluation.

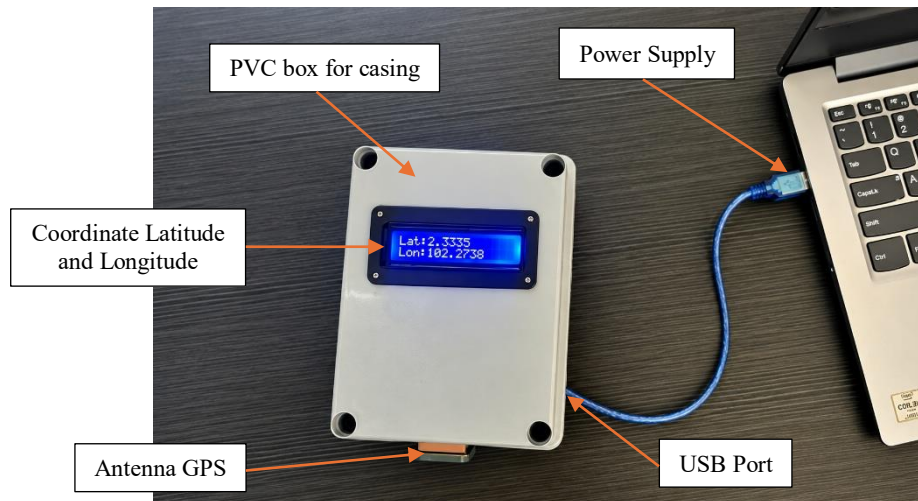


Fig. 3 Prototype of IoT-based Emergency Vehicle Alert System

System Performance Evaluation

The experimental evaluation of the proposed system was conducted under two testing settings to assess its functional operation and alert response. GPS data transmission and the real-time monitoring interface were tested on an actual road to evaluate the transmission and visualization of emergency vehicle location data under normal road movement conditions. Two vehicles were involved in the evaluation, with one vehicle representing the emergency vehicle and the other representing the road user. During the actual-road testing, the vehicle speed did not exceed 60 km/h and was dependent on the prevailing traffic conditions. Alert response time testing was conducted separately within the campus area for safety reasons, where the vehicle speed was maintained at approximately 30 km/h. During the response-time tests, the time taken from the defined alert condition to the activation of the system alert was measured using a stopwatch. These testing arrangements were used to evaluate the functional operation of GPS data transmission, real-time monitoring, and proximity-based alert generation under the available test conditions.

Cloud Database Integration Testing

The testing was conducted to verify the successful transmission, storage, and synchronization of real-time GPS data within the proposed system. The results show that the GPS coordinates obtained from the emergency vehicle, as presented in Fig. 4(a), were successfully processed by the ESP32 and transmitted through Wi-Fi to the Firebase real-time database, as presented in Fig. 4(b).

The stored records contain the corresponding latitude, longitude, and timestamp information, which are consistent with the GPS data generated by the emergency vehicle. The presence of multiple location records with different coordinate values and timestamps also indicates that the system was able to continuously update and store the vehicle location during operation.

These results confirm that the ESP32-based system successfully established communication with the Firebase real-time database and that the cloud platform was able to receive and store the emergency vehicle location data for subsequent retrieval by the web-based monitoring interface. The GPS update frequency, Firebase synchronization interval, and network latency were not independently measured during this test. Therefore,

this evaluation focuses on successful data transmission, storage and retrieval rather than isolated communication latency.

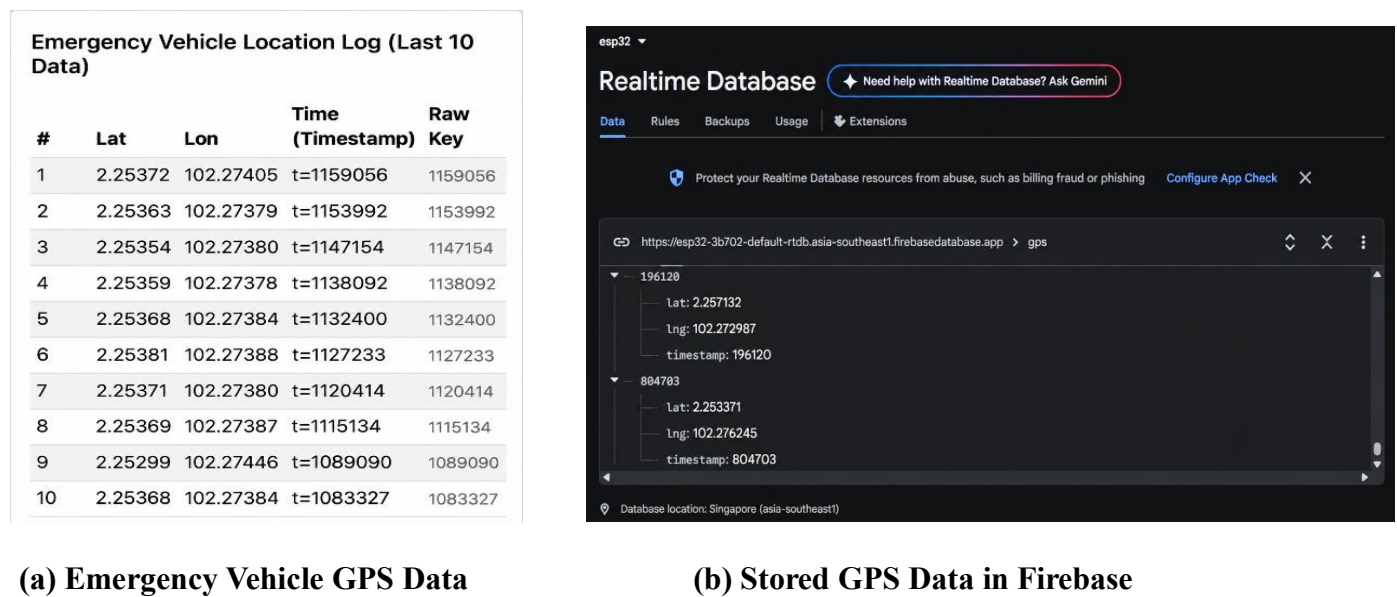


Fig. 4. GPS Data Transmission and Storage in the Firebase Realtime Database

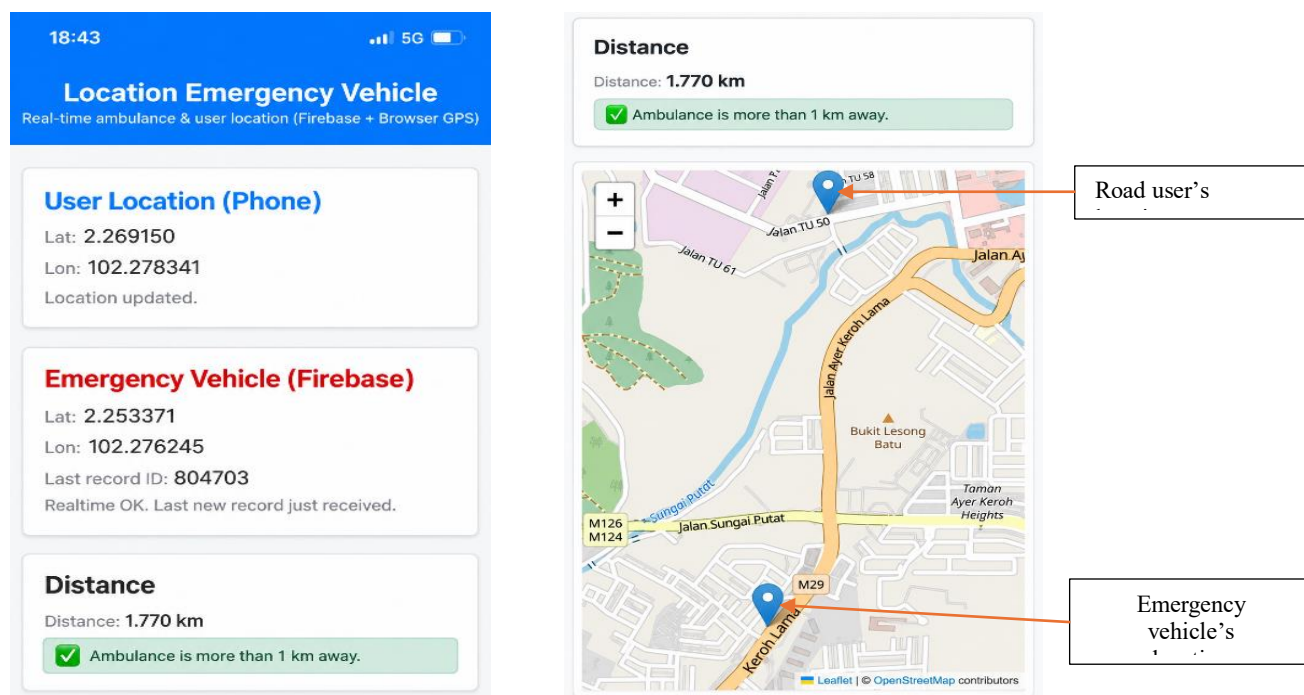


Fig. 5 Real-Time Emergency Vehicle Monitoring under Normal Condition

Fig.5 illustrates the real-time monitoring interface under the normal monitoring condition, where the simulated emergency vehicle is located outside the predefined 1 km geofence. In the experimental setup, one vehicle represented the emergency vehicle while a second vehicle represented the road user. The road user's location was obtained through the browser-based GPS at 2.269150° latitude and 102.278341° longitude, while the simulated emergency vehicle location retrieved from the Firebase Realtime Database was 2.253371° latitude and 102.276245° longitude. The interface simultaneously displays both locations as separate markers on the map, together with their respective coordinates and the calculated separation distance of 1.770 km. The latest emergency vehicle record received from Firebase is also indicated on the interface, demonstrating successful retrieval of the location data. Since the calculated distance exceeds the 1 km geofence threshold, the system

correctly maintains the normal monitoring state and displays the status message indicating that the emergency vehicle is more than 1 km away. This result also represents an improvement over the previous system reported by Ali and Nijar (2025), in which the interface primarily presented the location of the emergency vehicle and its proximity information to the user. In contrast, the proposed interface provides simultaneous visualization of both the emergency vehicle and road user locations, enabling the spatial relationship between the two entities to be directly observed. This additional location information provides a clearer representation of the proximity assessment and strengthens the monitoring capability of the proposed system under the tested condition.

Real-Time System Performance and Alert Response Testing

Fig. 6 demonstrates the activation of the proximity-based alert when the simulated emergency vehicle enters the predefined 1 km geofence. During the experiment, the road user's location was obtained through the browser-based GPS at 2.254573° latitude and 102.277283° longitude, while the simulated emergency vehicle location retrieved from the Firebase Realtime Database was 2.253371° latitude and 102.276245° longitude. The interface indicates that the latest emergency vehicle record was successfully received from Firebase and displays both locations as separate markers on the map. Based on the Haversine calculation, the separation distance between the two vehicles was 0.177 km. As this value is below the predefined 1 km threshold, the system automatically changed from the normal monitoring state to the alert state and displayed the warning message, "ALERT: Ambulance is within 1 km!". The visual representation of both locations further confirms that the alert condition corresponds to the proximity between the simulated emergency vehicle and road user. This result demonstrates the successful operation of the distance-based decision logic for the tested within-geofence condition. Compared with the previous system developed by Ali and Nijar (2025), which provided notifications to drivers when an emergency vehicle was detected within a defined 3.0 km radius, the proposed system introduces an explicit 1 km geofence condition for proximity-based alert activation. This provides a more clearly defined alert boundary and directly links the warning state to the calculated distance between the emergency vehicle and road user. Therefore, Fig. 6 provides experimental evidence that the proposed system can distinguish the tested proximity condition and automatically activate the corresponding visual alert. The alert was successfully activated in all ten response-time trials conducted within the 1 km geofence, demonstrating consistent alert activation under the tested conditions.

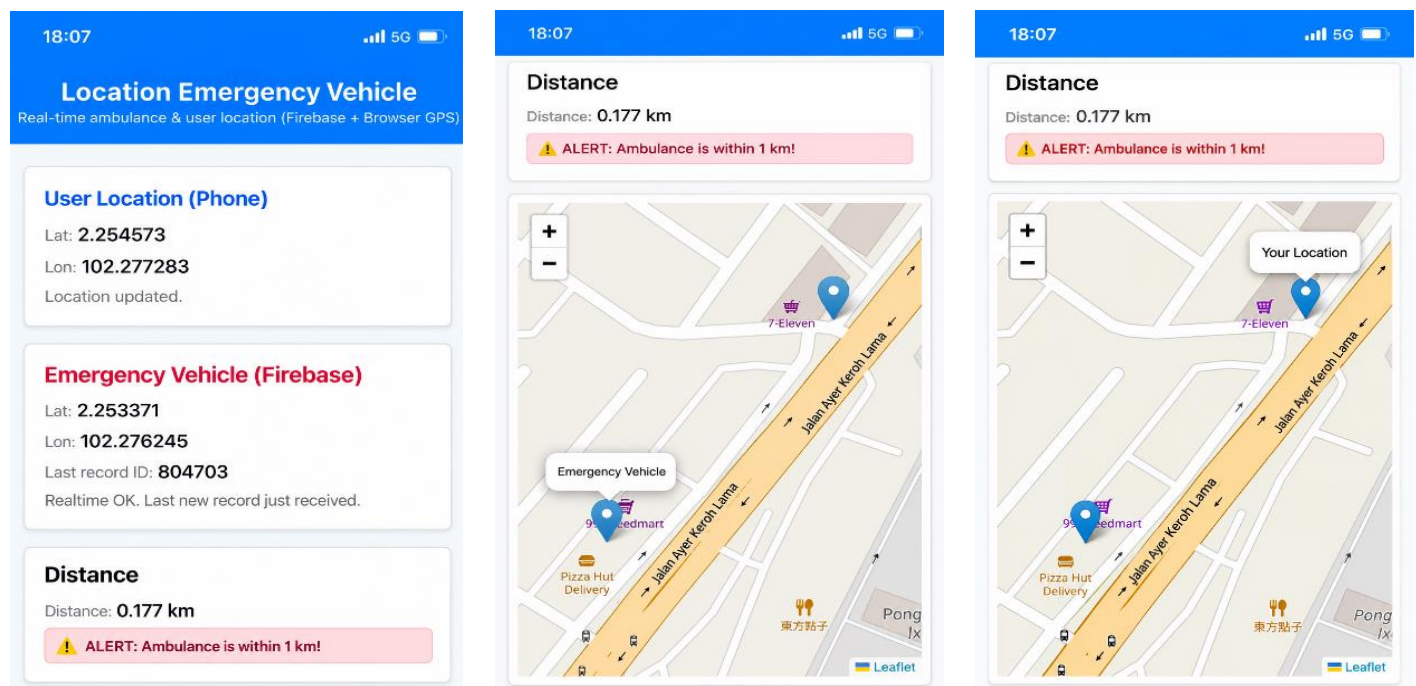


Fig. 6 Emergency Vehicle Alert Activation Based on 1 km Geofence

Fig. 7 presents the relationship between the separation distance of the simulated emergency vehicle and the alert response time based on ten experimental trials conducted within the proposed 1 km geofence. The

measured response times ranged from 4.3 to 5.6 seconds, with an average of 4.99 seconds, and the individual observations showed an overall increasing trend as the separation distance increased. Pearson correlation analysis produced a positive correlation of $r = 0.751$ ($n = 10$, $p \approx 0.012$), while the coefficient of determination, $R^2 = 0.565$, indicates that approximately 56.5% of the observed variation in response time was associated with distance in the tested dataset. These results indicate a positive relationship between separation distance and measured alert response time under the experimental conditions. However, the correlation should be interpreted cautiously because only ten observations were available and the result does not establish a causal relationship between distance and response time. The remaining variation may be associated with factors such as GPS update timing, wireless communication, Firebase data synchronization, browser processing, and network conditions, although these factors were not independently measured in this study. Therefore, the measured response time represents the overall system response under the tested conditions rather than an isolated communication or processing delay. Compared with the previous work by Ali and Nijar (2025), which reported notification response times at 1, 2, and 3 km using aggregated minimum, maximum, and average values, the present evaluation provides a more detailed trial-level assessment within the proposed 1 km alert range. The current results also show a maximum measured response time of 5.6 seconds, compared with approximately 6.4 seconds reported as the maximum at the 3 km test condition in the previous study. Nevertheless, direct performance superiority should be interpreted cautiously because the tested distance ranges and system architectures differ. These findings provide experimental evidence of the response behaviour of the proposed system within its defined 1 km monitoring range.

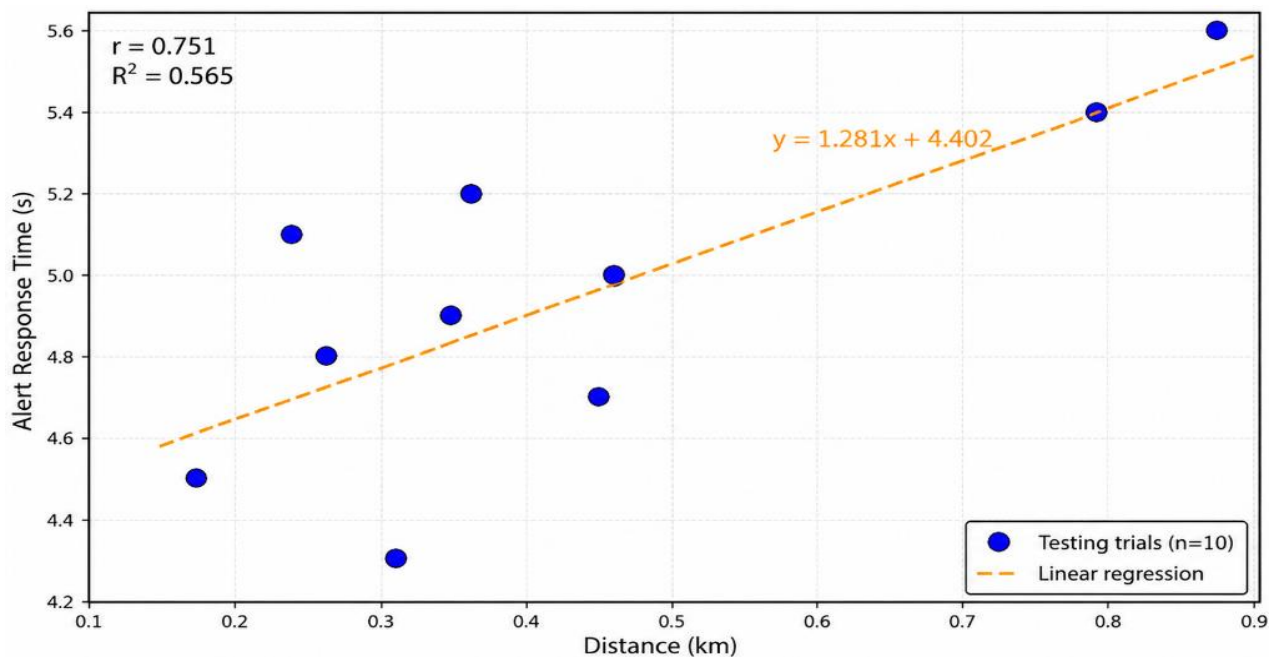


Fig. 7 Effect of Emergency Vehicle Distance on Alert Response Time

Experimental Limitations

The experimental results should be interpreted within the scope of the conducted prototype evaluation. The testing involved two vehicles, with one representing the emergency vehicle and the other representing the road user. GPS data transmission and real-time monitoring were evaluated on an actual road, where vehicle speed did not exceed 60 km/h and was dependent on traffic conditions, while alert response time was evaluated within the campus area at approximately 30 km/h for safety reasons. The response time was measured manually using a stopwatch. Vehicle speed, GPS update frequency, Firebase synchronization interval, network quality, and individual communication or processing delays were not independently controlled or measured. In addition, the 1 km geofence used in this study was a predefined design and experimental threshold selected for prototype evaluation and was not established through optimization or sensitivity analysis. Therefore, the 1 km threshold should not be interpreted as an optimal or universally applicable warning distance for all road conditions. The appropriate warning distance may vary depending on factors such as vehicle speed, traffic

density, road characteristics and communication conditions. The present results demonstrate the functional feasibility of the proposed system in distinguishing the tested proximity conditions based on the predefined 1 km threshold, rather than establishing its practical suitability for all emergency vehicle operating conditions. Further evaluation involving more trials, different vehicle speeds, network conditions, road environments, and alternative geofence thresholds would be required to assess its robustness and determine a more suitable warning distance for practical deployment.

CONCLUSION

In conclusion, this study designed, prototyped, and evaluated an IoT-based emergency vehicle alert system using an ESP32 microcontroller, GPS module, Wi-Fi communication, Firebase Realtime Database and a web-based monitoring interface. The proposed system integrates the emergency vehicle location retrieved from Firebase with the road user's location obtained through browser-based GPS and applies the Haversine formula to determine their separation distance. A predefined 1 km geofence was implemented as a design and experimental threshold to distinguish between normal monitoring and alert conditions. Experimental evaluation using two vehicles to represent the emergency vehicle and road user demonstrated successful GPS data transmission, cloud database integration, simultaneous visualization of both locations, and automatic proximity-based alert activation. The system maintained the normal monitoring condition at a separation distance of 1.770 km and activated the alert condition at 0.177 km. Across ten experimental trials, the measured alert response time ranged from 4.3 to 5.6 seconds, with a positive relationship observed between distance and response time ($r = 0.751$, $R^2 = 0.565$). The findings demonstrate the technical feasibility of the proposed system for near-real-time emergency vehicle monitoring and distance-based warning under the tested conditions. The proposed approach extends the previous cloud-based emergency vehicle monitoring system by providing simultaneous visualization of the emergency vehicle and road user locations together with an explicit geofence-based alert mechanism. The 1 km threshold should not be interpreted as an optimal or universally applicable warning distance for all road conditions, as alternative thresholds were not evaluated in this study. Further evaluation involving more trials, different vehicle speeds, network environments, road conditions, alternative geofence thresholds, and driver-response scenarios is recommended to assess the robustness and practical effectiveness of the system for real-world emergency vehicle deployment.

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