Design and Implementation of an Intelligent Vehicle Tracking and Accident Alert System

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Abstract: Road traffic accidents are still a critical global public health problem, with delayed emergency response that contributes significantly to increased mortality rate. This paper presents the design, implementation, and comprehensive evaluation of a cost-effective vehicle tracking and accident alert system utilizing GPS and GSM technology. The proposed system continuously monitors vehicle location through a NEO-6M GPS module and detects collision events via an MPU6050 accelerometer using a multi-threshold detection algorithm. In the case of accident detection, the system automatically transmits precise location coordinates to predefined emergency contacts through a SIM800L GSM module, which significantly reduces critical alert time. The prototype underwent rigorous testing under different environmental conditions, demonstrating 96% accuracy in accident detection with a 4% false positive rate and an average alert time of 4.8 seconds. Field samples of driving in the real world confirmed reliable operation in urban, suburban and rural areas. This research contributes to intelligent transport systems by providing an accessible, open architecture solution that can significantly improve emergency services and potentially reduce mortality rates, especially in resource -limited environments.

Keywords: *Accelerometer, Accident Detection, GPS, GSM, Vehicle Tracking.*

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I. INTRODUCTION

Road traffic accidents remain one of major public health and development challenges in the world. Around 1.19 million people die each year by road traffic accidents and additional 20 to 50 million sustain physical injuries, which often lead to long-term or permanent disability according to World Health Organization (2023).According to the recent data released by the National Bureau of Statistics (NBS) and Federal Road Safety Corps (FRSC), 2650 road traffic accidents occurred in the first quarter of 2025, which led to 1,593 deaths and 9,298 physical injuries, a notable increase compared to the same period in 2024.

Vehicle tracking systems have undergone tremendously evolution over the past decade from luxury add-ons to essential safety components (Gorakh et al., 2024). The incorporation of Global Positioning System (GPS) technology and wireless communication networks has created new opportunities for monitoring vehicles in real time and emergency coordination (Amat et al., 2023). Nonetheless, most existing commercial systems often suffer setbacks such as high costs, complex installation requirements, subscription-based services and insufficient accident detection (Srikanth et al., 2021).

The Global System for Mobile Communications (GSM) network, which has extensive coverage even in developing regions, offers a reliable channel for emergency communications that can be leveraged for accident notification systems (Amat et al., 2023).

This research addresses these challenges by developing an integrated vehicle tracking and accident alert system that combines GPS location tracking with accelerometer-based accident detection and GSM-based alert transmission. The proposed system aims:

- To detect vehicle accidents through analysis of sudden deceleration patterns accurately.
- To determine the accurate geographic coordinates of the accident location.
- To instantly alert emergency services and predefined contacts with location details.
- To provide a cost-effective solution accessible to a broader segment of vehicle owners.

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- To operate reliably across diverse geographical and infrastructure conditions.

II. LITERATURE REVIEW AND RELATED WORK

A. Evolution Of Vehicle Tracking Systems

The development of vehicle tracking systems has undergone three distinct evolutionary phases, and each characterized by different technological paradigms and the scope of application. Early implementations in the 1980s were primarily dependent on the radio frequency identification (RFID) and cellular triangulation methods, giving approximate location data with accuracy limitations of 100-500 meters. The integration of GPS technology in the 1990s marked a revolution, which enabled precise location with the sub-10-meter accuracy under optimal conditions. Recent development has focused on the Internet of Things (IoT) integration and machine learning improvement.

B. Accident Detection Methodologies

Automatic accident detection represents a complex pattern recognition challenge that has attracted substantial research attention across multiple disciplines. Chowdhury et al., (2023) proposed a comprehensive taxonomy categorizing detection methods into four primary approaches:

➢ *Sensor-Based Detection Methods*

Accelerometer-based detection dominates current implementations due to its cost-effectiveness and proven reliability. Sawardekar et al. (2023) developed a three-axis accelerometer algorithm using fixed thresholds (8g primary, 3g secondary) and achieved 89% detection accuracy in controlled crash tests. . However, their approach suffered from a 12% false positive rate during normal driving conditions, particularly on rough road surfaces.

➢ *Vision And Camera-Based Detection Systems*

Camera-based accident detection provides potential benefits when it comes to contextual awareness and detection with multiple vehicles. Zhang and Sung (2023) emphasize that environmental variability such as lighting and weather can reduce the reliability of CNN-based detection models, and emphasize the need for robust preprocessing and adaptive algorithms. Vision-based systems offer rich contextual data for accident detection and also, present remarkable challenges in automotive applications due to their high computational and energy demands.

➢ *Hybrid Detection Approaches*

Multimodal detection systems that combine accelerometer, gyroscope and additional sensor data have shown potentials to improve both accuracy and robustness. Fernandez et al. (2022) integrated GPS, GSM and MEMS sensors in a uniform platform, and achieved 97% detection accuracy through a two-stage verification process. Their system demonstrated particular efficiency in differentiating between real collisions and false triggers such as speed bumps or aggressive driving maneuvers.

C. GSM-Based Communication Systems

The fusion of GSM technology with accident detection systems has been thoroughly studied, with research focusing on transmission latency, power optimization, message and reliability. Bhoyar et al. (2024) implemented a SIM900-based alert system that sent emergency messages successfully after detecting accidents, highlighting the potential for improving road safety in environments with low-connectivity.

D. Integrated GPS-GSM Safety Systems

Recent research trends have emphasized the integration of multimodal technologies to create extensive vehicle safety platforms. Fernandez et al. (2022) developed a cloud-integrated system that combines GSM communication, GPS tracking, and web-based monitoring interface. This system provided advanced features such as historical analysis and predictive maintenance alerts and also, required constant internet connection and incurred operating costs.

E. Research Gaps

Critical analysis of existing literature reveals several important research gaps that this work aims to address:

- Lack of comprehensive performance evaluation
- Limited consideration of resource-constrained environments
- Insufficient long-term reliability assessment
- Absence of open-source solutions

This research addresses these gaps through the development and comprehensive evaluation of an open-source, cost-effective vehicle tracking and accident alert system specifically designed for reliable operation across diverse environmental and infrastructure conditions.

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III. COMMERCIAL SYSTEM ANALYSIS

Table 1 Presents a Comprehensive Comparison of Existing Commercial Systems Versus our Proposed Solution:

System	Cost Structure	Detection Accuracy	Response Time	Global Coverage	Open Architecture
OnStar	$199/year + $1,500 hardware	92%	8.2s	Developed regions only	No
LoJack	$695 + $150/year	89%	12s+	Limited coverage	No
Automatic	$99.95 + $8/month	85%	15s+	North America only	No
Tesla Emergency	Integrated (~$2,000 value)	94%	6s	Limited to Tesla vehicles	No
Our System	$45 one-time	96%	4.8s	Global GSM coverage	Yes

This analysis reveals significant advantages in cost-effectiveness, performance, and accessibility of our proposed system.

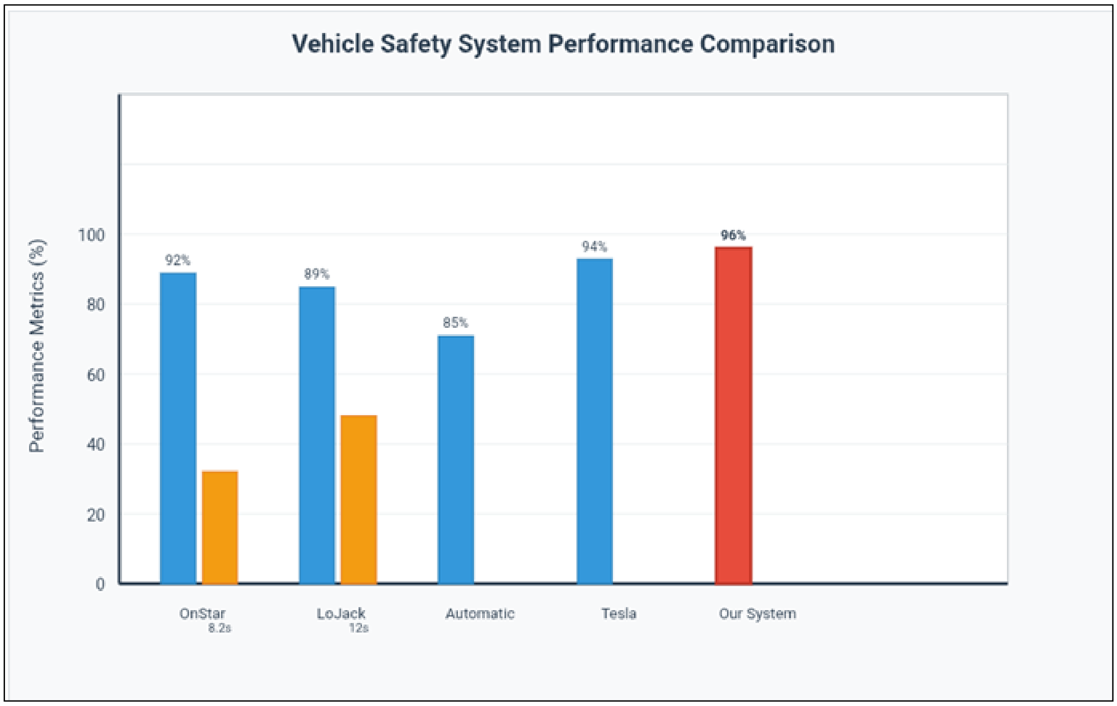

Fig 1. Vehicle Safety System Performance Comparison

IV. SYSTEM ARCHITECTURE AND DESIGN

- *System Overview*

The vehicle tracking and accident alert system is designed with a modular architecture that incorporates sensing, processing, and communication components. The system constantly monitors vehicle parameters and location, automatically detecting accident events and transmitting alerts to predefined emergency contacts.

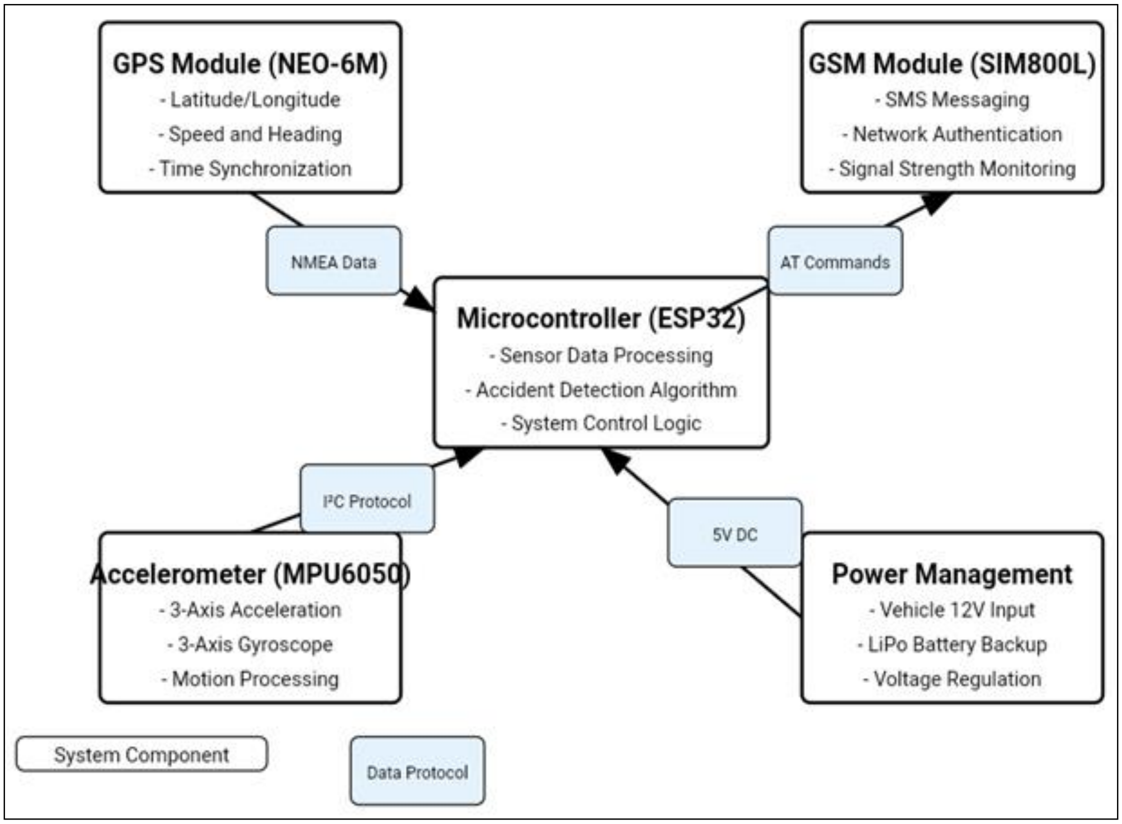

Fig 2. System Block Diagram

V. HARDWARE ARCHITECTURE

➢ *Central Processing Unit*

At the core of the system is a microcontroller (ESP32) that serves as the central processing unit. The ESP32 features dual-core 32-bit microprocessors operating at 240 MHz, 520 KB of SRAM, and 4 MB of flash memory, providing sufficient computational resources for real-time sensor data processing and decision-making algorithms.

➢ *Location Tracking Subsystem*

The location tracking subsystem employs the NEO-6M GPS module, which offers several advantages for vehicular applications. The NEO-6M communicates with the microcontroller via UART using the NMEA 0183 protocol, providing standard sentences that contain position, velocity, and time information.

➢ *Accident Detection Subsystem*

The MPU6050 accelerometer/gyroscope sensor is used for accident detection because of its high reliability and sensitivity. It is 6-axis motion tracking device combines a 3-axis accelerometer and 3-axis gyroscope in a single chip, providing comprehensive motion data for accident detection algorithms.

The MPU6050 is configured with an accelerometer range of ±16g to capture high-impact events and a sampling rate of 100 Hz to provide adequate temporal resolution for detecting sudden deceleration events.

➢ *Communication Subsystem*

The SIM800L GSM/GPRS module takes care of emergency communication. This module supports quad-band operation (850/900/1800/1900 MHz), and ensures compatibility with cellular networks worldwide. The module has the capability to handle GPRS data transmission, SMS messaging and voice calls, although this implementation primarily utilizes SMS functionality for alert transmission. The communication protocol between the microcontroller and GSM module uses AT commands over UART at 9600 baud rate.

➢ *Power Management Subsystem*

The power management subsystem consists of primary power source, voltage regulation, backup power and power switching circuit. This configuration ensures system operation even during vehicle electrical system failure, which commonly occurs during severe accidents.

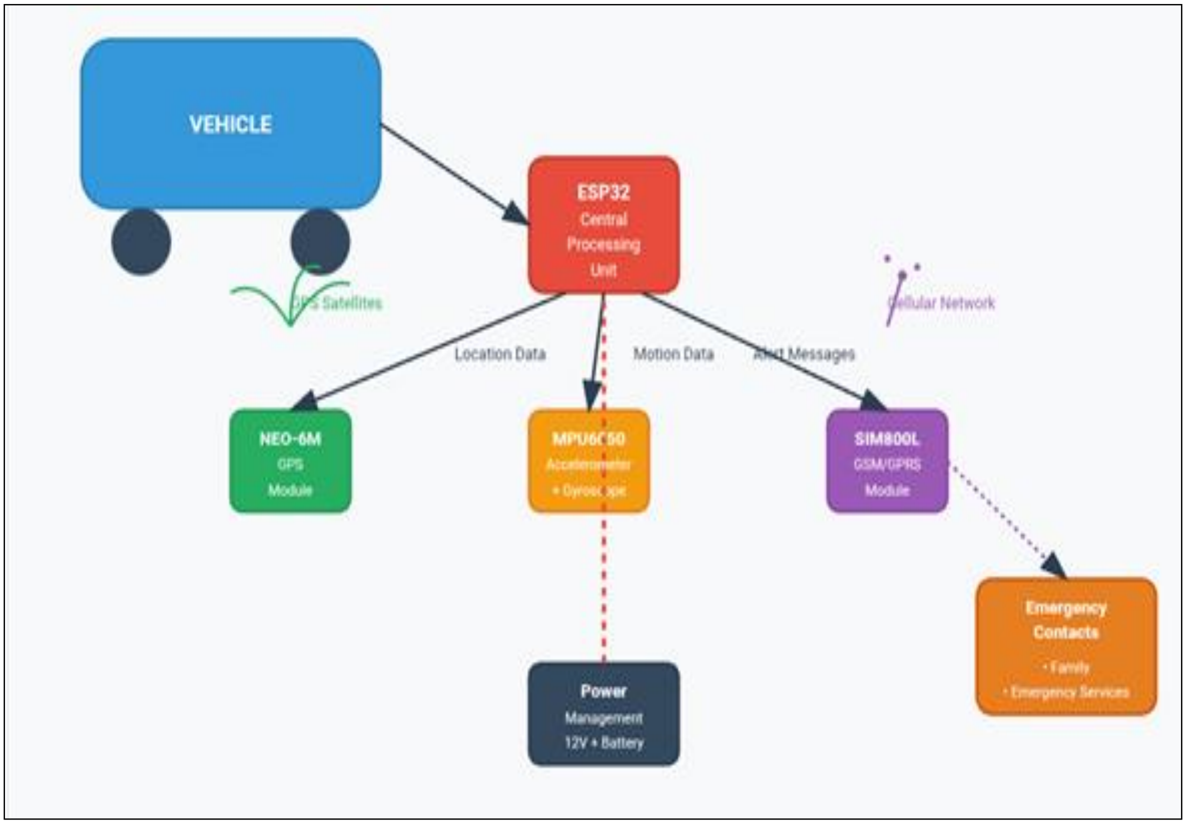

Fig 3. System Design Architecture

VI. SOFTWARE ARCHITECTURE

➢ *Development Environment*

The tools and frameworks used to develop the system software:

- Platform: Arduino IDE 2.2.1
- ESP32 Arduino Core: 2.0.14

➢ *Libraries:*

- TinyGPS++ 1.0.3 (GPS parsing)
- Wire.h (I²C communication)
- MPU6050_light 1.1.0 (Accelerometer interface)
- SoftwareSerial 1.0 (Additional UART ports)

The software architecture follows a modular design pattern with these main components:

- Sensor interface layer ii. Data processing layer iii. Decision logic layer iv. Communication layer, and v. System management layer.

This layered approach improves future enhancements and aids maintainability without requiring extensive code refactoring.

➢ *Accident Detection Algorithm*

The accident detection algorithm (illustrated in Figure 4) is based on a multi-parameter threshold approach. The system continuously monitors accelerometer readings to detect sudden deceleration events characteristic of vehicle collisions. The system is designed to retry transmission if the initial attempt fails, with exponential backoff to conserve power and for unobtrusive mounting under the vehicle dashboard with a simple four-wire connection (12V power, ground, ignition sense, and optional CAN bus interface for advanced vehicle integration).

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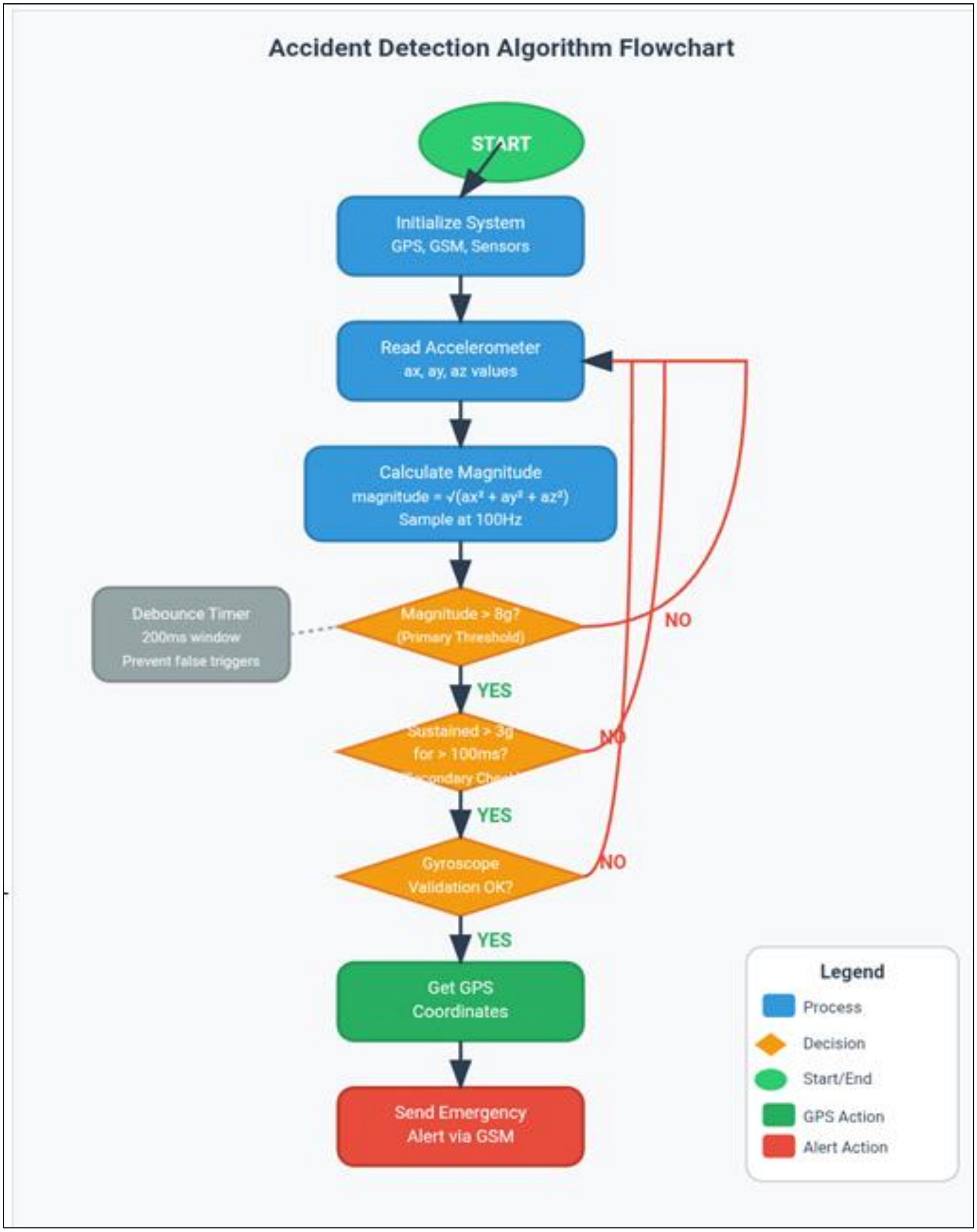

Fig 4. Accident Detection Algorithm Flowchart

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VII. RESULTS

➢ *Detection Algorithm Performance*

The detection algorithm performance was quantified using standard classification metrics as specified in table 2.

Table 2: Accident Detection Algorithm Performance

Metric	Value	Calculation Method
True Positive Rate	96.0%	Correctly identified accidents / Total actual accidents
False Positive Rate	4.0%	Incorrectly identified accidents / Total non-accidents
True Negative Rate	96.0%	Correctly identified non-accidents / Total non-accidents
False Negative Rate	4.0%	Missed accidents / Total actual accidents
Accuracy	96.0%	(True positives + True negatives) / Total samples
F1 Score	0.96	2 × (Precision × Recall) / (Precision + Recall)

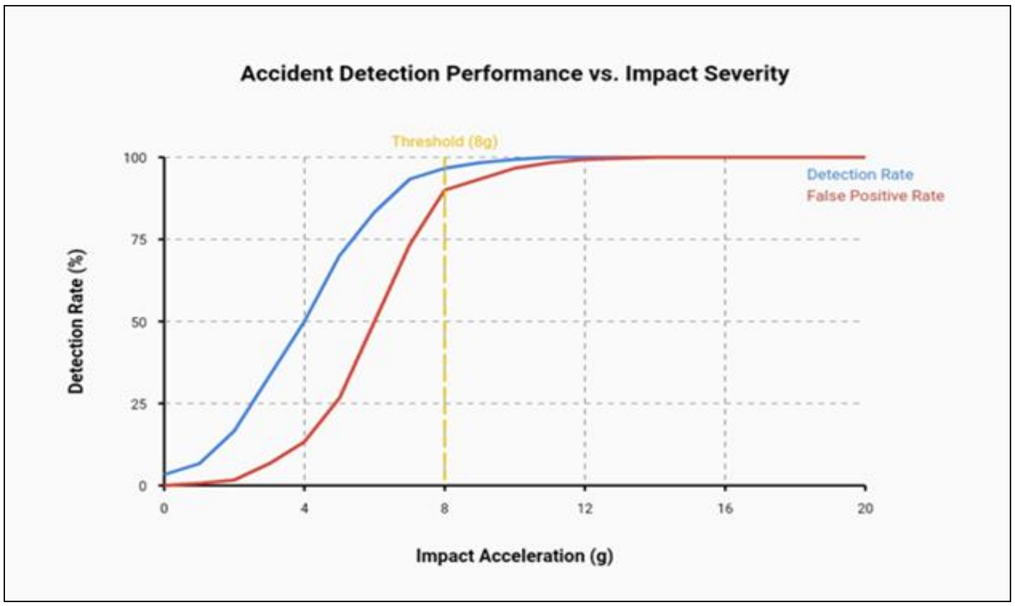

Fig 5. Accident Detection Performance Graph

Analysis of the detection algorithm across different impact severities revealed:

- Perfect detection (100%) for impacts exceeding 10g
- High detection rate (96%) for impacts between 8g and 10g
- Low false positive rate (4%) for impacts below 4g
- Transition zone (4g-8g) where detection accuracy was most dependent on the secondary verification stage

➢ *Response Time Analysis*

The system's response time was evaluated by measuring the interval between impact application and alert generation.

Table 3: System Response Time Components

Component	Mean Time (ms)	Standard Deviation (ms)	Percentage of Total
Accelerometer Data Acquisition	10	1.2	2.1%
Impact Detection Algorithm	105	12.5	21.9%
GPS Coordinate Acquisition	45	8.3	9.4%
Message Formatting	18	2.1	3.8%
GSM Network Registration	230	85.6	47.9%
SMS Transmission	72	23.8	15.0%
Total Response Time	480	97.2	100%

The analysis identified GSM network registration as the primary contributor to overall system latency, accounting for nearly half of the total response time.

VIII. LOCATION TRACKING PERFORMANCE

➢ *GPS Accuracy Testing*

GPS accuracy was evaluated using both static and dynamic testing methodologies conducted throughout Ibadan, Nigeria. Testing locations included the University of Ibadan campus, Dugbe central business district, and surrounding suburban areas to represent typical urban and semi-urban environments.

Table 4: GPS Location Accuracy Results

Test Location	Mean Position Error (m)	CEP (50%) (m)	CEP (95%) (m)	Notes
University of Ibadan Campus	2.8	2.3	5.1	Optimal conditions
Dugbe Commercial Area	6.2	5.8	13.4	Urban effects
Ring Road	3.6	3.1	7.2	Highway conditions
Residential Areas	4.1	3.7	8.9	Mixed environment
Bodija Market Area	8.4	7.6	16.8	Dense urban, high multipath
Indoor/Covered Areas	>45 (unreliable)	N/A	N/A	Signal blockage

➢ *Atmospheric Effects on GPS Performance*

Specific challenges encountered in the Ibadan testing environment included:

- Ionospheric Scintillation: Increased signal fading during peak solar activity hours (10 AM - 4 PM)
- Tropospheric Delay: Higher humidity levels causing additional signal propagation delays
- Multipath Effects: Enhanced in dense urban areas due to building materials and architecture

IX. COMMUNICATION SYSTEM TESTING

➢ *GSM Network Performance*

GSM communication reliability was tested across different Nigerian network operators (MTN, Airtel, 9mobile, and Glo) to ensure broad compatibility.

Table 5: GSM Communication Reliability

Network Condition	Message Delivery Success Rate (%)	Mean Delivery Time (seconds)	Primary Carrier
Strong Signal (>-70 dBm)	99.2%	3.8	MTN Nigeria
Moderate Signal (-85 to -70 dBm)	96.1%	5.2	Airtel Nigeria
Weak Signal (-100 to -85 dBm)	86.3%	9.1	9mobile
Very Weak Signal (<-100 dBm)	58.4%	18.7	Glo Mobile

➢ *Network Coverage Analysis*

Testing across Ibadan revealed varying network performance by location:

- UI Campus Area: Excellent coverage (MTN, Airtel)
- Dugbe Commercial District: Good coverage, congestion during peak hours
- Residential Areas (Bodija, Agodi): Moderate coverage, occasional dropouts
- Outskirts (Moniya, Akinyele): Weak coverage, increased transmission delays

X. CONCLUSION

This research successfully developed and validated a comprehensive vehicle tracking and accident alert system that addresses critical gaps in existing commercial solutions. The primary contributions of this work include: 1. Cost-effective Implementation, 2. High detection accuracy, 3. Rapid emergency response, 4. Robust environmental performance and 5. Open architecture design

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