

# Advanced Vehicle Safety System with Multi-Sensor Fusion

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**Abstract**—Road traffic accidents are still a major cause of death around the world. This is largely due to delays in detecting vehicle impacts and the emergency responses that follow, which often worsen injuries and damage. The proposed Advanced Vehicle Safety System with Multi-Sensor Fusion addresses this issue by continuously monitoring accelerations with the MPU6050 IMU, tracking GPS location using the NEO-6M, and processing information with an ESP32 for real-time collision detection. It utilizes adaptive threshold algorithms in conjunction with Kalman filter fusion. Once an impact is confirmed, the system automatically sends accurate accident coordinates and severity information via SMS using the GSM module (SIM800L) to emergency contacts that have been pre-registered. It also activates onboard LED indicators and a buzzer to alert occupants. The cost-effective design, around ₹2500, integrates multi-sensor data fusion with a sampling rate of 100Hz, ensuring strong performance across different road conditions. It eliminates false positives through dual-threshold validation and includes a manual override option using a push button.

**Keywords:** Multi-sensor fusion, vehicle impact detection, real-time accident alerting, ESP32, MPU6050, GPS/GSM integration, IoT safety systems, Kalman filtering.

## I. INTRODUCTION

Road traffic accidents pose a serious global public health issue, claiming more than 1.3 million lives each year, according to WHO statistics. In 30-40% of cases, emergency responses take more than 30 minutes, especially in rural and remote areas. This delay leads to significantly higher fatality rates and long-term injuries. In India, over 150,000 road deaths occur annually due to poor infrastructure, reliance on bystanders for detection, and dependence on post-impact alerts that often fail during critical moments. Conventional safety systems, such as airbags, only activate after a collision and do not provide external notifications. Premium advanced driver assistance

systems (ADAS) like radar and LiDAR are still too expensive, costing over ₹50,000, making them inaccessible for mass-market vehicles, motorcycles, and less developed regions. Many existing IoT prototypes struggle with false positives, unreliable GSM signals, or no warnings for occupants.

This project aims to fill these gaps with the Advanced Vehicle Safety System using Multi-Sensor Fusion. It builds on phase 1 hardware, which includes the ESP32 microcontroller, MPU6050 IMU for tracking acceleration and gyroscope data, NEO-6M GPS, and SIM800L GSM. The system uses adaptive dual-threshold algorithms for detecting impacts (greater than 4g jolts plus any change in orientation at 100Hz) and optionally leverages Kalman filtering to achieve 98% accurate real-time impact detection. Once an impact is confirmed, the system quickly captures precise coordinates and sends severity data via SMS to establish emergency contacts within 5 seconds. It also activates LED strobes and an 85dB buzzer for immediate awareness among occupants. This approach reduces response times from more than 30 minutes to just seconds while integrating a 10-second push-button override and vibration pattern analysis to avoid false alarms. Additional features include SD card logging for post-event review and future predictive zoning, all within a cost-effective (~₹2500) embedded design using readily available components that suit personal cars, public transport, and commercial fleets.

By reducing notification delays and improving situational awareness, this dependable IoT solution provides essential protection without human intervention, lessens the severity of accidents, and supports broader smart transportation goals through optimized C++ firmware running on the ESP32.

## II. LITERATURE SURVEY

Numerous studies have looked into vehicle accident detection and alert systems that use GPS, GSM, accelerometer sensors, and IoT technologies. These works provide foundational insights for safety applications in real-time. [1] Gaikwada et al. performed a systematic literature survey on accident alert and detection systems, categorizing techniques into sensor-based (accelerometer/gyro), video analytics, and hybrid IoT models. The review assesses detection accuracy (85-95% for IMU thresholds), GSM notification latency (less than 10 seconds), and scalability challenges like rural coverage. They propose frameworks for integrating smart transportation. [2] Patil et al. examined GPS/GSM-enabled prototypes, focusing on systems featuring the MPU6050 for impact sensing (thresholds above 3g) and automated SMS alerts. They discuss reducing false positives through dual-sensor validation and cloud logging, emphasizing low-cost solutions for developing regions while acknowledging issues in vibration-heavy terrains. [3] Azlan et al. designed an accelerometer-based collision detector using jerk and tilt analysis on Arduino, achieving 92% accuracy in tests with motorcycles and cars. The lightweight GSM integration sends coordinates within 7 seconds, tuning thresholds for road bumps, demonstrating viability for two-wheelers without ADAS. [4] Arefin et al. introduced YOLOv8 for real-time video accident detection from CCTV, reporting 45 frames per second inference and 96% mean average precision on collision events. When integrated with traffic management, it can reroute congestion, but camera dependency limits performance in low visibility. [5] ElSahly et al. systematically classified incident detection methods, ranging from statistical models to deep learning, covering various sensors, vision, and crowdsourcing. They connect IoT fusion to energy-efficient smart cities, finding hybrid IMU-camera systems to be optimal for achieving 98% accuracy in urban areas. [6] Adewopo et al. presented an ensemble CNN framework (VGG, ResNet, EfficientNet) for accident detection in video streams, boosting precision to 94% on edge devices. The real-time feasibility (less than 50ms latency) suits surveillance applications, outperforming single models by 12% in F1-scores. [7] Zhang et al. reviewed deep learning techniques for predicting vision-based accidents using CNN-RNN

hybrids on DAD/A3D datasets. Their end-to-end models can foresee crashes 2-5 seconds in advance with 88% accuracy, addressing occlusions through spatiotemporal fusion; however, high computational demands restrict embedded use. [8] Arefin et al. advanced YOLOv11 for detecting high-speed collisions and lane violations from CCTV (52 FPS, 97% precision), integrating it into intelligent transportation systems for emergency routing. It outperforms YOLOv5 by 8% in mean average precision and excels in congested traffic, but needs stable infrastructure. [9] INDJST authors introduced a stand-alone system combining GPS, GSM, and IMU to counter false alarms from potholes. This autonomous alert system for rescue centers confirms embedded intelligence for intelligent transportation systems, achieving 95% reliability in field tests. [10] Another study demonstrated an MPU6050, GPS, and GSM prototype with calibrated thresholds to minimize false triggers (less than 2%). The low-cost design targets developing nations, sending SMS with coordinates in 6 seconds for easy retrofitting. [11] A wireless review compared ZigBee, LoRa, and GSM for transmitting accident data, evaluating factors like range (LoRa at 10km), power consumption, and cost. Mesh networks are ideal for vehicle-to-vehicle and vehicle-to-infrastructure safety, reducing latency by 40% compared to cellular-only solutions. [12] Adewopo et al. explored 3D CNN and Transformer action recognition for urban accident videos, categorizing spatiotemporal models. They found that adding multimodal context can boost anticipation by 15%, with benchmarks showing that transformers perform better in complex collisions.

## III. METHODOLOGY

### 3.1 System Architecture

The proposed Advanced Vehicle Safety System with Multi-Sensor Fusion is built around the ESP32 microcontroller, which serves as the main processing unit. It integrates the MPU6050 IMU (a 6-axis accelerometer plus gyroscope), NEO-6M GPS, SIM800L GSM, HC-SR04 ultrasonic sensor, and other peripherals like an RGB LED, an 85dB buzzer, a push button, and an SD card. All modules connect through I2C (for the MPU6050), UART (for GPS and GSM), and GPIO (for sensors and outputs). The system is powered by a 3.7V LiPo battery, using a

TP4056 charger and a 5V boost converter to ensure uninterrupted operation after an impact. This layered architecture allows for 100Hz sensor fusion, real-time decision-making, and multiple alert channels.

#### Multi-Sensor Data Acquisition

The MPU6050 samples triaxial acceleration ( $\pm 16g$  range) and angular velocity ( $\pm 2000^\circ/s$ ) at a rate of 100Hz through I2C, capturing impact signatures (greater than 4g peaks, over  $30^\circ/s$  rotation). The HC-SR04 ultrasonic sensor measures obstacle distances (2-400cm) to provide context before a collision. An optional Hall effect speed sensor tracks velocity, raising sensitivity above 60km/h. The raw 16-bit data goes through FIFO buffering and the Madgwick filter for orientation compensation, reducing noise by 25% before fusion.

#### Data Fusion and Impact Detection Algorithm

Dual-threshold logic is used to confirm collisions. The primary threshold is based on acceleration (accel\_x/y/z over 4g or resultant over 6g) and the secondary validation checks if the gyroscopic z-axis is over  $45^\circ/s$  or tilt exceeds  $60^\circ$  within 500ms. The Kalman filter fuses IMU and GPS velocity for smoother trajectory tracking (state vector: position, velocity, acceleration), achieving 98% accuracy compared to an 82% rate with a single IMU. To reduce false positives, the system includes:

- A 500ms debounce window
- Vibration pattern analysis (FFT peaks below 10Hz to detect potholes)
- A 10-second push-button override through a debounced GPIO26

#### GPS Location Retrieval and Formatting

After impact confirmation, the ESP32 queries the NEO-6M GPS (UART1, 9600bps) for the NMEA \$GPGGA sentence and parses latitude and longitude (from DDMM.MMMM to DD $^\circ$ MM.MMM') with an accuracy of less than 3m. It formats the coordinates as a Google Maps URL: <https://maps.google.com/?q=LAT,LNG>, adding a

#### Hardware Setup

The Advanced Vehicle Safety System with Multi-Sensor Fusion uses the ESP32-WROOM-32 as the central controller. It integrates these modules on a custom PCB measuring 10x8cm

timestamp, speed, and severity (mild, moderate, critical depending on g-force).

#### Emergency Notification via GSM

The SIM800L GSM module (UART2, AT commands) sends a concatenated SMS within 5 seconds that states: "ACCIDENT DETECTED! Severity: CRITICAL | Location: <https://maps.google.com/?q=13.0470,80.2073> | Time: 2026-02-12 08:30 | Speed: 65km/h | SOS: Reply STOP to cancel." The system can send alerts to three emergency contacts. If the SIM balance is low, it uses USSD (\*100#) as a backup. Cloud logging via the ThingSpeak API stores event data for analysis.

#### Local Alert Signalling and User Override

The system immediately alerts occupants with an RGB LED that cycles through red, white, and red for a strobe effect at 2Hz, accompanied by an 85dB piezo buzzer that emits a 1kHz tone. For user interaction, a single press on GPIO0 silences local alerts for a 10-second window. A long press (3 seconds) cancels SMS transmission, logging it as a "false positive" on the SD card for machine learning.

#### Power Management and Fault Tolerance

A 3.7V 2000mAh LiPo battery provides 48 hours of monitoring (20mA idle, 150mA during transmission), with an INA219 monitor tracking voltage drops after impact. The watchdog timer on the ESP32 resets the system in case of hangs, while brown-out detection keeps GSM functions active. The PCB layout is designed to maintain signal integrity with 0.1 $\mu$ F decoupling capacitors for each IC and to manage heat for automotive vibration, accommodating temperatures from  $-20^\circ C$  to  $85^\circ C$ .

### IV. SYSTEM IMPLEMENTATION

The complete system is built using custom C++ firmware on the ESP32. This was developed in the Arduino IDE with RTOS task scheduling for simultaneous sensor polling at 100Hz, GPS parsing, GSM transmission, and alert management. The system ensures a latency of less than 7 seconds from impact to multi-channel notification.

Component	Connection	Function	Specs
MPU6050 IMU	I2C (GPIO 21/22)	Impact Detection	±16g accel, ±2000°/s gyro
NEO-6M GPS	UART1 (GPIO16/17)	Location tracking	<3m accuracy, 10Hz
SIM800L GSM	UART2 (GPIO18/19)	SMS alerts	Quad-band, 2A peak
HC-SR04 Ultrasonic	GPIO25/26/27	Pre-collision range	2-400cm
RGB LED + Buzzer	GPIO2/4/5	Local alerts	WS2812B, 85dB piezo
Push Button	GPIO0	False alarm cancel	Debounce, 10s window
SD Card	SPI (GPIO12-15)	Event logging	MicroSD, FAT32
Power	3.7V LiPo + TP4056	48hr backup	2000mAh, INA219

VI. RESULTS AND PERFORMANCE TESTING

Test Methodology

Controlled scenarios were established with 100 trials for each:

- Drop tests: 1m freefall simulating a 5g impact
- Shaker table: 4-8g sinusoidal and random vibration
- Vehicle simulation: 60km/h "crash" with dummy loads

- False positive suite: Potholes, speed bumps, sudden braking

Metrics measured include:

- Detection latency from impact to alert
- GPS fix time with a target of less than 3 seconds
- SMS delivery across urban and rural coverage
- Power consumption from idle to peak

Quantitative Results

Test Case	Detection Accuracy	Latency (s)	False Positives	GPS Accuracy
Drop Test (5g)	98.2%	2.8	0%	2.1m
Shaker (6g+)	96.5%	3.2	1.2%	2.8m
Vehicle Crash	97.8%	4.1	0.8%	1.9m
Pothole/Bump	N/A	N/A	0.5% (mitigated)	N/A

Key findings:

Overall accuracy was 98% compared to an 82% baseline for a single IMU. The end-to-end latency was 4.1 seconds for impact to SMS delivery. Power consumption was 22mA during idle time and 180mA at peak, providing a 3.8-hour transmit reserve. In rural areas, the GSM system achieved a 92% first-attempt delivery rate and a 98% rate within 30 seconds on retry. Figure 2: Impact Detection ROC indicates an optimal threshold of more than 4.2g acceleration and more than 42°/s gyro with a true positive rate of 0.97 and a false positive rate of 0.005.

- GPS cold start taking 38 seconds, which was lessened by using assisted GPS
- GSM coverage in fringe areas showed a 12% initial failure rate, which is resolved through auto-retry
- Extreme vibration resulted in 2% missed detections, which will be addressed in phase 2 with machine learning fixes

Qualitative Validation

Occupant alerts were visible 100% of the time, with day/night strobe lights and an 85dB audible range. User override success was 94% within an 8-second window. Event logging recorded 1200 events on an 8GB SD card in JSON format.

Challenges observed included:

VI. CONCLUSION

The Advanced Vehicle Safety System with Multi-Sensor Fusion successfully shows real-time vehicle impact detection with 98% accuracy, a notification latency of 4.1 seconds, and full autonomy. This directly addresses gaps identified by WHO, where 30 to 40% of accidents experience response delays exceeding 30 minutes.

The ESP32-MPU6050-GPS-GSM design offers high performance at a cost of ₹2450, making collision detection more affordable for India's 300 million

vehicles compared to alternatives costing over ₹50,000. Key achievements include:

- 98% detection accuracy achieved through Kalman fusion and dual-threshold validation
- 5-second multi-channel alerts via SMS and local notifications in both urban and rural settings
- Mitigation of false alarms with a 0.5% false positive rate through vibration analysis and user override
- A 48-hour battery backup to ensure transmission occurs post-impact

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