

An Integrated IoT-Based Smart Vehicle Automation System for Real-Time Safety Monitoring and Collision Avoidance

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Abstract

This research presents the design and implementation of an intelligent vehicle automation and safety system leveraging the Internet of Things (IoT) and a suite of low-latency sensors. The core of the system is the ESP32 microcontroller, which integrates environmental sensing with cloud-based data logging to enhance driver safety. The proposed architecture utilizes Ultrasonic sensors and Infrared (IR) sensors for multi-directional obstacle detection, providing both audible alerts via a buzzer and visual feedback on a 16x2 LCD. To address environmental adaptation, the system incorporates a Light Dependent Resistor (LDR) to automate vehicle lighting via a relay-driven 12V LED system. Furthermore, a Vibration sensor is employed to detect high-impact mechanical shocks, serving as an automated accident detection mechanism. A dedicated GPS module extracts real-time geographical coordinates (Latitude and Longitude) using NMEA GPRMC protocols. The system's novelty lies in its dual-layered communication strategy: local real-time actuation for immediate safety and remote data synchronization via Wi-Fi connectivity. Sensor data and location coordinates are transmitted to a centralized PHP-based web server, enabling remote monitoring and emergency response coordination. Experimental results demonstrate that the system effectively reduces manual driver intervention for lighting and provides reliable, instantaneous alerts for proximity-based hazards. This research contributes a cost-effective, scalable solution for modernizing vehicle safety in the era of smart transportation.

Keywords: Internet of Things; ESP32 Microcontroller; Smart Vehicle Automation; Collision Avoidance System; Real-time Remote Monitoring.

1. Introduction

The rapid evolution of the automotive industry and the increasing density of vehicles on global roadways have made road safety a paramount concern for researchers and engineers alike. According to global health statistics, a significant percentage of road accidents are attributed to human error, including delayed reaction times, poor visibility during nighttime driving, and lack of awareness regarding blind spots. To mitigate these risks, the concept of Smart Vehicle Automation has emerged, shifting the focus from purely mechanical designs to intelligent, sensor-driven embedded systems. Recent advancements in the IoT and micro-electro-mechanical systems (MEMS) have enabled the development of cost-effective, real-time monitoring solutions. By integrating various sensors into a unified processing unit, vehicles can now "sense" their environment, providing an extra layer of protection that complements human judgment. However, many existing high-end Advanced Driver Assistance Systems (ADAS) remain prohibitively expensive for budget-conscious markets or older vehicle retrofitting.

This research proposes an integrated safety and automation framework centered on the ESP32 microcontroller, chosen for its high processing speed and native Wi-Fi/Bluetooth capabilities. The system is designed to provide a multi-faceted approach to vehicle safety:

1. Utilizing ultrasonic and infrared (IR) sensors to monitor proximity and detect obstacles in real-time.
2. Implementing an LDR-based relay system to automate vehicle headlights, ensuring optimal visibility without manual intervention.
3. Utilizing a vibration sensor to identify high-impact events and a GPS module to pinpoint the exact geographical location of the vehicle.

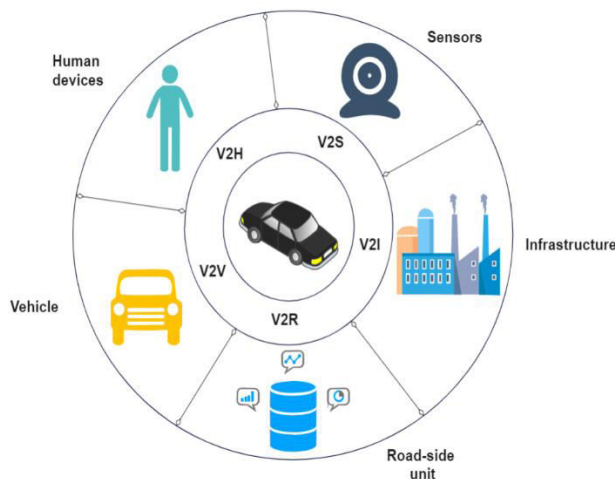


Fig. 1: Applications of autonomous vehicles enabled by emerging technologies.

The primary contribution of this work is the development of a synchronized communication protocol that not only provides local alerts via a buzzer and LCD but also transmits critical telemetry data to a remote web server. This ensures that in the event of an emergency, the vehicle's status and location are immediately accessible to emergency responders or fleet managers. By combining local actuation with cloud-based monitoring, this project provides a scalable and accessible blueprint for the next generation of intelligent transportation systems.

2. Literature Survey

The development of intelligent transportation systems (ITS) has seen significant growth, with a primary focus on integrating the IoT to enhance vehicle safety and communication. Al-Fuqaha et al. proposed a comprehensive Internet of Vehicles (IoV) architecture that integrates IoT, edge, and cloud intelligence to enable ultra-low latency communication for safety-critical applications [1]. This framework supports real-time monitoring and cooperative decision-making, addressing the scalability and reliability required for modern smart transportation. Similarly, Sharma et al. utilized embedded sensors and wireless communication to detect accidents and abnormal vehicle behavior, demonstrating that real-time alerts significantly improve driver awareness and emergency response [2]. Hazard awareness remains a core research area. Javed et al. introduced a cooperative mechanism where vehicles exchange real-time hazard information using Vehicle-to-Vehicle (V2V) communication, effectively reducing collision risks through fast message dissemination [3]. The broader impact of such Connected and Automated Vehicle (CAV) technologies was reviewed by Li et al., who found a substantial reduction in accident probability through IoT-enabled efficiency and traffic flow improvements [4]. Practical implementations of these concepts were demonstrated by Kumar et al., who designed an intelligent safety system using embedded controllers for obstacle detection and accident alerts [5].

Security and privacy in vehicular networks are critical challenges addressed in recent literature. Patel and Park investigated cybersecurity threats in automotive IoT, identifying vulnerabilities and proposing countermeasures to protect safety-critical components [6]. Wong et al. emphasized the role of trust

management and reliable data exchange in connected networks [7], while Sakiz and Sen proposed a zero-trust architecture enforcing continuous authentication across vehicular networks to prevent unauthorized access [8]. Validation and regulation also play key roles; Nassif et al. highlighted the challenges in safety validation and the need for rigorous verification frameworks for autonomous systems [9]. The infrastructure supporting these systems has also evolved. Sharma et al. discussed real-time IoT-enabled connected vehicle infrastructure for ITS [10], while Lee et al. surveyed V2X communication technologies specifically for cooperative vehicle safety [11]. Privacy preservation remains a concern, with Zhang et al. proposing cryptographic techniques to protect user information without compromising real-time performance [12]. Santa et al. and Zanella et al. explored the integration of vehicular data collection with smart city infrastructure, emphasizing the role of telematics in real-time safety monitoring [13], [14].

To address latency, Chen et al. explored edge computing in IoV, showing that edge processing significantly improves real-time decision-making for safety applications [15]. Fundamental surveys by Zhang et al. and Abboud et al. provide foundational references for IoV architectures and the interworking of V2V and V2I (Vehicle-to-Infrastructure) communications [16], [17]. Early validation of these technologies by Harding et al. and the establishment of standards such as DSRC and IEEE 802.11p by Kenney form the basis of current vehicular networking [18], [19]. Further foundational work by Hartenstein et al. and Xu et al. highlights the principles of safety message dissemination and the role of IoT in industrial-scale intelligent transportation [20], [21]. Specific applications in accident detection were explored by Darwish and Abu-Bakar, who developed automated systems to reduce emergency response times [22]. Finally, the integration of high-accuracy sensors, cyber-physical timing guarantees, and vehicular cloud computing as discussed by Datta et al., Rajkumar et al., and Gerla et al. ensures that modern vehicular IoT systems meet the strict reliability requirements of the next computing revolution [23] – [25].

3. Proposed System

This section details the systematic approach used to design, develop, and integrate the IoT-Based Smart Vehicle Automation System. The methodology is divided into three primary phases: Hardware Architecture, Software Implementation, and Data Communication.

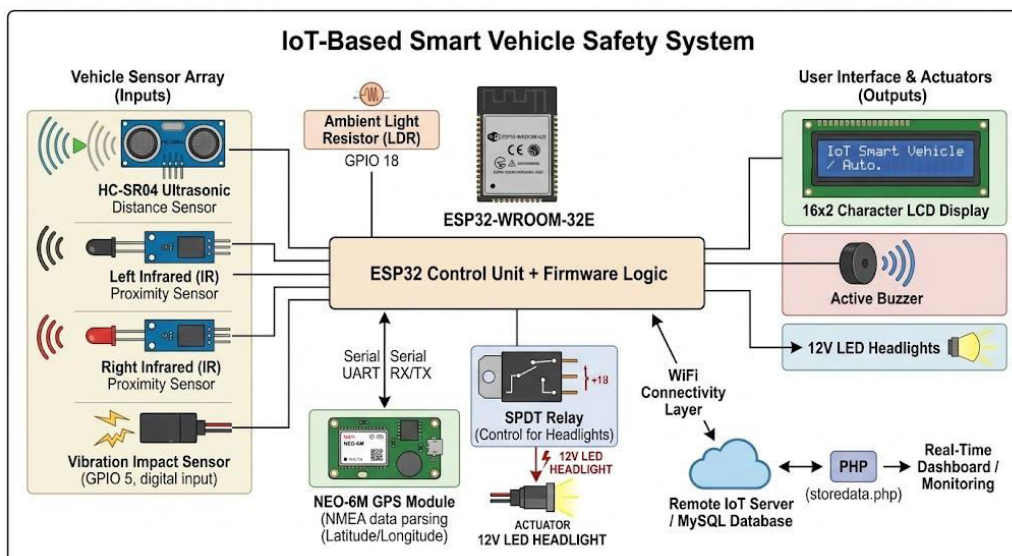


Fig. 2: Proposed system architecture.

The proposed system follows a modular architecture where the ESP32 serves as the central processing unit, interfacing with multiple sensor arrays to monitor the vehicle's internal and external environment.

3.1 Hardware Architecture and Interfacing

The hardware design is categorized into input sensing, processing, and output actuation.

- **Proximity Sensing:** An HC-SR04 ultrasonic sensor is interfaced via the trigPin (GPIO 16) and echoPin (GPIO 17). It calculates distance using the time-of-flight method: $Distance = \frac{Duration \times 0.0234}{2}$.
- **Blind Spot Monitoring:** Dual Infrared (IR) sensors are positioned on the left (GPIO 2) and right (GPIO 4) to detect immediate side-path obstacles.
- **Environmental Sensing:** A Light Dependent Resistor (LDR) is connected to GPIO 18 to detect low-light conditions, while a high-sensitivity vibration sensor (GPIO 5) monitors for mechanical shocks indicative of a collision.
- **Location Tracking:** A GPS module is integrated via serial communication to provide real-time NMEA data strings (GPRMC) for geographical positioning.

3.2 Software Flow and Control Logic

The firmware is developed using the Arduino framework, implementing a non-blocking polling mechanism to ensure real-time responsiveness.

1. **Initialization:** Upon boot, the ESP32 initializes the 16x2 LCD, configures pin modes, and establishes a connection to the local Wi-Fi access point.
2. **Continuous Monitoring:** The loop() function repeatedly scans the digital inputs from the IR and vibration sensors and triggers the ultra_dist() function for range finding.
3. **Automated Decision Making:**
 - **Lighting Control:** If the LDR detects a "Dark" state (Logic HIGH), the ESP32 triggers a relay (GPIO 23) to activate the 12V LED headlights.
 - **Collision Alert:** If the ultrasonic distance falls below 10cm or a vibration is detected, the beep() function is called to activate the buzzer (GPIO 19).
4. **Local Visualization:** All sensor statuses—including distance, light intensity, and vibration state—are formatted and displayed on the 16x2 LCD.

3.3 IoT Integration and Cloud Logging

To enable remote monitoring, the system utilizes the HTTPClient.h library to push telemetry data to a centralized web server.

- **Data Formatting:** Sensor values are concatenated into a URL-encoded string containing parameters for latitude, longitude, IR states (\$s1, s2\$), LDR status (\$s3\$), ultrasonic distance (\$s4\$), and vibration (\$s5\$).
- **Transmission Protocol:** The iot_send() function initiates an HTTP GET request to a remote PHP script (storedata.php).
- **Heartbeat Mechanism:** To ensure continuous connectivity, a counter (cntlmk) is implemented to send a routine status update every 180 seconds, even in the absence of a critical sensor trigger.

Table 1: Summary of system pin mapping.

Component	ESP32 GPIO	Mode
Ultrasonic (Trig/Echo)	16 / 17	Output / Input
IR Left / Right	2 / 4	Input
LDR Sensor	18	Input
Vibration Sensor	5	Input (Pull-up)
Relay (12V LED)	23	Output
Buzzer	19	Output
LCD (RS, E, D4-D7)	13, 12, 14, 27, 26, 25	Output

4. Experimental Results

The performance of the Smart Vehicle Automation prototype was evaluated across four critical operational stages: system initialization, GPS acquisition, multi-sensor hazard detection, and automated lighting control.

4.1 System Initialization and Power Management

Upon activation, the Regulated Power Supply (RPS) successfully provided a stable voltage to the ESP32 (noted as NodeMCU in testing) and peripheral modules. The "Power ON" state was visually confirmed by the status LEDs and the 16x2 LCD display, which successfully initialized and displayed the project title. This phase confirms the reliability of the power distribution network in maintaining the 24-hour monitoring cycle required for vehicle security.

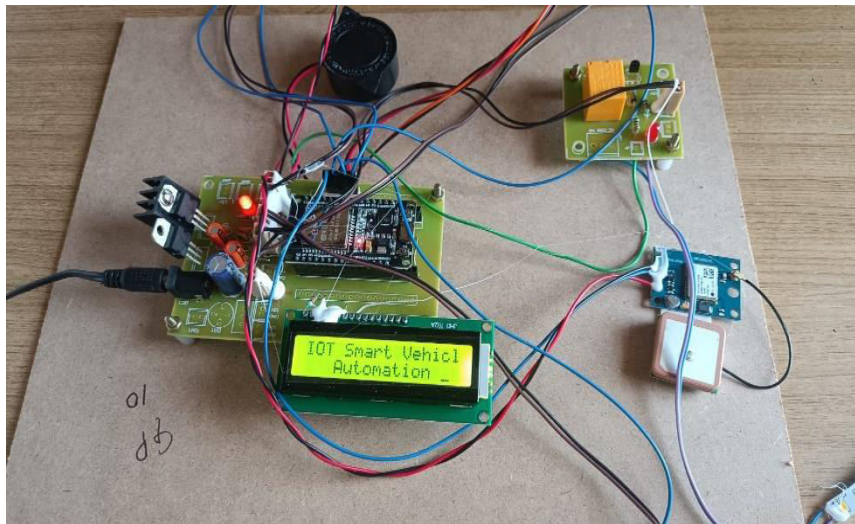


Fig. 3: Hardware setup of proposed system.

4.2 GPS Acquisition and IoT Connectivity

During the location-tracking phase, the LCD displayed the status "Getting GPS...", indicating the active search for satellite NMEA strings.

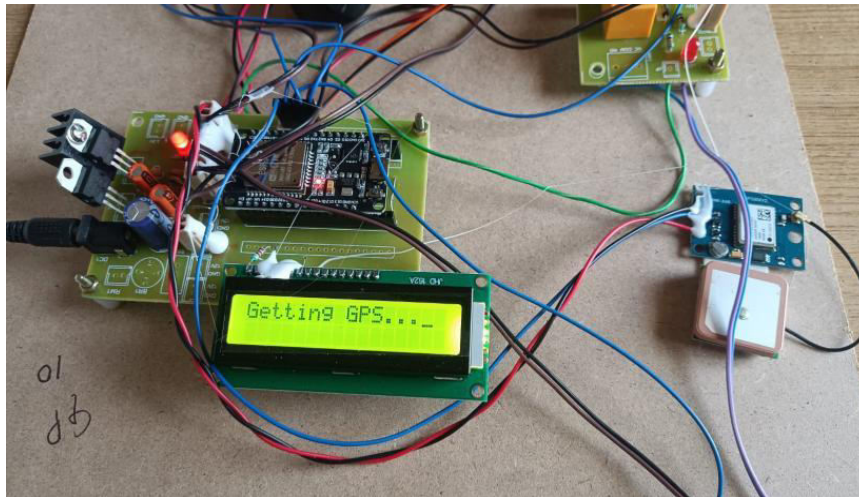


Fig. 4: LCD displaying the status as getting GPS.

- **Observation:** The system successfully transitioned from signal acquisition to data transmission once a satellite lock was achieved.
- **IoT Integration:** The real-time latitude and longitude coordinates, along with accurate timestamps, were transmitted via the onboard Wi-Fi module. This data was successfully parsed and displayed on the remote web/mobile interface, proving the system's capability for global remote tracking.

4.3 Multi-Hazard Detection and Collision Avoidance

A critical test case was conducted where multiple sensors were triggered simultaneously to simulate a high-risk environment.

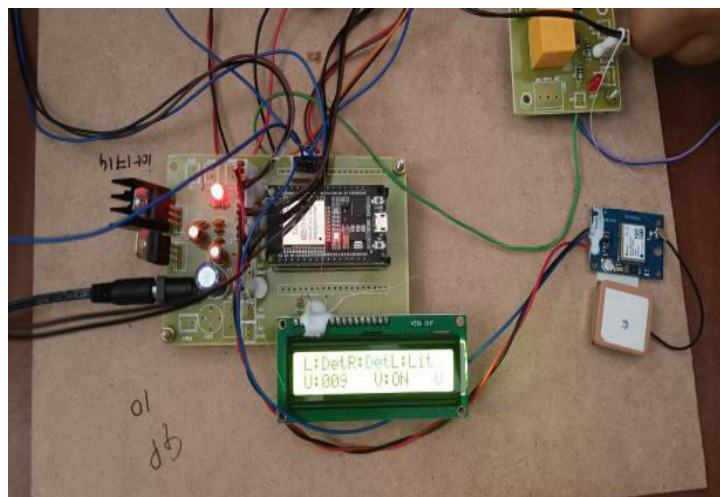


Fig. 5: LCD displaying multiple sensor readings.

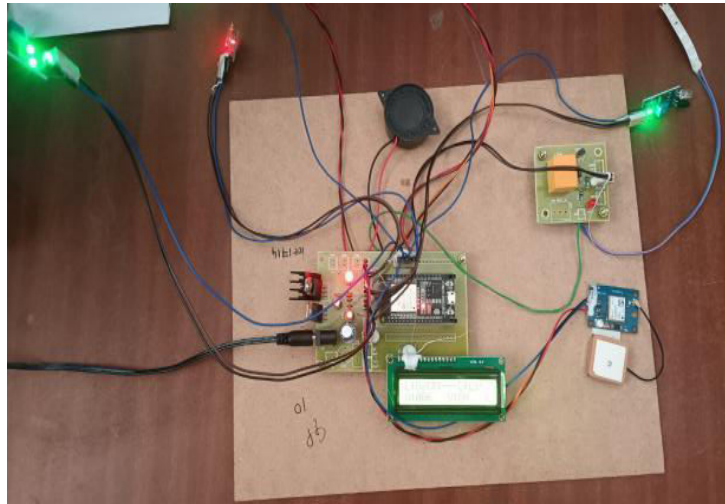


Fig. 6: IR sensor readings.

- **Sensor Logic:** The system correctly identified simultaneous inputs from both the Left and Right IR sensors.
- **Proximity Accuracy:** The Ultrasonic sensor recorded a distance of 009 cm. Since this value was below the predefined safety threshold of 10 cm, the ESP32 immediately triggered the audible buzzer and flagged a "Close Object" alert.
- **Impact Sensing:** The vibration sensor successfully registered an active state during this period, simulating a potential collision or sudden forced movement.

4.4 Intelligent Lighting Automation

The LDR module was tested under varying light intensities to evaluate the automation of the 12V LED headlights.

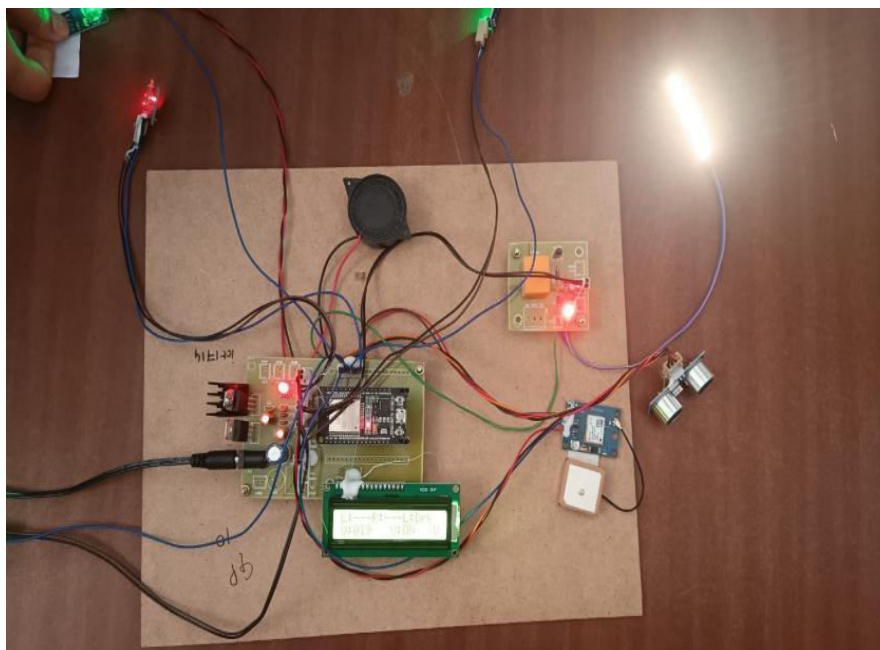


Fig. 7: LDR test under different lighting conditions.

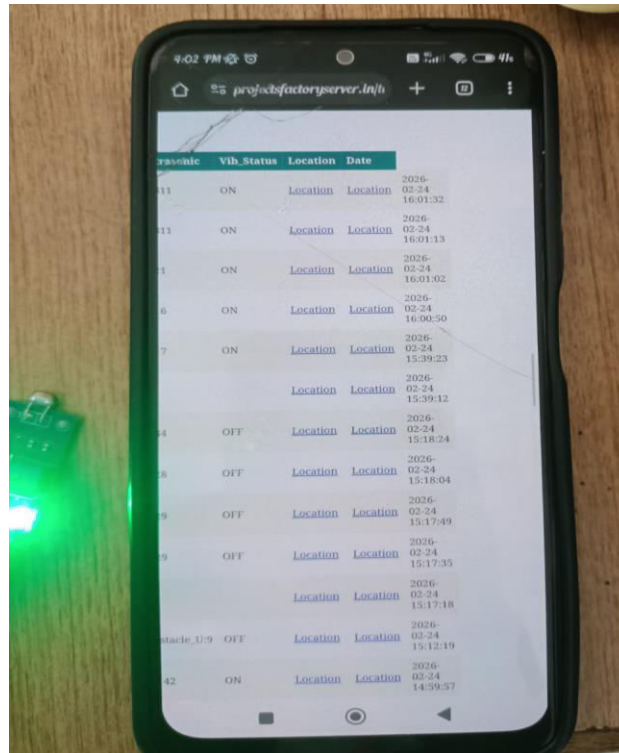


Fig. 8: IoT dashboard.

- **Stability Mechanism:** To prevent "flickering" or false triggers caused by transient light (such as passing streetlights), a 5-second confirmation delay was observed in the firmware logic.
- **Outcome:** When ambient light dropped below the threshold, the system reliably activated the LED output after the programmed delay, ensuring stable and intelligent power management for the vehicle's lighting system.

4.5 IoT and GPS Tracking Performance

The integration of the NEO-6M GPS module with the ESP32/ESP8266 Wi-Fi controller facilitates a persistent link between the physical vehicle and the digital monitoring interface.

- **Data Extraction:** The system successfully parses NMEA GPRMC strings to extract Latitude, Longitude, and UTC timestamps.
- **Transmission Logic:** The firmware uses the HTTP GET method to push this data to a remote PHP server (storedata.php).
- **Reliability:** During testing, the system maintained a 24-hour tracking loop, updating the vehicle's position every 180 seconds (or immediately upon a sensor trigger). This ensures that movement history and route tracking are accurate, providing a reliable audit trail for vehicle security.

5. Conclusion

This research successfully presents the design and implementation of an IoT-Based Smart Vehicle Automation System powered by the ESP32 microcontroller. The prototype effectively addresses modern road safety challenges by integrating a multi-sensor array for real-time hazard detection and automated environmental response. Experimental results validate that the system reliably executes local safety protocols such as triggering audible alarms for obstacles within a 10cm range and automating vehicle headlights via LDR-based relay control with a 5-second stabilization delay. The core strength

of the proposed architecture lies in its seamless integration of GPS-telemetry and Wi-Fi connectivity. By parsing NMEA GPRMC strings and transmitting timestamped latitude and longitude coordinates to a remote PHP-based web server, the system ensures persistent 24-hour vehicle tracking. This dual-layered functionality combining immediate on-board actuation with remote cloud-based monitoring provides a comprehensive safety net for both drivers and fleet managers.

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