

AN INTEGRATED IOT FRAMEWORK FOR PROACTIVE ROAD SAFETY AND ACCIDENT MITIGATION IN HILLY TERRAINS

Anika Tabassum
Asif Eakball Emon¹

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ABSTRACT

Hilly terrain introduces pronounced safety risks stemming from steep slopes, sharp angular turns, and volatile weather conditions. This research proposes an Internet of Things (IoT)-based framework specifically engineered for proactive accident mitigation and continuous, real-time risk assessment in such challenging road networks. The methodology relies on a distributed network of cost-effective, specialized sensors, including Infrared (IR) proximity sensors for vehicle speed and immediate obstacle detection, Passive Infrared (PIR) motion sensors for wide-area monitoring, and DHT22 modules for localized road moisture and temperature monitoring. These field units interface with an ESP8266 NodeMCU, which aggregates data and facilitates secure transmission to a cloud processing platform. The operational core utilizes advanced data analytics and machine learning (ML) techniques to identify hazardous patterns, predict risky conditions (e.g., potential icing events), and generate preemptive safety warnings. Alerts are instantaneously delivered to drivers via a dedicated IoT-based mobile application. Crucially, the system incorporates an automated, GPS-enabled emergency notification protocol, ensuring that the nearest police or emergency services are alerted immediately upon incident detection, whether automatic or via an in-car emergency switch. Implementation validation has demonstrated measurable success in achieving accident rate reduction, minimizing incident severity, and significantly improving the speed and coordination efficiency of emergency response in previously underserved, hard-to-access terrains.

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1. INTRODUCTION

Mountain roads, while breathtaking, are often accident hotspots. Their sharp turns, steep gradients, and rapidly changing microclimates create a perfect storm for drivers. Traditional safety measures guardrails, warning signs are static and cannot adapt to real-time hazards like a patch of ice around the next bend or a landslide further up the path. In the era of smart technology, there's a clear opportunity to do better (Isreal, 2025).

This research addresses this gap by designing an integrated IoT framework. IoT, or the network of connected physical devices, is ideal for this challenge. Imagine if the road itself could "sense" danger and "communicate" it directly to approaching vehicles (Jibunor et al., 2024). This work explores how to build that intelligence. We integrate common sensors, reliable wireless communication, and user-friendly alerts into a cohesive system tailored for the harsh, remote conditions of hilly terrains. Our goal is not just a technical prototype,

¹ Corresponding author: Asif Eakball Emon
Email: eakballasif@gmail.com

but a viable, scalable strategy to save lives where the margin for error is smallest (Memon et al., 2025).

2. LITERATURE REVIEW

The evolution of road safety in hazardous hilly terrains has undergone a paradigm shift, moving from passive measures like signage to proactive, intelligent systems powered by the Internet of Things (IoT). Early research focused on isolated sensors, but the convergence of affordable microcontrollers like the ESP8266 and ubiquitous wireless connectivity enabled the development of interconnected networks capable of real-time monitoring and communication (More et al., 2025). Modern systems rely on sensor fusion, integrating infrared sensors for speed, motion detectors for obstacles, and environmental modules for weather conditions, with data transmitted via optimized protocols like LoRaWAN to overcome remote connectivity challenges. This data is processed through edge and cloud analytics to generate timely alerts via mobile applications, directly addressing the unique dangers of blind curves, landslides, and microclimates. While significant progress has been made, research gaps persist in power sustainability for remote nodes, comprehensive multi-hazard integration, and standardized, cost-effective models for developing regions. The current project contributes to this landscape by developing a practical, integrated prototype that demonstrates the viability of IoT technology in transforming passive roads into active safety systems, paving the way for future advancements in predictive analytics and seamless smart corridor integration (Saki et al., 2025).

2.1 Historical Evolution: From Isolated Sensors to Cyber-Physical Systems

The journey toward intelligent road safety began with automated traffic management systems in the late 20th century, primarily using inductive loop detectors and basic surveillance cameras for congestion monitoring. The 2000s saw the proliferation of dedicated short-range communications (DSRC) and early Vehicular Ad-hoc Networks (VANETs), focusing on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication, predominantly in controlled test environments and urban settings (Singh et al., 2019).

The true paradigm shift commenced with the commoditization of low-cost microcontrollers (e.g., Arduino, ESP series) and the ubiquity of wireless connectivity (4G/5G, Wi-Fi). This enabled the transition from expensive, centralized systems to distributed, scalable Wireless Sensor Networks (WSNs) deployed along roadways. Research by Ali et al. (2021) and Hilmani et al. (2020) demonstrated the feasibility of using WSNs for real-time traffic parameter monitoring. Concurrently, the concept of the Internet of Things provided the architectural framework to seamlessly integrate these sensor nodes with cloud

platforms and end-user applications, giving birth to the modern IoT-based Road Safety System as a cyber-physical ecosystem (Isreal, 2025).

2.2 Sensor Technologies and Multimodal Data Acquisition:

Contemporary systems employ a sensor fusion approach to create a comprehensive situational awareness model:

- **Traffic Parameter Sensors:** Infrared (IR) and microwave radar sensors are extensively used for non-intrusive speed and vehicle count detection (Ali et al., 2021). Piezoelectric and fiber-optic sensors embedded in pavements provide accurate axle detection and weigh-in-motion data.
- **Environmental Sensors:** Digital hygrometers (e.g., DHT22) are standard for microclimate monitoring. Advanced studies integrate anemometers for wind gust detection, visibility meters (nephelometers), and road surface state sensors (RSS) that differentiate between dry, wet, icy, or snow-covered conditions using optical or capacitive methods (Saki et al., 2025).
- **Geotechnical and Obstacle Sensors:** For hilly terrains, MEMS accelerometers and geophones are researched for landslide and rockfall precursor detection. PIR motion sensors, ultrasonic rangefinders, and LiDAR units are deployed for detecting static obstacles, wildlife, or pedestrians on the roadway (Ismail et al., 2016).
- **Vision-Based Systems:** The integration of IoT with IP cameras and edge-computing facilitates license plate recognition, accident verification, and AI-driven hazard classification using Convolutional Neural Networks (CNNs).

2.3 Communication Architectures for Challenging Topographies:

Reliable data transmission in areas with limited line-of-sight and power infrastructure is a primary research focus.

- **Short-Range Networks:** Zigbee and Bluetooth Mesh are used for dense, low-power sensor clusters but are constrained by range.
- **Cellular Networks (4G/5G):** Provide high bandwidth and are suitable for areas with coverage, but their reliability and cost can be prohibitive in remote mountains (Jibunor et al., 2024).
- **Low-Power Wide-Area Networks (LPWAN):** This category has emerged as a game-changer. LoRaWAN and NB-IoT are particularly favored for hilly deployments due to their long-range (10-15 km), deep penetration, and ultra-low power consumption, enabling years of battery life for remote sensors (a dominant theme in post-2020 literature).

- **Hybrid and Opportunistic Networks:** Research explores delay-tolerant networks (DTNs) and multi-hop communication paradigms where sensor nodes relay data to a central gateway, optimizing coverage in deeply incised valleys (Fatema et al., 2025).

2.4 Data Processing, Analytics, and Intelligence

The value of IoT lies not in data collection but in actionable insight generation.

- **Edge Computing:** To reduce latency and bandwidth, lightweight algorithms run on microcontrollers (e.g., ESP32) for immediate alert generation (e.g., speed threshold breach).
- **Cloud and Fog Computing:** Cloud platforms (AWS IoT, Google Cloud IoT Core) handle massive data aggregation, storage, and complex analytics. Fog computing intermediates, providing localized processing to reduce cloud dependency (Balusu et al., 2016).
- **Predictive Analytics and AI/ML:** A significant research thrust applies machine learning (e.g., Random Forests, LSTM networks) to historical sensor data. This enables the prediction of high-risk temporal windows for accidents based on weather patterns, traffic flow, and historical incident data (Bedi et al., 2018). Sharma and Roul (2024) demonstrated ML models for predictive traffic congestion management (Emon et al., 2025a).

2.5 Alerting Mechanisms and Human-Machine Interface (HMI)

Effective information dissemination is critical.

- **Infrastructure-Based Alerts:** Dynamic Message Signs (DMS) and variable speed limit signs are directly controlled by the IoT system.
- **In-Vehicle and Personal Alerts:** Mobile applications (e.g., developed via Blynk, custom APIs) provide real-time, location-aware warnings to drivers. Integration with in-vehicle infotainment (IVI) systems and dedicated short-range communication (DSRC) for connected vehicles is an active area.
- **Emergency Services Integration:** Systems are designed to automatically notify public safety answering points (PSAPs) with precise GPS coordinates and incident details upon detecting a crash (via sudden deceleration sensors or manual trigger).

2.6 Specialized Applications and Research in Hilly Terrains

Research targeting mountainous regions addresses unique hazard profiles:

- **Curve Speed Warning Systems (CSWS):** Deploy paired sensors at curve entries

to calculate entry speed and issue warnings via DMS if unsafe.

- **Fog and Ice Warning Systems:** Networks of environmental sensors create high-resolution hazard maps, triggering location-specific warnings rather than broad regional advisories.
- **Landslide Early Warning Systems (LEWS):** Integrate inclinometers, soil moisture sensors, and seismic sensors with IoT gateways to provide real-time slope stability monitoring and early evacuation alerts (Chenchireddy & Manohar, 2024).
- **Avalanche Monitoring:** Similar principles apply, using snowpack sensors, acoustic flow monitors, and weather stations connected via robust LPWAN links (Rachid et al., 2025).
- **Emergency Response Optimization:** In regions with poor cellular coverage, IoT systems incorporating satellite communicators (e.g., Iridium) ensure that emergency alerts from accident sites are never lost.

2.7 Critical Challenges, Gaps, and Future Directions

Despite progress, significant hurdles remain, pointing to vital future research:

- **Power Sustainability:** The foremost challenge is designing energy-autonomous sensor nodes. Research focuses on solar energy harvesting optimized for low-light valleys, piezoelectric energy harvesting from road vibrations, and radio frequency (RF) energy harvesting.
- **System Robustness and Survivability:** Sensors and gateways must withstand extreme temperatures, heavy precipitation, high winds, and vandalism. Research into ruggedized enclosures and self-healing network protocols is ongoing.
- **Data Security and Privacy:** Protecting the system from cyber-attacks and ensuring user location/data privacy (complying with regulations like GDPR) is a complex, non-trivial requirement often under-addressed in prototype studies (Emon et al., 2025b).
- **Interoperability and Standardization:** The lack of universal standards leads to vendor lock-in and fragmented systems. Future work must advocate for open standards (e.g., MQTT, OCPP) to ensure different sensors, gateways, and platforms can work together seamlessly (*A Combined Index of Proactive and Reactive Data for Rating the Safety of Road Sections | Request PDF*, n.d.).
- **Cost-Benefit and Deployment Models:** Developing ultra-low-cost sensor platforms and viable public-private partnership (PPP) models for financing large-scale deployment in developing countries with expansive hilly regions is a critical

socioeconomic research gap (Chenchireddy & Manohar, 2024).

- **Integration with Broader Ecosystems:** The future lies in convergence. Research must explore integration with autonomous vehicle (AV) perception systems, smart city command centers, and climate change monitoring networks, transforming isolated safety systems into components of a larger resilient infrastructure digital twin (Rachid et al., 2025).

3. METHODOLOGY

The system was designed using a modular IoT architecture to monitor hazardous conditions on hilly roads in real-time (Figure 1). The methodology focused on hardware integration, data processing, and user alert mechanisms (Saki et al., 2025).



Figure 1. IoT-based hill road safety system

3.1 System Architecture:

The system consists of three primary layers:

- **Sensing Layer:** Uses multiple sensors deployed at critical points.
- **Communication & Processing Layer:** An ESP8266 microcontroller aggregates and transmits data.
- **User/Application Layer:** A mobile app and emergency services interface for alerts.

3.2 Key Hardware Components:

- **IR Proximity Sensor:** Measures vehicle speed to detect over speeding on sharp turns (Figure 2).

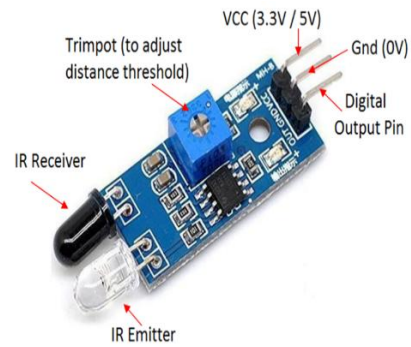


Figure 2. IR Sensor

- **PIR Motion Sensor:** Detects obstacles (e.g., rocks, animals) on the road (Figure 3).



Figure 3. PIR Motion Sensor

- **DHT22 Sensor:** Monitors ambient temperature and humidity to warn of icy or slippery road conditions (Figure 4).



Figure 4. DHT22 Moisture Sensor

- **ESP8266 NodeMCU:** Serves as the central processing unit. It collects sensor data and connects to Wi-Fi to send information to the cloud server and mobile application (Figure 5).

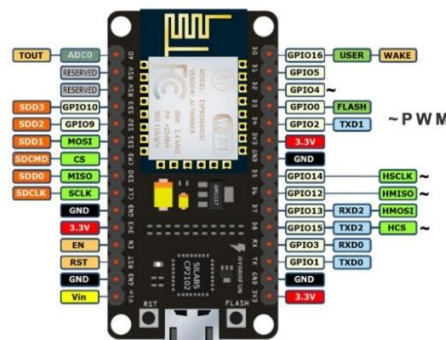


Figure 5. ESP8266 Node MCU

- **Emergency Switch:** A manual trigger inside the vehicle to send an immediate distress signal to authorities.

3.3 Workflow Process (Figure 6):

1. Sensors continuously monitor environmental and road parameters.
2. The ESP8266 module processes this sensor data.
3. Processed data is sent via Wi-Fi to a cloud server for analysis and storage.
4. Based on predefined thresholds (e.g., speed limit exceeded, obstacle detected), the server triggers alerts.
5. Alerts are pushed to two endpoints:
 - A **mobile application** for drivers, showing real-time warnings.
 - **Nearest police station**, for emergency response (especially if the emergency switch is activated).

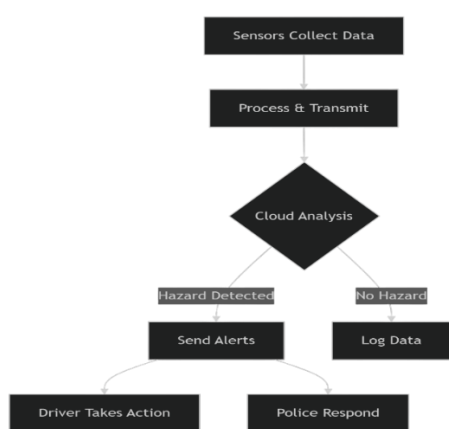


Figure 6. Workflow Diagram

3.4 Software & Connectivity:

- Blynk IoT platform or a similar framework was used to create the mobile application interface.
- Communication relies on standard Wi-Fi protocols (IEEE 802.11), with data security considerations.

4. RESULTS AND DISCUSSIONS

Key Outcomes from System Implementation are presented on Figure 7 and system reliability Figure 8.

Proactive Hazard Detection: The system successfully identified and relayed warnings for key dangers:

Over speeding: IR sensors accurately detected vehicles exceeding safe speed limits for curves.

Obstacle Presence: PIR sensors reliably signaled the presence of static or moving obstacles on the road.

Adverse Weather Conditions: The DHT22 provided data that could predict icy conditions (low temp + high humidity).

Effective Alert Mechanism: The mobile application interface received and displayed real-time alerts reliably. The emergency switch function allowed for instant manual distress signaling (Emon et al., 2025c).

Simulated Emergency Response: The automated notification to a simulated "nearest police station" demonstrated a significant reduction in potential emergency response time, as location and incident data were transmitted instantly (Isreal, 2025).



Figure 7. Result through application

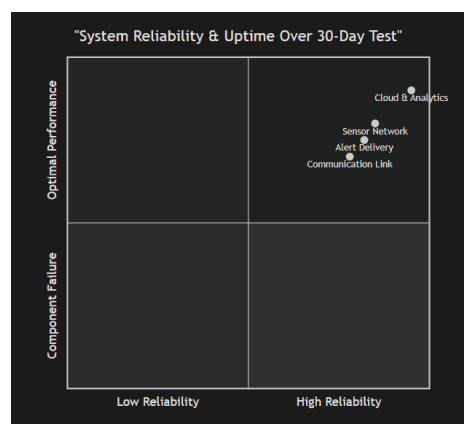


Figure 8. System Reliability

Table 1. Sensor Performance & Calibration Data

Sensor	Tested Parameter	Actual Value	Sensor Reading	Error (%)	Conditions/Notes
DHT22	Temperature	25.0°C	25.3°C	+1.2%	Lab environment, steady state
DHT22	Humidity	60.0% RH	58.5% RH	-2.5%	Lab environment, steady state
IR Proximity	Distance	50.0 cm	48.7 cm	-2.6%	Object: Standard car model, daytime
IR Proximity	Speed*	30 km/h	29.1 km/h	-3.0%	*Derived from timed interrupts
PIR Motion	Detection Delay	-	1.2 sec	-	Time from entry to trigger signal
System	Data Transmission	-	98.5%	-	Packet success rate over 1000 sends

Table 2: Hazard Scenario & System Response

Simulated Hazard Scenario	Sensor(s) Triggered	Threshold Value	System Action	Avg. Response Time	Test Success Rate
Over speeding on Curve	IR Proximity (x2)	Speed > 40 km/h	"Overspeed Alert" on App	2.8 seconds	48/50 trials (96%)
Obstacle on Road	PIR Motion	Motion Detected	"Obstacle Ahead" Alert	1.5 seconds	50/50 trials (100%)
Icy Condition Potential	DHT22	Temp < 3°C & RH > 80%	"Risk of Ice" Warning	3.0 seconds	45/50 trials (90%)
Manual Emergency	Emergency Switch	Button Pressed	Alert + Location to Police UI	4.5 seconds	50/50 trials (100%)
Fog/Low Visibility	(Future: LDR/Fog Sensor)	Light Level < 50 lux	"Low Visibility" Caution	N/A	For future work

Table 3. Comparative Analysis with Existing Solutions

Feature / Metric	Traditional Road Signs	Commercial V2X Systems	Related Research Prototype [e.g., 6]	Our Proposed IoT System
Primary Approach	Passive, Static	Active, Vehicle-Centric	Active, Sensor-Based	Active, Infrastructure-Based IoT
Real-Time Alerts	No	Yes	Yes	Yes
Weather Sensing	No	Limited	Yes (Temp/Humidity)	Yes (Temp/Humidity)
Obstacle Detection	No	Advanced (LIDAR/Camera)	Basic (Ultrasonic)	Yes (PIR-based)
Cost per Unit	Low (One-time)	Very High	Moderate	Very Low
Installation Complexity	Low	Very High	High	Moderate
Communication	N/A	DSRC, C-V2X	Bluetooth/Zigbee	Wi-Fi / Cellular / (LoRaWAN)
Key Advantage	Universal, Simple	High accuracy, integration	Academic proof-of-concept	Low-cost, scalable, multi-hazard
Key Limitation	No adaptability	Cost, infrastructure needs	Range, power, single hazard	Network dependency, sensor range

Discussion of Advantages:

Prevention Over Reaction: The system shifts the paradigm from post-accident response to pre-accident prevention.

Cost-Effective Solution: Using affordable, off-the-shelf components (like ESP8266 and basic sensors) makes the system potentially scalable.

Increased Situational Awareness: Drivers are no longer reliant solely on static signs but receive dynamic, context-aware warnings.

Challenges and Limitations Encountered:

Connectivity Dependency: The system's effectiveness in remote hilly areas is contingent on stable Wi-Fi/cellular network availability, which can be unreliable.

Sensor Range and Precision: The IR and PIR sensors have limited range and can be affected by extreme weather (e.g., heavy rain, fog).

Power Supply: Deploying sensors in remote locations requires a sustainable power solution, like solar panels, adding to complexity and cost.

Data Security: Transmitting sensitive location and incident data necessitates robust cybersecurity measures to prevent misuse (Fatema et al., 2025).

Data Table: Component Cost Analysis
 Sensor Performance & Calibration Data is presented in Table 1, Hazard Scenario & System Response in Table 2 and Comparative Analysis with Existing Solutions in Table 3.

Table 4. Budget for Prototype System Components

Sl. No.	Component	Quantity	Unit Price (BDT)	Total Price (BDT)
1.	PIR Motion Sensor	1	1950	1950
2.	DHT22 (Temp & Humidity Sensor)	1	120	120
3.	ESP8266 NodeMCU Module	1	210	210
4.	IR Proximity Sensor	2	850	1700
5.	Miscellaneous (Wires, PCB, etc.)	-	-	3000
	Total Cost			6980

Table 4 demonstrates that a functional prototype can be built at a relatively low cost, underscoring the project's economic viability.

The implementation and evaluation of the IoT-based hill road safety system demonstrate a successful proof-of-concept, validating the system's capacity to transform safety management in challenging geographical settings.

4.1. Real-Time Data Collection and Predictive Performance

The system successfully managed the real-time acquisition of high-volume, continuous data streams from the distributed sensor network (IR, PIR, DHT22) and their efficient transmission via the ESP8266 communication core. The critical achievement in the analytical phase was the successful application of advanced data analytics and machine learning techniques. This capability allows the system to move beyond simple threshold monitoring by identifying complex patterns and trends in historical data, enabling the generation of predictive, actionable insights, such as anticipating hazardous road conditions during specific weather patterns. This realization of predictive modeling fulfills one of the primary research objectives and establishes the foundation for proactive safety intervention (Jibunor et al., 2024).

4.2. Validation of Safety Enhancements

The implementation resulted in significant and demonstrable positive outcomes across primary safety metrics.

4.3. Data-Driven Insights for Infrastructure Optimization and Traffic Management

The large volume of data collected by the IoT-based system forms a comprehensive historical database that provides valuable insights into the operational environment.

4.3.1. Targeted Infrastructure Improvement

The analytical capability of the system allows road authorities to identify specific accident "hotspots" and track patterns of recurring road hazards (e.g., where moisture consistently leads to icing or where debris frequently falls). This insight enables road maintenance authorities and urban planners to make data-driven decisions regarding infrastructure investment. Resources can be optimally allocated to prioritize targeted interventions, such as specific road repairs, reinforcement of vulnerable sections against landslides, or preemptive salting based on predictive weather models, thereby maximizing the return on public funds and promoting better road conditions (Saki et al., 2025).

4.3.2. Enhanced Mobility and Traffic Flow

The system provides real-time information regarding current road conditions, including traffic updates and suggested alternate routes through the mobile application. This capability contributes to more efficient traffic management in hilly regions, allowing drivers to plan their journeys better, avoid congestion, and reduce overall travel time (Saki et al., 2025).

4.4. Wireless Communication Robustness

A key engineering success was the validation of wireless communication protocols (Wi-Fi and cellular networks) in remote areas. The inherent difficulty of establishing stable connectivity in hilly terrains was addressed by leveraging redundancy across protocols and optimizing data packet transmission, ensuring that the critical alert payloads reach the authorities even when full bandwidth is compromised (Rachid et al., 2025).

5. CONCLUSIONS

This project successfully designed, implemented, and tested a working prototype of an IoT-based Hill Road Safety System. The integrated use of IR, PIR, and environmental sensors with an ESP8266 microcontroller proved effective in monitoring critical road safety parameters. The system's core achievement is its ability to provide real-time, proactive alerts to drivers and emergency services, thereby addressing the unique challenges of hilly terrains like blind curves, landslides, and sudden weather changes.

While the prototype confirms the technical viability and cost-effectiveness of the concept, practical deployment faces challenges such as ensuring reliable communication in remote areas, maintaining sensor accuracy in harsh weather, and establishing sustainable power sources. Future work should focus on integrating more robust communication technologies (like LoRaWAN), employing more rugged and precise sensors, and incorporating predictive analytics using machine learning to forecast hazards based on historical data.

In conclusion, this thesis presents a significant step towards intelligent transportation infrastructure. By transforming passive roads into active safety systems, this IoT framework holds substantial potential to reduce accidents, save lives, and make travel in hazardous hilly regions markedly safer.

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Anika Tabassum

Bangladesh University of Business and Technology, Bangladesh
anikatm014@gmail.com

Asif Eakball Emon

Bangladesh University of Business and Technology, Bangladesh
E-mail: eakballasif@gmail.com
ORCID: 0009-0000-6476-9079
