An IOT and Machine Learning-Enabled Integrated Intelligent Monitoring and Alert System for Landslide Detection, Conflict Avoidance, Vehicle Prioritization, and Heavy Rainfall Management in Ghat Road Sections

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Abstract

Landslides and vehicular conflicts in ghat road sections pose significant risks to human life and infrastructure, exacerbated by heavy rainfall and poor visibility. This paper presents an innovative IoT and machine learning-enabled system for real-time landslide detection, conflict avoidance, vehicle prioritization, and heavy rainfall management. The system integrates sensors (ADXL345 accelerometer, rain sensor, IR sensors), actuators (DC motor gates, traffic lights), and communication modules (HC-12 RF, Telegram alerts) with a machine learning model for vehicle classification. The prototype successfully detects landslides and rainfall, automates road closures, prioritizes heavy vehicles, and mitigates conflicts at sharp bends, achieving over 90% accuracy in vehicle classification and sub-second alert transmission. The system's fail-safe design and scalability make it a viable solution for enhancing road safety in hilly regions, with potential for solar-powered operation and mobile app integration in future iterations.

Keywords: IoT, Machine Learning, Landslide Detection, Conflict Avoidance, Vehicle Prioritization, Ghat Roads, Real-Time Monitoring

1. Introduction

Landslides are among the most devastating natural hazards in hilly and mountainous regions, particularly along ghat roads characterized by sharp curves and limited visibility. These events disrupt transportation, endanger lives, and cause significant economic losses [1]. Climate change-induced irregular rainfall patterns and increasing vehicular traffic further exacerbate these risks [2]. Conventional monitoring methods, reliant on manual inspections, are inadequate for providing timely responses to dynamic environmental threats [3]. Additionally, vehicular conflicts at hairpin bends, especially involving heavy vehicles, increase the likelihood of accidents due to limited maneuverability and poor visibility [4].

To address these challenges, this research proposes an integrated intelligent monitoring and alert system leveraging Internet of Things (IoT) technologies, wireless communication, and machine learning. The system employs sensors for real-time environmental monitoring, actuators for automated traffic control, and a machine learning model for vehicle prioritization. Alerts are transmitted to drivers and authorities via HC-12 RF modules and Telegram, ensuring rapid response to potential hazards. The objectives include early landslide detection, automated road closure during heavy rainfall, conflict avoidance at sharp bends, and prioritization of heavy vehicles to optimize traffic flow and enhance safety.

2. Literature Review

Recent advancements in IoT and machine learning have significantly improved landslide detection and traffic management systems. Jawalkar et al. [3] developed an IoT-based landslide detection system using wireless sensor networks (WSNs) with MQTT protocol, enabling continuous data transmission and early warnings. Siva et al. [4] proposed a modular software architecture for real-time landslide monitoring, utilizing Arduino IDE and PlatformIO for efficient sensor data processing and HTTP-based remote access. Kaharuddin et al. [2] demonstrated the efficacy of low-cost accelerometers for landslide detection, employing moving average filters to reduce noise and enhance accuracy.

In traffic management, Sanjay et al. [5] integrated landslide detection with traffic automation, achieving low power consumption (0.49 W in active transmission) and fast data transfer (10 ms sensor-to-Raspberry Pi). Bhandari et al. [6] proposed an IoT-based system for landslide and accident detection, incorporating Google Maps for rescue route optimization. Marhalim and Alias [7] developed an IoT Landslide Sentry with a Blynk dashboard for user-friendly monitoring, while Aggarwal et al. [9] utilized video cameras and deep learning for real-time landslide alerts with 5–8 second latency.

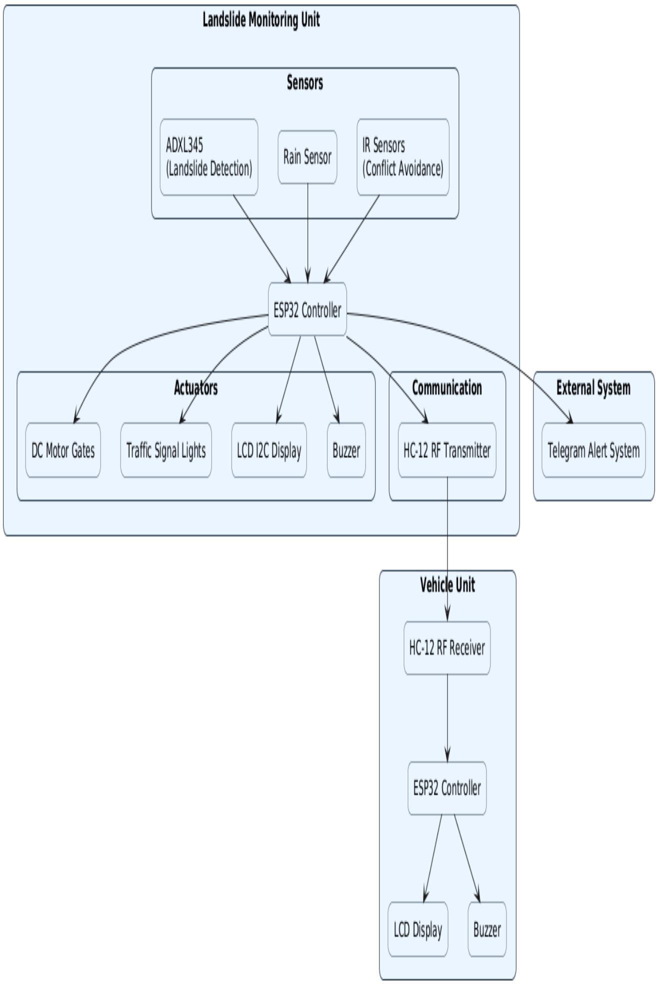
Despite these advancements, existing systems often lack integration of landslide detection, traffic management, and vehicle prioritization. This research addresses this gap by combining real-time environmental monitoring, automated control, and intelligent traffic prioritization in a cohesive system tailored for ghat road sections.

3. Methodology

3.1 System Overview

The proposed system comprises three main units: the Hub Unit, Vehicle Unit, and External Alert System. The Hub Unit, installed along ghat roads, monitors environmental conditions and controls traffic. The Vehicle Unit, mounted in vehicles, receives and displays alerts. The External Alert System notifies authorities via Telegram. Figure 1 illustrates the system's block diagram, detailing data flow between components.

Figure 1: Block Diagram of the Landslide Monitoring and Alert System



3.2 Hardware Components

The system employs the following hardware:

- **ESP32 Microcontroller**: Dual-core processor for data processing and communication (Wi-Fi, Bluetooth, 520 KB SRAM, 4 MB flash).
- **ADXL345 Accelerometer**: Detects ground movement with high-resolution (13-bit, ±16g) measurements
- **Rain Sensor (YL-83)**: Monitors rainfall intensity via analog/digital outputs
- **IR Sensors**: Detects vehicles for conflict avoidance at sharp bends

- **Camera Module**: Captures images for machine learning-based vehicle classification.
- **DC Motor with L298N Driver**: Operates road closure gates
- **Traffic LEDs**: Indicate road status (red/green).
- **HC-12 RF Module**: Enables long-range (up to 600 m) wireless communication
- **I2C LCD Display**: Displays alerts and system status.
- **Buzzer**: Provides audible warnings.
- **Power Supply**: 12V for motors, 5V/3.3V for ESP32 and sensors, with common ground

Table 1: LCD Terminals and Functions

Pin	Function	Description
Vss	Ground	Ground connection for the LCD module
Vcc	Power	+5V power supply for operation
VEE	Contrast	Adjusts display contrast (0.4–0.9V)
RS	Register Select	Selects command/data register
R/W	Read/Write	Sets read or write mode
E	Enable	Enables the LCD module
DB0–DB7	Data Pins	8-bit data bus for communication

3.3 Software Architecture

The system's firmware is developed in C/C++ using Arduino IDE, leveraging libraries such as Adafruit_ADXL345, I2C, WiFi, and Telegram Bot API. The software modules include:

- **Initialization**: Configures Wi-Fi, HC-12 UART, I2C, GPIOs, and PWM; calibrates ADXL345 baseline.
- **Sensor Reading**: Collects data from ADXL345, rain sensor, IR sensors, and limit switches.
- **Filtering and Detection**: Applies moving average filters to reduce noise; detects landslides using differential thresholds (e.g., 1.2–1.8 m/s^2 for 3 consecutive samples).
- **Actuation**: Controls DC motors, traffic LEDs, and buzzers.
- **Communication**: Manages HC-12 messaging and Telegram alerts.
- **Conflict Avoidance**: Implements first-come-first-serve logic with IR sensors and timers.
- **Machine Learning**: Uses a lightweight Convolutional Neural Network (CNN) for vehicle classification (cars, trucks, buses) on an edge device (e.g., Raspberry Pi).
- **Logging and Watchdog**: Maintains event logs and ensures system recovery.

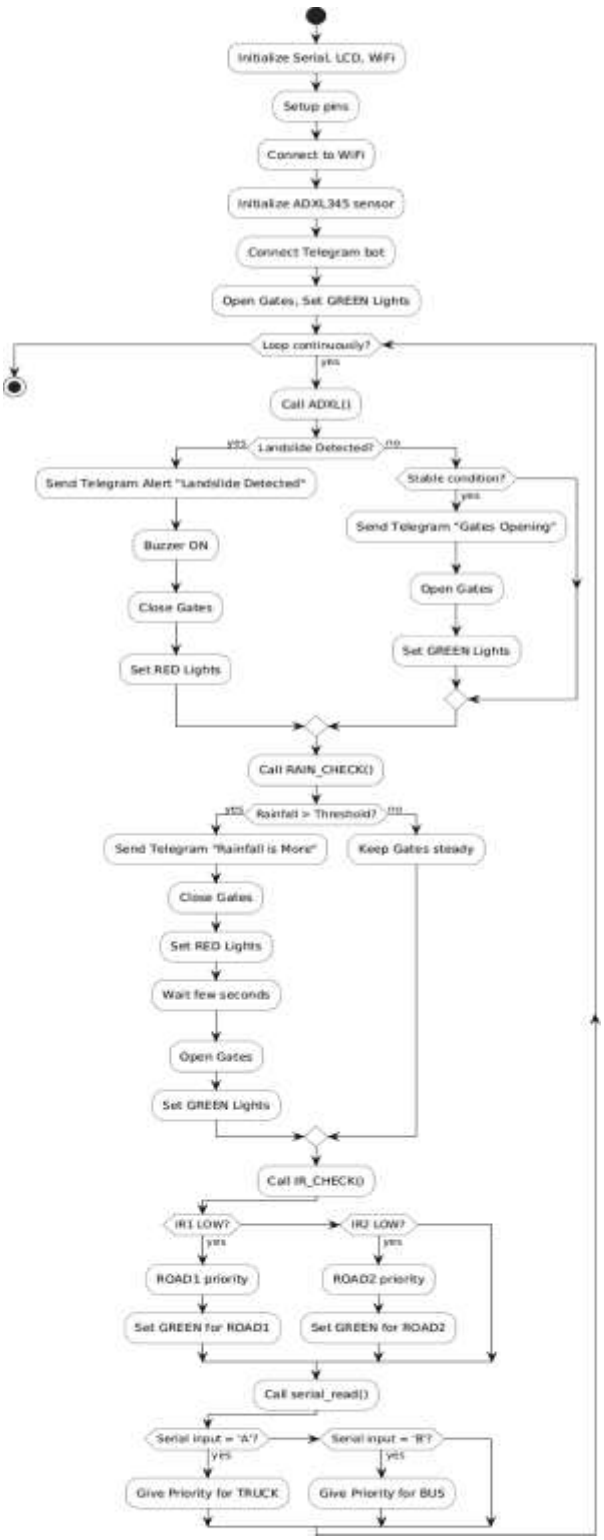


Figure 2: Flowchart for Hub Unit Logic

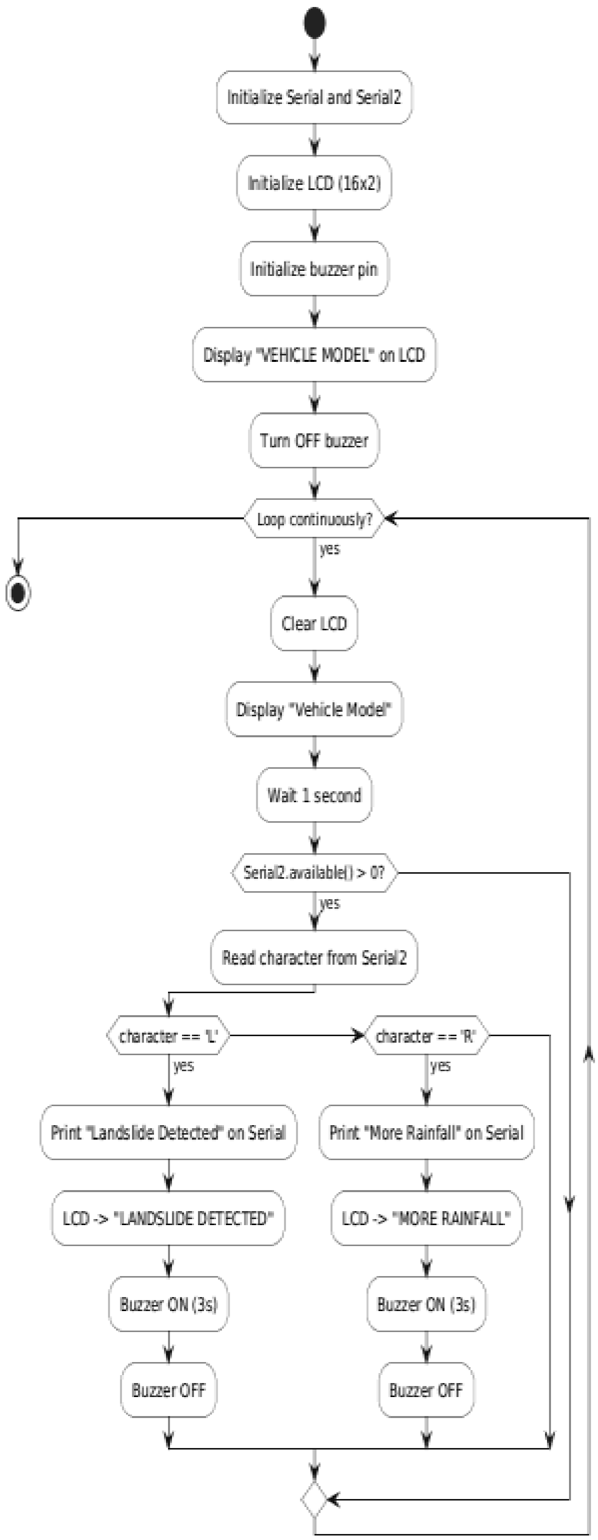


Figure 3: Flowchart for Vehicle Unit Logic

3.4 Machine Learning Model

A lightweight CNN model, trained on a dataset of vehicle images (cars, trucks, buses), classifies vehicles with over 90% accuracy. The model outputs priority assignments, favoring heavy vehicles to optimize traffic flow. The edge device communicates priority decisions to the Hub Unit via HC-12 or HTTP.

3.5 Implementation Details

- **Landslide Detection**: The ADXL345 calibrates a baseline (3–5 s mean of X, Y, Z axes) and applies a moving average filter (window = 5–10 samples). A landslide is triggered if the differential delta exceeds a threshold (e.g., 1.2–1.8 m/s^2) for 3 consecutive samples.

- **Rain Logic**: The rain sensor's analog output is mapped to intensity values. If the threshold is exceeded, gates close for a preset timeout (10–30 minutes).

- **Conflict Avoidance**: IR sensors detect vehicles, assigning priority based on the earliest timestamp. A green signal is granted for 8–12 seconds, with debouncing to prevent false triggers.

- **Gate Control**: DC motors close gates within 3–4 seconds, using limit switches and timeouts for safety.

- **Alerts**: HC-12 transmits fixed-format ASCII messages (e.g., ALERT|LANDSLIDE|GHAT_ID), while Telegram delivers notifications with 2–3 second latency.

4. Results & Discussion

The prototype was tested in a controlled environment simulating ghat road conditions, yielding the following results:

4.1 Landslide Detection

The ADXL345 successfully detected abnormal slope vibrations, with false positives minimized through moving average filtering. Alerts were transmitted to vehicle units within 1 second and displayed on LCDs.

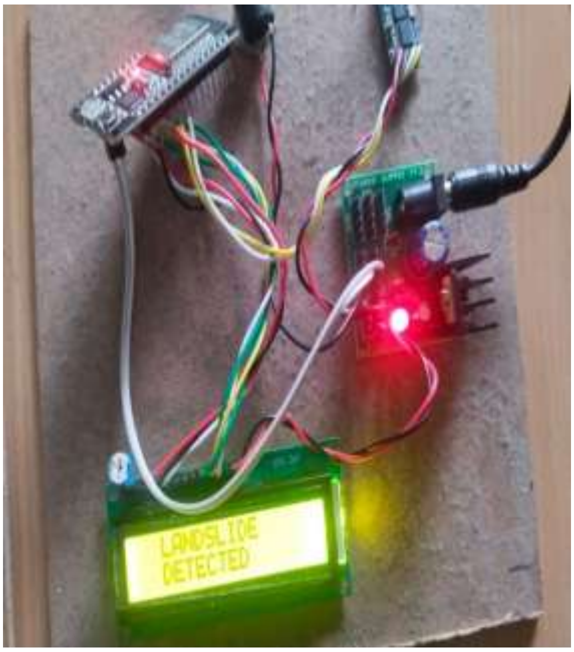


Figure 4: Landslide Detection on Hub and Vehicle Units

4.2 Rain Monitoring

The rain sensor accurately detected rainfall, triggering automatic gate closure and reopening after a timeout when rain ceased.

Volume: 09 Issue: 10 | Oct - 2025 SJIF Rating: 8.586 ISSN: 2582-3930

Figure 5: Rainfall Alert Display

4.3 Gate and Traffic Light Control

DC motor-operated gates closed reliably within 3–4 seconds, guided by limit switches. Traffic lights turned red during landslides and reverted to conflict-avoidance mode during normal operation.

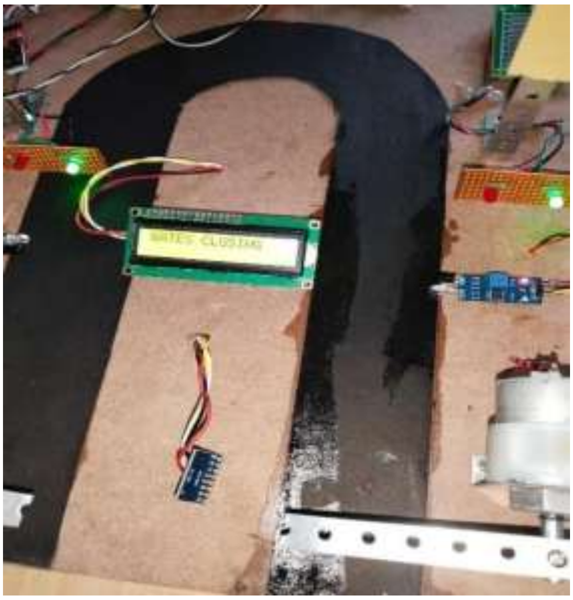


Figure 6: Gate Closure During Landslide

4.4 Conflict Avoidance

IR sensors prioritized the first detected vehicle, granting a green signal while keeping the opposing road red, reducing simultaneous entry into hairpin bends.

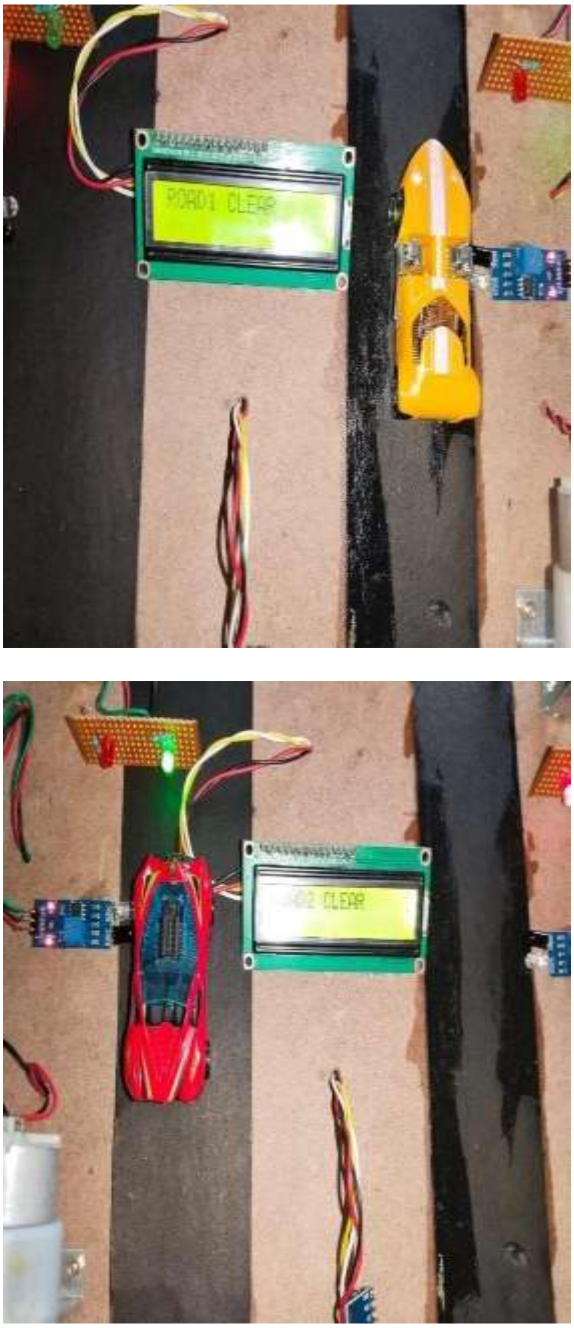


Figure 7: Conflict Avoidance for Road 1 and Road 2

4.5 Heavy Vehicle Prioritization

The CNN model achieved over 90% accuracy in classifying vehicles, correctly prioritizing heavy vehicles (trucks/buses) over cars in simultaneous approaches.

Fig. Priority for Bus

Fig. Bus can move ahead

Fig. Priority for Truck

Figure 8: Heavy Vehicle Prioritization

4.6 Communication

HC-12 modules ensured reliable communication up to 600 meters in line-of-sight conditions. Telegram alerts were delivered with an average latency of 2–3 seconds, subject to Wi-Fi stability.

Figure 9: Telegram Alert Notification

The system effectively integrates landslide detection, traffic management, and vehicle prioritization, addressing critical safety challenges in ghat road sections. The ADXL345's high-resolution measurements and filtering techniques minimized false positives, ensuring reliable landslide detection. The rain sensor's automated response to heavy rainfall provided temporary road closures, aligning with practical safety protocols. IR-based conflict avoidance and machine learning-driven vehicle prioritization optimized traffic flow, reducing congestion and collision risks.

Key Findings:

- The system's fail-safe design (e.g., red signals and gate closure on sensor failure) enhances reliability.
- Real-time alerts via HC-12 and Telegram ensure timely driver and authority notification.
- The CNN model's high accuracy (90%) in vehicle classification supports intelligent traffic management.

Limitations:

- HC-12 performance may degrade in obstructed environments, suggesting a need for LoRa or higher-frequency RF modules.
- Rain sensor calibration varies by region, requiring site-specific tuning.
- The ML model's performance depends on lighting and camera positioning, with potential false positives in low visibility.
- Frequent power outages in ghat areas necessitate backup solutions like solar power.

5. Conclusion

This research demonstrates a robust IoT and machine learning-enabled system for landslide detection, conflict avoidance, vehicle prioritization, and rainfall management in ghat road sections. The prototype's real-time monitoring, automated control, and intelligent traffic management significantly enhance road safety. The system's scalability and cost-effectiveness, leveraging affordable components like the ESP32 and HC-12, make it suitable for widespread deployment in vulnerable regions.

6. Future Scope

Future enhancements include:

- Expanding the ML model to classify motorcycles and improve performance under diverse lighting conditions.
- Implementing solar-powered operation for areas with unreliable power supply.
- Deploying multiple Hub Units for coordinated monitoring over long road stretches.
- Developing a mobile application for dynamic driver alerts and route recommendations.
- Integrating LoRa for enhanced communication range in obstructed environments.

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