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PROJECT TITLE: SMART RAILWAY SAFETY PROTOTYPE WITH IMU-BASED STABILITY MONITORING, RFID STATION IDENTIFICATION AND COLLISION PREVENTION

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Declarations

I hereby certify that the work which is being presented in the project entitled **A Smart Railway Safety Prototype with IMU-Based Stability Monitoring, RFID Station Identification and Collision Prevention** in the partial fulfillment of the requirements for the award of the degree of **BACHELOR OF SCIENCE** and submitted in the **DEPARTMENT OF ELECTRONIC ENGINEERING, BINDURA UNIVERSITY OF SCIENCE EDUCATION**, is an authentic record of my own work carried out during the time period from **August 2022 to June 2026** under the supervision of **Mr Ngombe, Lecturer, Electronic engineering department.**

The matter presented in this project has not been submitted by me for the award of any other degree of this or any other institute.

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This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Supervisor

Mr T Ngombe

Ngombe **Date** 27/08/26

Dedication

This project is dedicated to my family for their continuous support, encouragement and motivation throughout my academic journey. Their sacrifices, guidance and belief in my abilities gave me the strength to complete this study successfully.

I also dedicate this work to my lecturers and colleagues whose advice and encouragement contributed greatly to the completion of this project.

Finally, this project is dedicated to the National Railways of Zimbabwe and to all individuals working towards improving railway safety through technology and innovation.

Abstract

Railway accidents such as collisions and derailments remain a major challenge, especially in developing countries like Zimbabwe, where ageing infrastructure and limited safety monitoring systems increase operational risks. Existing railway systems often rely on manual inspections and outdated signalling methods, which can result in delayed fault detection and increased accident rates.

This study presents the design and development of a low-cost embedded railway safety prototype aimed at improving train safety through automated monitoring and control. The prototype was developed using an ESP32 microcontroller and integrates an ultrasonic sensor for obstacle detection, an MPU6050 sensor for train stability monitoring, RFID technology for station and checkpoint identification, and an IR sensor for line tracking. The system also uses Firebase Realtime Database and a web-based dashboard for remote monitoring of train conditions and safety events.

An engineering design and experimental methodology was used to design, build and test the prototype. The ESP32 continuously receives data from the sensors and makes safety decisions based on predefined thresholds. When an obstacle is detected within the warning distance, the system automatically reduces motor speed. If the obstacle reaches a critical distance, the train is brought to a complete stop. Similarly, abnormal tilt conditions detected by the MPU6050 trigger safety responses to reduce the risk of derailment. RFID tags placed at selected points on the track provide location updates, which are transmitted to the dashboard through Firebase.

Testing results showed that the system successfully detected obstacles, monitored train stability, identified RFID checkpoints and transmitted data for real-time monitoring. The automatic speed reduction and emergency stopping functions operated as expected under different test conditions.

The study demonstrates that low-cost embedded technologies can be combined to improve railway safety through automated monitoring, collision prevention and remote supervision. The proposed system provides a practical solution that can be adapted for railway environments with limited resources, such as those found in Zimbabwe.

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List of Abbreviations

Abbreviation	Full Meaning
ADC	Analogue-to-Digital Converter
API	Application Programming Interface
BBR	Bulawayo Beitbridge Railway
DC	Direct Current
ESP32	Espress if Systems 32-bit Microcontroller
GPIO	General Purpose Input/Output
GPS	Global Positioning System
GSM	Global System for Mobile Communication
HC-SR04	Ultrasonic Distance Sensor Module (Model HC-SR04)
HTTP	Hypertext Transfer Protocol
I2C	Inter-Integrated Circuit
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
IoT	Internet of Things
IR	Infrared
JSON	JavaScript Object Notation
L298N	Dual H-Bridge Motor Driver Module (Model L298N)
LED	Light-Emitting Diode
LoRa	Long Range (wireless communication technology)
MFRC522	RFID Reader/Writer Integrated Circuit (NXP Model MFRC522)
MPU6050	6-Axis Motion Processing Unit (Invent Sense Model MPU-6050)
NRZ	National Railways of Zimbabwe
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation
RC522	RFID Reader Module (based on MFRC522 IC)
RFID	Radio Frequency Identification

SADC	Southern African Development Community
SMS	Short Message Service
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver-Transmitter
Wi-Fi	Wireless Fidelity (IEEE 802.11 standard)

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CHAPTER 1: INTRODUCTION

1.1 Background

Railway transport remains one of the most efficient and economical modes of transport for both passengers and freight. It plays a critical role in national development by supporting industrial activities, agriculture, mining and regional trade. In Zimbabwe, the National Railways of Zimbabwe (NRZ) serves as an important transport backbone connecting major cities, industrial zones and border points. The safety and reliability of railway operations are therefore essential for protecting human life, safeguarding infrastructure and sustaining economic productivity.

Globally, the railway systems have evolved from traditional manually operated systems to intelligent automated systems that utilize embedded electronics, wireless communication and sensor-based monitoring technologies. Modern railway safety systems increasingly rely on microcontrollers, embedded control systems, sensor fusion and automated decision-making to improve operational safety and reduce human error. These systems continuously monitor train movement, speed, stability, environmental conditions and track occupancy in order to detect hazardous situations early and trigger corrective actions automatically (Patel & Bhagat, 2019) (Roy & Dey, 2020).

Despite these technological advancements, railway accidents continue to occur worldwide due to excessive speed, signalling failures, communication breakdowns, human error, poor infrastructure conditions and delayed hazard detection (Tang, et al., 2023). Train collisions remain among the most dangerous railway accidents because they often result in severe injuries, fatalities, infrastructure destruction and disruption of railway operations.

In Southern Africa and Zimbabwe in particular, railway safety challenges remain a major concern due to ageing infrastructure, obsolete signalling systems and continued dependence on manual monitoring approaches. Several derailments and train collisions have occurred over the years, demonstrating the limitations of traditional railway safety mechanisms.

A notable example occurred in April 2025 when a Rovos Rail passenger train carrying international tourists collided with a Bulawayo Beitbridge (BBR) goods train near Gwanda, Zimbabwe. The accident resulted in injuries and significant train damage (Reporter, 2025). Importantly, this incident demonstrated that train collisions are not limited to level crossings involving road vehicles. Collisions can occur directly between trains operating on railway tracks due to signalling errors, communication failures, poor visibility, human error or inadequate train separation mechanisms. Such accidents highlight the need for intelligent collision prevention systems capable of monitoring train movement, detecting unsafe conditions and initiating automatic preventive actions before impact occurs.

Similarly, derailments continue to affect railway operations in Zimbabwe. In November 2018, a goods train derailed near Thompson Junction close to Hwange (Ncube, 2018), while another coal-laden goods train derailed near Kadoma in February 2025 after heavy rainfall caused mud to cover sections of the railway track (PindulaNews, 2025). These incidents demonstrate the vulnerability of railway systems deterioration, environmental hazards and insufficient real-time monitoring.

Traditional railway safety methods such as manual signalling, visual inspection and human supervision are increasingly inadequate because they rely heavily on human judgement and delayed response (Devi, et al., 2021). In many situations, hazardous conditions may only be identified after an accident has already occurred. Furthermore, many existing railway monitoring systems focus only on isolated functions such as location tracking, communication or obstacle detection rather than providing fully integrated low-cost safety solution suitable for developing countries.

Now arriving - affordable tools like embedded systems, wireless links, and modern sensors open paths toward smarter rail safety setups suited for low-resource settings. A device such as the ESP32 packs many sensing units together, merging them inside one small unit able to watch conditions while making decisions on the spot. Real-time automation becomes possible when these components work under tight coordination. This integration supports instant responses through built-in logic without relying on distant servers. Roy and Dey showed how this works back in 2020 using similar hardware frameworks.

This study proposes a smart embedded railway safety prototype based on the ESP32 microcontroller. The system integrates an MPU6050 Inertial Measurement Unit (IMU), RFID technology, ultrasonic sensing, infrared line detection, PWM-based motor control and Wi-Fi communication to improve railway operational safety.

The MPU6050 sensor unit tracks movement by merging three-dimensional acceleration data along with rotational rate measurements. As noted in Song et al. (2022), such inertial sensors help identify irregular behaviors during operation - patterns often linked to potential imbalance or track departure threats. Motion shifts, shakes, and angular deviations are captured continuously through this setup. (Zhou, et al., 2020) further explain that sudden vibrations in pitch, roll and vibration patterns may indicate unsafe train operating conditions. Within the proposed system, abnormal tilt conditions trigger corrective actions such as speed reduction or emergency stopping.

RFID tags positioned at predefined railway sections are used for station identification and location referencing whenever the train passes specific checkpoints (Aditya, et al., 2022). Unlike continuous GPS tracking, RFID provides discrete location updates only at predefined point. In real-world railway systems, GPS technology may additionally be integrated to provide accurate continuous train positioning over long distances. However, due to prototype complexity and implementation limitations, this study focuses on RFID-based location identification.

The ultrasonic sensor is used to detect nearby obstacles or unsafe train proximity. Using threshold-based logic, the ESP32 automatically reduces train speed through PWM control and stops the train when critical distances are reached. This forms the basis of the collision prevention mechanism (Shinde & Jadhav, 2019).

In this study, collision prevention refers not only to avoiding level-crossing accidents but also preventing train-to-train collisions on railway tracks. The 2025 Gwanda railway collision involving a Rovos Rail passenger train and a BBR goods train demonstrates that collisions can occur directly on railway lines due to signalling failures, communication breakdowns or inadequate train separation mechanisms (Reporter, 2025).

Remote oversight via Wi-Fi links to Firebase (Firebase, 2024), so live operational updates appear instantly on a browser-accessible interface. Rail staff gain easier access to train status and incident tracking thanks to this online display panel. Still, vital safety responses happen directly on the onboard device - no reliance on internet signals needed. Stability checks, impact warnings, stop-point detection, plus centralized viewing fit inside an affordable hardware setup. Such integration offers a working safety model tailored for regions with limited infrastructure, like Zimbabwe.

1.2 Problem Statement

The National Railways of Zimbabwe (NRZ) continues to experience frequent railway safety incidents, including derailments, train collisions and level-crossing accidents. These incidents are largely attributed to human error, excessive train speed, delayed hazard detection and continued reliance on manual signalling and monitoring systems (Tang, et al., 2023). The challenge is further intensified by the ageing rolling stock, deteriorating track infrastructure and limited adoption of automated railway safety technologies (Song, et al., 2022).

The various railway accidents that have taken place in the past few years in Zimbabwe through trains colliding and derailing have shown the importance of introducing a new safety system. The railway accidents in Zimbabwe indicate that the current monitoring and control systems are not efficient enough to prevent the accidents from happening. Therefore, there is a need for introducing an efficient railway safety system that detects the dangers early and takes the necessary action.

Most traditional railway systems rely heavily on manual supervision, visual inspection and operator judgement. These approaches often result in delayed response to dangerous operating conditions, increasing the risk of collisions, derailments and infrastructure damage (Devi, et al., 2021).

Although several railway safety studies have proposed RFID-based tracking systems, GSM communication systems and obstacle detection mechanisms, many existing solutions focus on isolated safety functions and lack integrated monitoring capabilities. Some systems depend heavily on continuous network connectivity, while others do not adequately address train stability monitoring or automatic response to hazardous conditions (Kumar & Singh, 2021); (Roy & Dey, 2020).

Furthermore, accurate continuous train positioning remains a challenge in many developing railway environments. Advanced railway systems in developed countries commonly utilise GPS-based train tracking for real-time geographic positioning and operational monitoring. However, such systems are often expensive and difficult to implement within resource-constrained railway infrastructures due to hardware, communication and maintenance requirements.

Therefore, there remains a need for improved railway safety approaches capable of enhancing hazard detection, train stability monitoring, station identification and real-time operational monitoring within low-cost and infrastructure-limited railway systems such as those in Zimbabwe.

1.3 Aim of the Project

To design and implement an ESP32-based embedded railway safety system that utilises RFID, ultrasonic and MPU6050 sensors for station identification, collision prevention, train stability monitoring and real-time monitoring through a web-based dashboard.

1.4 Specific Objectives

1. To implement an obstacle detection and collision prevention mechanism using ultrasonic sensing and threshold-based speed control.
2. To monitor train stability and detect unsafe tilt conditions using the MPU6050 sensor for derailment risk reduction.
3. To implement RFID-based station identification and checkpoint monitoring for train location referencing.
4. To develop a web-based dashboard integrated with Firebase for real-time visualisation of train status, sensor readings and safety alerts.

1.5 Scope of the Study

This work explores building a compact smart rail safety model. Through combining sensors and control units, automation in train protection gets tested. A motion-sensing unit captures tilt and movement data. Wireless connectivity allows remote monitoring capabilities. Sensor inputs feed into a central processing chip. Operation relies on real-time feedback from proximity detection hardware. Identity verification happens via contactless tagging technology. Data flows between

components using onboard circuit integration. Testing checks how well responses align with expected outcomes.

From time to time, the IMU tracks how much the train tilts sideways or forward, spotting unusual leans that could mean it's becoming unsteady. Nearby objects or other trains are sensed by an ultrasonic device, which gauges separation distances precisely. When readings cross safe limits, motion slows down - sometimes halting altogether - to avoid impacts. Stopping decisions happen without delay if danger levels rise.

The RFID tags are set up at specific spots along the railway tracks to represent stations, checkpoints, or segments of the railway line. Upon passing over an RFID tag, the train's location will be identified by the system and reported back to the monitoring system. Discrete location detection has been achieved in this manner rather than constant tracking.

The use of RFID technology for location referencing is the case in the system. The study acknowledges that GPS integration will be required for continuous location reporting in an actual railway system due to the fact that railway lines cover vast stretches of land and accuracy of train location needs to be achieved.

Even though Wi-Fi connectivity is used by the ESP32 to relay specific information about train operations through the Firebase Realtime Database and the Internet-based monitoring system, safety mechanisms have been kept independent. Safety mechanisms include speed control, unexpected halts, and collision avoidance which are all handled directly by the train device. This way, performance will be dependable even without network connectivity.

The scope is limited to prototype-level validation and does not include deployment on actual NRZ railway infrastructure or full-scale operational trains. Advanced railway technologies such as artificial intelligence, machine learning, satellite communication, advanced railway signalling standards and fully integrated GPS navigation are beyond the scope of this study.

The proposed system is therefore intended as a proof-of-concept embedded railway safety prototype demonstrating the feasibility of combining IMU stability monitoring, RFID station identification and automated collision prevention within a low-cost embedded platform.

1.6 Significance of the Study

Though focused on railways, the work shows how sensors and computing fit together where safety matters most. Built around a small computer, the system ties motion detection, distance checks, and location tagging into one flow. Instead of working alone, each sensor adds context that others use. When movement shifts too far, alerts rise before danger appears. Station markers trigger updates without relying on GPS. Even in poor visibility, nearby objects get detected early. Safety gains come not from one part but from constant coordination across components.

The IMU component contributes significantly to the system by enabling real-time monitoring of train orientation and stability. Through accelerometers and gyroscopes, the IMU measures roll, pitch and motion changes that may indicate excessive vibration, imbalance or derailment risk. This introduces an additional layer of safety beyond traditional obstacle detection systems.

The study demonstrates the use of threshold-based PWM motor control for automated railway safety response. By automatically reducing motor speed or stopping the train when unsafe conditions are detected, the system minimises dependence on human intervention and improves response time during hazardous situations.

The use of a web-based dashboard technology for railway monitoring applications is also demonstrated by the study. By integrating Firebase with a monitoring dashboard, operational information can be viewed in real time, improving system visibility and supporting more effective monitoring of railway safety conditions.

From a railway safety perspective, the proposed system contributes towards preventing train collisions and derailments. The concept of collision prevention in this study extends beyond level-crossing accidents involving road vehicles. The system is also intended to reduce the risk of train-to-train collisions occurring directly on railway tracks, such as the collision between the Rovos Rail passenger train and the BBR goods train near Gwanda in 2025. Such accidents demonstrate

the need for intelligent systems capable of monitoring train separation, detecting unsafe proximity and executing automatic preventive actions.

Looking at things through a tech lens, this research offers an approach that is both budget-friendly and able to grow with demand - ideal for rail systems in places like Zimbabwe, where high-end signal technology might not exist. Instead of relying on complex setups, it uses accessible tools: the ESP32 chip, paired with off-the-shelf sensors, makes real-world installation more realistic even when funds and equipment are tight.

The study further highlights how RFID technology can be used for station identification and location referencing, while recognising the future importance of GPS integration for accurate continuous train positioning in real-world railway systems.

Societally, improved railway safety has the potential to reduce injuries, fatalities, cargo losses and infrastructure damage while improving public confidence in railway transportation. Safer railway systems also support economic productivity by improving freight reliability and reducing service disruptions.

1.7 Chapter Summary

This chapter introduced the background and motivation for the study by discussing railway safety challenges such as train collisions, derailments and inadequate monitoring systems within Zimbabwe and other railway environments. The chapter highlighted that collisions may occur not only at level crossings but also directly between trains operating on railway tracks, emphasising the need for improved safety mechanisms. The problem statement identified limitations associated with traditional railway monitoring approaches, while the aim, objectives, scope and significance established the direction of the study. The chapter further introduced the proposed smart embedded railway safety prototype integrating MPU6050-based stability monitoring, RFID station identification, ultrasonic collision prevention and Firebase-based remote monitoring as a low-cost approach suitable for resource-constrained railway systems.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This section examines prior work on rail safety setups, onboard tracking tools, methods to avoid train crashes, besides smart regulation strategies. Its aim lies in setting up the conceptual and technical base for the current project, at the same time spotting missing elements that support building the suggested model.

The chapter focuses on railway sensing technologies, embedded control systems, IMU-based monitoring, RFID-based station identification, ultrasonic collision prevention systems and communication technologies used in railway safety applications, including web-based dashboard monitoring. Main focus is on technologies suitable for low-cost and resource-constrained railway environments such as Zimbabwe.

The chapter is structured as follows:

Section 2.2 presents the theoretical background underpinning the proposed system, including control theory, IMU sensing theory, RFID identification principles and communication systems. Section 2.3 reviews related systems and technologies by analysing existing designs, tools, sensors and algorithms used in railway safety applications. Section 2.4 identifies gaps in the reviewed literature, particularly within the context of developing countries and Zimbabwe. Section 2.5 develops the conceptual framework for the proposed system, demonstrating how existing research informs the design decisions. Finally, Section 2.6 concludes the chapter with a concise summary of key insights and motivations for the research.

2.2 Theoretical Background

Automated Railway Safety Systems are based on various theories of engineering that allow accurate monitoring, effective communication, and intelligent control. The major theories applicable to this topic are control theory, sensor theory and signal processing theory, location and identification theory and communication theory.

2.2.1 Control Theory

(Patel & Bhagat, 2019) describe control theory as a fundamental engineering discipline concerned with regulating dynamic system behaviour through feedback mechanisms. Feedback control allows a system to continuously monitor its operational state and adjust its output in order to achieve a desired objective. In practical engineering applications, feedback control is widely used to regulate variables such as speed, position, temperature and pressure within safe and stable operating limits.

Despite its broad use, the PID controller isn't always ideal when cost matters. Where resources are tight, simpler methods take priority - efficiency gains come through lean computation instead. Real-time demands push design toward lightweight solutions more than sophisticated ones. Hardware constraints shape choices just as much as performance goals do. Nise noted this trade-off in 2020: minimalism wins under pressure.

In railway safety systems, control algorithms can be used to regulate train motion and ensure that speed adjustments occur in response to detected hazards or unsafe operating conditions. Sensor inputs such as obstacle distance or motion instability can be processed by a controller to determine the appropriate corrective action, such as reducing speed or emergency stopping.

The proposed system uses the ESP32 microcontroller as the central embedded controller. Inputs from the ultrasonic sensor and MPU6050 IMU are continuously analysed to determine whether the train prototype is operating within safe conditions. The ultrasonic sensor monitors obstacle proximity and train separation distance, while the MPU6050 monitors motion stability, vibration and tilt conditions associated with derailment risk.

The system implements a simplified control strategy inspired by PID principles is used to regulate motor speed during collision avoidance scenarios. Instead of relying on wheel encoder feedback for continuous speed measurement, the ESP32 microcontroller adjusts the Pulse Width Modulation (PWM) duty cycle supplied to the L298N motor driver according to sensor conditions.

The control error in this context can be expressed as the difference between a predefined safe distance and the measured obstacle distance:

$$e(t) = D_{safe} - D_{measured}$$

where **Dsafe** represents the minimum safe separation distance and **Dmeasured** represents the distance detected by the ultrasonic sensor.

Once the sensed distance drops under the initial safety limit, the system lowers the PWM duty cycle sent to the motor unit, slowing the model train in a managed way. Should that gap shrink more and hit the second stricter boundary, power delivery stops entirely through full cutoff of the PWM signal, forcing a total halt. In parallel, irregular angles or shaky movement picked up by the MPU6050 can prompt self-initiated adjustments without human input.

This two-stage response ensures gradual speed reduction followed by emergency stopping when necessary. By adjusting motor speed through PWM control signals, the system maintains a single yet effective method of implementing automated safety responses. This approach reduces implementation complexity while still demonstrating the fundamental principles of feedback control and embedded system automation within railway safety applications.

2.2.2 Sensor Theory and Signal Processing

Sensor technologies form an important part of modern embedded railway safety systems because they enable continuous monitoring of train motion, obstacle proximity and operating conditions. The proposed system integrates the MPU6050 IMU and ultrasonic sensing technology to support stability monitoring and collision prevention.

One study by Song and colleagues from 2022 looked into how Inertial Measurement Units support movement tracking within transport setups. These units operate through principles linked to Newtonian physics, capturing data on speed changes, spin rates, and positioning as events unfold. Inside the tested model, an MPU6050 sensor was selected due to its built-in fusion of three-directional acceleration detection and rotation sensing capabilities. Linear shifts across vertical, horizontal, and depth planes are caught by the accelerometer component. Meanwhile, spinning motions around those same directions get recorded via the gyroscope element. Through merging such inputs, behavior patterns like tilt angle shifts, sideways lean, and overall dynamic response of the small-scale train could be reconstructed.

Within railway systems, abnormal tilt conditions, excessive vibration and sudden angular changes may indicate instability or derailment risk. (Song, et al., 2022) further explain that raw IMU measurements are often affected by sensor noise, bias drift and vibration-induced disturbances, which can reduce measurement accuracy. To improve reliability, signal processing and filtering techniques such as complementary filtering and Kalman filtering are commonly used to combine accelerometer and gyroscope data while reducing noise effects.

The MPU6050 communicates with the ESP32 using the I2C communication protocol, allowing continuous transmission of motion data for real-time processing. In the proposed system, tilt and motion data are continuously monitored to detect unsafe operating conditions. When predefined stability thresholds are exceeded, the embedded controller initiates corrective actions such as speed reduction or emergency stopping.

(Zhou, et al., 2020) further expand on vibration-based monitoring by analysing derailment precursors in rail vehicles. They show that lateral acceleration and tilt angles significantly increase prior to derailment events. Their research confirms that signal processing techniques applied to IMU data can distinguish between normal operational vibrations and hazardous conditions. The authors argue that such data-driven approaches enable predictive rather than reactive safety systems. Their findings reinforce the importance of real-time motion sensing in preventing rail accidents.

One important advantage of IMU-based monitoring systems is that they do not depend on external infrastructure. Unlike track-based monitoring systems, the MPU6050 operates directly on the train prototype and continuously monitors train behaviour in real-time. This makes the technology suitable for railway environments with limited infrastructure and resource constraints.

(Kumar, et al., 2022) examined ultrasonic sensing technology for obstacle crack detection on railway tracks. They explain that ultrasonic sensors operate based on acoustic wave propagation and reflection principles. Their study demonstrates that ultrasonic sensors can detect track discontinuities and nearby obstacles with high accuracy over short distances. However, the authors note that ultrasonic systema are often limited to local detection and require integration with

communication modules for broader system effectiveness. This highlights the need for combining sensing with communication technologies.

In the proposed system, the ultrasonic sensor is used for collision prevention by continuously monitoring the distance between train prototype and nearby obstacles or trains. The ESP32 processes distance measurements using threshold-based logic. When an object enters the warning distance, the controller reduces motor speed through PWM control. If the object approaches a critical threshold, the controller stops the train completely while activating warning alerts such as LED's and a buzzer.

(Kumar, et al., 2022) note that ultrasonic sensor systems are generally limited to local short-range detection and often require integration with communication systems for broader operational effectiveness. This highlights the importance of combining sensing technologies with embedded communication and control systems. In the proposed prototype, Wi-Fi communication through Firebase is incorporated to support remote monitoring while maintaining local embedded decision-making for safety-critical operations.

2.2.3 Location and Identification Models

Location identification and train positioning are important components of modern railway safety systems because they assist operators in monitoring train movement, track occupancy and operational status. Various technologies such as Radio Frequency Identification (RFID) and Global Positioning System (GPS) technology are commonly used for train localisation and monitoring applications.

(Bhuvaneswari & Porkodi, 2021) examined the use of Radio Frequency Identification (RFID) technology for train identification and localisation in railway systems. They describe RFID as a wireless technology that uses radio-frequency electromagnetic signals to uniquely identify tagged assets without requiring line-of-sight communication. Their study demonstrates that RFID tags strategically placed along railway tracks enable reliable train identification and discrete location updates as trains pass predefined points. The authors highlight that RFID systems are relatively

low-cost, energy efficient and robust under harsh environmental conditions such as dust, vibration and temperature variation.

RFID systems usually comprise RFID tags, an RFID reader and an embedded controller. In the proposed RFID system, the passive RFID tags are attached to predetermined sections of the railway track that signify stations, checkpoints or railway sites. As the train passes through a tag, the RC522 RFID reader senses the unique identification code and sends the information to the ESP32 microcontroller for processing.

As compared to the Global Positioning System (GPS) technology, the use of RFID technology in railway safety applications in developing nations like Zimbabwe is advantageous due to the following factors: The GPS systems usually require visibility to satellites, consistent power source on board and communication channels to transmit location data. Continuous GPS tracking may be expensive and challenging to maintain in the railway environment.

However, RFID technology is less complex, locally installed, and does not require satellite transmission, thus being more reliable in tunnels, cuttings, and other places of signal obstruction. Even though GPS can continuously monitor the geographical position of trains, RFID technology offers better accuracy regarding specific railroad locations, including stations, tracks connections, and checkpoints that are crucial for operations and safety reasons.

In the discussed prototype, RFID technology is mainly used for station and checkpoint location rather than continuous tracking. The train location is constantly updated via Firebase upon passing any predetermined checkpoint of the railway route. With this technology, it is possible to monitor the location of the prototype via the dashboard and determine the part of the railway route that the train occupies at the moment.

Even though RFID technology is the main one for location identification in the discussed prototype, GPS technology remains essential in modern real-world railway systems, since it allows for the continuous train positioning over great distances. Thus, the further development of the discussed system might involve the integration of GPS into the system.

The above listed advantages make RFID a feasible system for implementing railway safety solutions at the prototype level within resource scarce environments such as Zimbabwe while ensuring future growth to GPS-based railway safety systems.

2.2.4 Communication Theory

Communication systems play an important role in modern railway safety applications because they enable the transmission of safety alerts, train status data between trains, monitoring stations and control centres. Effective communication improves coordination, monitoring and response during hazardous operating conditions.

(Kumar & Singh, 2021)analyse GSM-based communication for railway safety applications. They explain that GSM enables wide-area digital communication by utilising existing cellular infrastructure. In railway safety applications, GSM communication can be implemented using Short Message Service (SMS) or packet-switched data services. While GSM enables wide-area communication, recent developments in embedded systems favour Internet-based communication using Wi-Fi and cloud platforms (Roy & Dey, 2020).

Although internet-based communication provides improved data accessibility and scalability, it may be limited in remote areas with poor connectivity (Tang, et al., 2023). Therefore, the proposed system ensures that all safety-critical decisions are executed locally, while communication is used primarily for monitoring, data visualisation and system status reporting.

2.2.5 Redundant Collision Prevention and Proximity Sensing

Collision prevention in railway systems requires reliable detection of train proximity and timely control intervention. Depending on a single sensing technology may expose the system to failure due to sensor malfunction, environmental interference or communication delays. For this reason, safety-critical transportation systems often employ redundant sensing architectures to enhance reliability and fault tolerance (Kumar, et al., 2022).

In the course of this study, an ESP32 microcontroller was used for the sake of Wi-Fi connection. With the help of HTTP request, information is being sent to a Firebase Realtime Database – quick

access and cloud-based storage. Information received is displayed via a web-based interface, rail workers can monitor locomotive conditions, stop alterations or emergencies from a distance. Despite simple equipment, the solution is highly responsive and works efficiently under different network conditions. Thus, remote monitoring becomes possible without the need to use proprietary systems. The information updates become available almost immediately after logging by the sensors. This solution is applicable for the environment where constant internet connection is not assured. Instead of complicated infrastructure, the process relies on lightweight protocols for stability purposes. However, the solution provides high accuracy throughout the tests. Minimal settings are needed for its deployment due to the reconnection abilities. The maintenance is also greatly simplified as components report problems. Patterns of delays and failures become visible through logs over time. The security is based on authentication levels that are controlled by Firebase. Local servers are not required to ensure smooth operation of the system. Since the frontend is operated by regular browsers, installation of additional software becomes irrelevant. Test feedback indicates reliability despite variations in the signals. Latency is maintained low to allow time for intervention in case of problems. The simplicity of the design is prioritized while functionality is not neglected. In effect, there is a functional monitoring system created using inexpensive components. It can operate independently or can be easily integrated into bigger systems. With minimal components, the failure points are greatly reduced. Most processes are automated after the system is powered up once.

High-frequency sound waves travel out from a device, then bounce back when they hit something. The span between sensor and target comes from timing how long the echo takes to arrive. Kumar and colleagues in 2022 noted these systems deliver precise readings up close, along with quick reactions. Because of that speed and accuracy, such detection works well where instant obstacle responses are needed.

Unlike RFID, which provides train identification and location referencing at predefined checkpoints (Aditya, et al., 2022), ultrasonic sensors continuously measure physical separation distance between moving objects. This makes ultrasonic sensing particularly important for detecting nearby obstacles, trains or unsafe proximity conditions in real-time.

In the proposed system, RFID and ultrasonic sensing operate as a redundant collision avoidance mechanism. RFID provides station identification and location awareness, while ultrasonic sensors continuously measure the distance between adjacent trains. This redundancy ensures that if RFID data is delayed, corrupted or unavailable, ultrasonic sensing can still trigger safety actions. Such redundancy improves system dependability and supports fail-safe operation, where the system defaults to a safe state under fault conditions.

The proposed collision prevention approach is not limited to avoiding level-crossing accidents involving vehicles or pedestrians. It also addresses train-to-train collisions that may occur directly on railway tracks due to signalling failures, communication delays or inadequate train separation mechanisms. The 2025 Gwanda collision involving a Rovos Rail passenger train and a BBR goods train demonstrate the importance of continuous train proximity monitoring and automatic safety intervention mechanisms (Reporter, 2025).

The control intervention in the proposed system is achieved through the use of PWM (Pulse Width Modulation) control technique based on the thresholds controlled through the ESP32 controller. In case the first threshold is breached, the controller lowers the PWM duty cycle provided to the motor driver, which leads to the slowing down of the train. Should the distance be reduced even further and reach the critical safety threshold, the controller would stop the motor driver completely, stopping the train.

Multiple sensors improve the fault-tolerance of the system. The suggested system can operate under the principles of the fail-safe system, where the system defaults to a safe state when hazards are detected.

2.3 Review of Related Systems and Technologies

This section discusses the safety systems and technology in the railway systems currently in use, with emphasis on sensing, location determination, communications architecture and intelligent controls. The discussion will look at the current approach by the modern railways of utilising sensor, wireless communication and automation for enhancing safety.

2.3.1 Sensor-Based Accident Detection and Collision Prevention

Though Devi et al. (2021) introduce a railway accident detection model using IoT combined with motion and environmental monitors to catch irregular operations, their setup shows potential in spotting dangers and sending quick warnings. Despite this strength, heavy dependence on numerous sensors, constant data flow, and cloud computation raises complexity, energy demands, and expense. Because these challenges hinder usability where resources are limited, the team suggests leaner, adaptable architectures could work better across railways in less developed areas.

(Moyo & Dewa, 2022) investigate railway safety practices across Southern Africa and report that many rail networks continue to depend largely on manual inspections and visual observation. While the methods are low-cost, the authors argue that they are inherently reactive and prone to human error, resulting in delayed fault detection and elevated accident risk. Their findings expose a substantial technological gap between railway systems in developed and those operating within developing regions such as Zimbabwe.

Recent railway accidents within Zimbabwe further demonstrate the limitations of traditional monitoring approaches. The 2025 Gwanda collision involving a Rovos Rail passenger train and a BBR goods train highlighted that train-to-train collisions can occur directly on railway tracks due to signalling failures, delayed communication or inadequate train separation mechanisms (Reporter, 2025). This shows that railway collision prevention should extend beyond level-crossing protection to include continuous train proximity monitoring and automated intervention systems.

Modern railway safety systems increasingly utilise IMUs, ultrasonic sensors and embedded controllers to improve accident prevention. (Song, et al., 2022) explain that IMU-based systems cam monitor vibration, tilt and motion conditions associated with instability or derailment risk, while (Zhou, et al., 2020) show that abnormal tilt and lateral acceleration may indicate unsafe operating conditions. In the proposed system, the MPU6050 IMU monitors train stability, while the ultrasonic sensor detects obstacles and train proximity. The ESP32 processes sensor data locally and automatically performs speed reduction or emergency stopping when hazardous conditions are detected.

Taken together, these studies reveal a trade-off between advanced sensor-based systems and practical deployment constraints. Highly integrated IoT solutions offer improved detection capabilities but are often financially and operationally unsuitable for developing contexts, while manual monitoring lacks timelines and reliability. These limitations motivate the need for a low-cost, automated and modular railway safety system that leverages essential sensors and existing communication infrastructure to provide timely accident detection without excessive complexity or cost.

2.3.2 Location Tracking and Collision Avoidance Technologies

(Bhavsar & Kulkarni, 2016) demonstrate the effectiveness of Radio Frequency Identification (RFID) technology for train localisation in railway systems. Their study shows that RFID provides accurate and reliable location updates at predefined railway checkpoints while operating under strict budgetary constraints. The authors emphasise RFID's robustness, low power consumption and low maintenance requirements, making it suitable for railway environments where continuous positioning technologies are impractical or too costly. Their findings support RFID as a viable solution for train identification and station referencing in cost-sensitive railway applications.

(Shinde & Jadhav, 2019) further validate the applicability of RFID by implementing a prototype collision prevention system capable of identifying trains approaching the same track segment. Their system successfully detected potential conflict scenarios and generated warning alerts to improve operational safety. However, the authors note that the system relied on a single sensing modality and focused mainly on identification and alerting, with limited provision for redundancy or obstacle detection. As a result, system reliability may be reduced in situations involving tag failure, environmental interference or unexpected obstacles present on the railway track.

The other railway collision solutions use GPS-based technology for train localisation. Despite the broad range of coverage provided by GPS technology, it cannot work effectively in tunnels, urban cuttings and areas with weak satellite signals. Besides, GPS technology is costly and requires continuous communication.

While RFID cannot offer continuous geographic location like GPS, RFID provides higher accuracy of location at definite checkpoints of the railway, such as stations, track joints, and control sections. Therefore, RFID may be used for the station identification and location referencing applications when accurate checkpoint verification is of higher importance than tracking.

This set of restrictions proves that there should be a redundant collision avoidance system which would not rely on the usage of any specific technology of sensing or location. The proposed system fulfils this need because it integrates location identification via RFID with ultrasonic sensing of the obstacles in close proximity. Through the use of different sensors, the system increases its reliability and fault tolerance to guarantee that collision threats will still be recognized even if one of the sensing channels fails.

2.3.3 Communication Frameworks

Communication frameworks are important in railway safety systems because they enable transmission of operational data, alerts and train status information between onboard systems and monitoring platforms. (Zhang, et al., 2023) evaluated the reliability of Global System for Mobile Communication (GSM) in railway communication systems and found that GSM remains effective for long-distance communication and SMS alert transmission. However, recent railway monitoring systems utilise IoT-based communication platforms more because of their scalability and real-time monitoring capabilities (Cai, et al., 2022).

The system is able to transmit information related to RFID locations, train conditions, and warning messages using ESP32 microcontroller through Wi-Fi to the Firebase Real-time Database. The data will be processed, and it appears on the web dashboard where the trains' statuses and warning states can be monitored in real-time. Despite the fact that the data will appear to be coming from weak signals to the distant areas – something common in rail transport in the rural areas – the system is still able to take the necessary precautions including deceleration and stopping locally.

2.3.4 Intelligent Control Approaches

Intelligent control systems improve railway safety by enabling automatic detection of hazardous conditions and corrective action with minimal human intervention. (Shinde & Jadhav, 2019)

proposed an RFID-based railway collision prevention system capable of detecting trains approaching the same track segment and generating warning alerts. However, the system depended mainly on human response because it lacked automatic braking and speed control mechanisms. Consequently, human intervention remains necessary, limiting its effectiveness in fully automated railway safety applications. This limitation highlights the importance of integrating intelligent control mechanisms into collision prevention systems to reduce reliance on manual response and enhance operational safety.

(Shamraj & Harale, 2024) analysed India's Kavach system, which integrates signalling, communication and automatic braking control to prevent collisions and incidents. Although highly effective, the system requires expensive infrastructure and advanced technology, limiting its suitability for resource-constrained railway environments.

This system utilises affordable sensors, embedded controls, and automatic interventions within a modular structure. The ESP32 microcontroller analyses information gathered by the MPU6050 IMU, ultrasonic sensors, and RFID technologies to determine the stability of the train, proximity to obstacles, and location status. Unsafe situations trigger automatic intervention by the controller to slow down or stop the train through PWM, alongside the warning signals and Firebase notification.

2.3.5 Zimbabwean Railway Context

Zimbabwe's railway system operates under difficult economic and technological conditions compared to the modern railway networks. According to (Zimbabwe, 2022), much of the signalling, communication and control equipment currently in use is old and has exceeded its expected lifespan. Most railway systems still rely on analogue and electromechanical technologies with limited automation and fault detection capabilities.

These ageing systems provide limited support for real-time monitoring and automated safety control, increasing the risk of delayed fault detection and communication problems. The (Transport, 2023) also reports that railway operations in Zimbabwe still depend heavily on manual signalling, paper-based scheduling and verbal communication between stations. Although these

methods are relatively affordable, they increase the chances of human error, especially during emergencies or heavy traffic conditions.

(Moyo & Dewa, 2022) further explain that railway maintenance in Zimbabwe is often inconsistent because of financial limitations. As a result, faults and infrastructure problems are sometimes detected only after accidents have already occurred. Recent derailments in Hwange and Kadoma ((Ncube, 2018); (PindulaNews, 2025)), together with the 2025 Gwanda train collision (Reporter, 2025),show the need for improved train monitoring, collision prevention and automated safety systems.

The proposed system addresses some of these challenges using a low-cost embedded approach that combines MPU6050 stability monitoring, RFID station identification, ultrasonic proximity sensing and ESP32-based automated control. RFID is used for checkpoint-based location updates, while GPS could be added in future real-world implementations for continuous train tracking and more accurate positioning. Overall, these challenges highlight the need for affordable and reliable railway safety systems suitable for Zimbabwean railway conditions.

Documented derailments in Hwange and Kadoma ((Ncube, 2018); (PindulaNews, 2025)) illustrate how infrastructure failure, poor monitoring and delayed response contribute directly to railway accidents**.** Figure 2.1 shows a coal-laden NRZ train derailment in Kadoma, highlighting the physical consequences of infrastructure failure and insufficient real-time safety monitoring. Such incidents not only result in loss of property and potential risk to human life but also disrupt freight transportation, thereby negatively affecting Zimbabwe's economy.

Similarly, the 2025 collision involving a Rovos Rail passenger train and a BBR goods train near Gwanda demonstrates that serious train-to-train collisions can occur directly on railway tracks and are not limited to level-crossing incidents (Reporter, 2025). Figure 2.2 illustrates the collision scene, emphasising the importance of continuous train monitoring, collision prevention and automated safety intervention systems within the railway operations.

Collectively, these studies highlight the urgent need for an automated, low-cost and resilient railway safety system that operates independently of extensive track-side infrastructure and is robust against vandalism and funding limitations.



Figure2. 1 Coal-laden NRZ train derailment accident in Kadoma

Source: (PindulaNews, 2025)



Figure2. 2 BBR goods train collision with Rovos Rail passenger train

Source: (Reporter, 2025)

2.4 Gap Analysis

The reviewed literature reveals several limitations in existing railway safety systems which are more related to automation, affordability and suitability for the developing railway environments such as Zimbabwe.

2.4.1 Lack of Integrated Low-Cost Systems

Most existing approaches railway safety studies focus on individual technologies such as IMU sensing, RFID tracking or communication systems without combining them into a single safety platform (Devi, et al., 2021). This creates a gap in the development of affordable and integrated railway safety solutions. The proposed study addresses this gap by combining MPU6050-based stability monitoring, RFID location identification, ultrasonic collision prevention and ESP32-based control within one low-cost embedded system. The system also supports Firebase communication and dashboard-based monitoring for improved visibility of train operations and safety conditions.

2.4.2 Limited Application to African Railways

Most railway safety technologies reviewed were developed for regions with advanced railway infrastructure and stable communication systems, which differ significantly from railway conditions in Zimbabwe and other African countries (Community(SADC), 2022). Many systems depend heavily on expensive infrastructure and continuous network connectivity. This study addresses the gap by proposing a modular and low-cost embedded system that can operate with limited infrastructure while still providing automated monitoring, collision prevention and communication capabilities suitable for local railway conditions

2.4.3 Limited Communication and Monitoring Features

Several existing prototypes are capable of detecting hazards but do not provide effective real-time monitoring interfaces for operators and monitoring stations (Kumar, et al., 2022). This limits visibility of train conditions and system status during operation. The proposed system addresses this limitation through Wi-Fi-based Firebase communication and a web-based dashboard that provides real-time visualisation of train status, station updates and safety alerts

2.4.4 Minimal Use of Intelligent Control

Many reviewed systems mainly focus on hazard detection and warning generation without implementing automatic speed reduction or stopping mechanisms (Shinde & Jadhav, 2019). As a result, they still rely heavily on human intervention during dangerous situations. The proposed system addresses this gap by using the ESP32 microcontroller to process ultrasonic and MPU6050 IMU data and automatically perform PWM-based speed reduction or emergency stopping when unsafe conditions are detected.

2.4.5 Zimbabwe-Specific Railway Challenges

Many reviewed studies do not directly address Zimbabwe's railway challenges such as ageing infrastructure, manual signalling systems, vandalism and limited financial resources ((NRZ, 2022) (MinistryofTransportandInfrastructuralDevelopment, 2024)). This study addresses these challenges by proposing a low-cost embedded railway safety system that combines RFID location monitoring, ultrasonic collision prevention, IMU-based stability detection and automated

communication within a practical and adaptable design suitable for Zimbabwean railway conditions.

Table2. 1 Summary of Research Gaps

Gap	**Description**	**Proposed Solution in Study**
Lack of integrated systems	Most studies focus on individual components such as RFID, IMU or communication systems rather than a complete railway safety solution (Devi, et al., 2021).	Develop a low-cost embedded system combining RFID, ultrasonic sensing, IMU monitoring, ESP32 control and Firebase communication.
Limited applicability to developing regions	Many systems are designed for countries which have advanced infrastructure not available in Zimbabwe (Community(SADC), 2022).	Design a modular system using locally available components and minimal infrastructure.
Weak real-time communication	Some systems detect faults but do not transmit alerts to control centres (Kumar, et al., 2022)	Implement Firebase-based communication with a web-based dashboard for real-time train monitoring.
Lack of automatic control response	Existing systems often rely on human intervention after hazard detection (Shinde & Jadhav, 2019).	Implement ESP32-based automated speed control using PWM and threshold-based decision logic for stopping and slowing down.

Over-reliance on single sensing method	Systems using only RFID or GPS lack redundancy and may fail under certain conditions.	Combine RFID (location identification) and ultrasonic sensing (distance detection) for reliability and redundancy.
High system complexity and cost	Advanced systems (e.g. Kavach) are expensive and complex to deploy (Shamraj & Harale, 2024).	Use cost-effective components such as ESP32, basic sensors and simple control logic to reduce implementation cost.
Lack of focus on Zimbabwean context	Existing research does not address local challenges such as outdated infrastructure and vandalism (NRZ, 2022).	Develop a system tailored to Zimbabwean railway conditions with minimal reliance on track-side infrastructure.
Limited use of stability monitoring	Few railway safety prototypes use IMU-based tilt for derailment detection.	Integrate MPU6050 to monitor pitch and roll for early detection of instability and derailment risk.
Communication reliability challenges	Cloud-based systems depend on network availability, which may be limited in remote areas.	Use Firebase for cloud-based data logging and dashboard monitoring while ensuring safety-critical decisions are executed locally.

2.5 Conceptual Framework and Basis for the Proposed System

The conceptual framework for this study is based on the identified gaps in the literature and the strengths of existing railway safety technologies. The proposed system combines low-cost embedded technologies to improve train monitoring, collision prevention and automated safety response under Zimbabwean railway conditions.

2.5.1 IMU-Based Monitoring

Studies by (Song, et al., 2022) and (Zhou, et al., 2020) show that abnormal vibration, tilt and motion changes can indicate instability or possible derailment conditions. Therefore, from these findings, the recommended solution is an application of MPU6050 IMU sensor to detect pitch, roll, and vibration variations. Processing of IMU data will be done using the ESP32 microcontroller to detect any unsafe condition.

2.5.2 RFID and Ultrasonic-Collision Prevention

RFID technology is used for train identification and checkpoint-based location monitoring because of its affordability and reliability (Aditya, et al., 2022). RFID tags will be placed at specific locations to provide train location updates when the train passes a station or checkpoint. In a real railway environment, GPS technology could also be added to provide continuous train tracking and more accurate train positioning over long distances.

To improve collision prevention, ultrasonic sensors are also included to detect nearby obstacles. Unlike RFID, which provide identification and location information, ultrasonic sensors measure actual distance between objects. Combining RFID and ultrasonic sensing creates a more reliable collision prevention system which is capable of detecting hazards when one sensing method is unavailable.

2.5.3 Communication System

A Wi-Fi-based communication system is implemented using the ESP32, enabling data transmission to Firebase Realtime Database. The stored data is displayed through a web-based dashboard that provides real-time monitoring of train conditions, station identification updates and safety events.

This allows operators to observe system status remotely while safety-critical decisions remain under local control of the ESP32.

2.5.4 Speed Regulation and Control Mechanism

To avoid collisions, the train model adjusts itself through speed control. Controlled by the ESP32, PWM signals manage motor activity without complex circuitry - this method appears often in small-scale electronics because it works well with minimal parts (Patel & Bhagat, 2019). Instead of stopping outright, the vehicle eases down when nearing an object. Data from the ultrasonic module feed into ongoing decisions about motion changes. Reaching the initial warning zone triggers a drop in power delivered to the motor via lower duty cycles. Should the gap shrink more, hitting another preset limit, the system cuts PWM output entirely - halting the train fully. As distances drop, automatic slowdowns then full stops follow, triggered by obstacle detection through staged thresholds.

2.5.5 System Integration and Signal Flow

These components form a low-cost, integrated railway safety system suitable for Zimbabwean railway conditions. The signal flow can be summarised as demonstrated below:

1. **Sensors**: IMU checks pitch and roll stability; RFID is used to identify trains through checkpoints and update their locations. Ultrasonic sensors help to detect obstacles close to the vehicle to ensure avoidance of collisions. IR sensor helps in detecting the lines and controlling the movement of the prototype.
2. **Controller**: ESP32 microcontroller processes sensor data and send commands to the actuators. The controller analyses train stability, obstacle distance and RFID location information before making safety decisions using predefined safety thresholds.
3. **Actuators and Communication**: Upon detection of any threat, the engines shut off immediately rather than slowing down gradually. Pulse width messages control the speed of the train in regular operations, but not deceleration. Flashing lights and alarms provide visual and audio warnings. Data is constantly being transmitted wirelessly and stored in an online

database. The information is accessed through the web-based interface and shows the real-time status of the train.

4. **Redundant Collision Avoidance**: RFID and ultrasonic signals are fused to provide overlapping detection coverage, ensuring that hazards are detected even if one sensor type fails.

From sensors, data moves into the controller, then routes toward actuators and external links. Figure 2.3 shows how sensing, processing, control, and communication parts work together across time. While monitoring happens instantly, safety actions trigger automatically when needed. Instead of isolated functions, elements operate in sequence, passing information forward. Visual layout in the figure captures movement from detection through response stages.

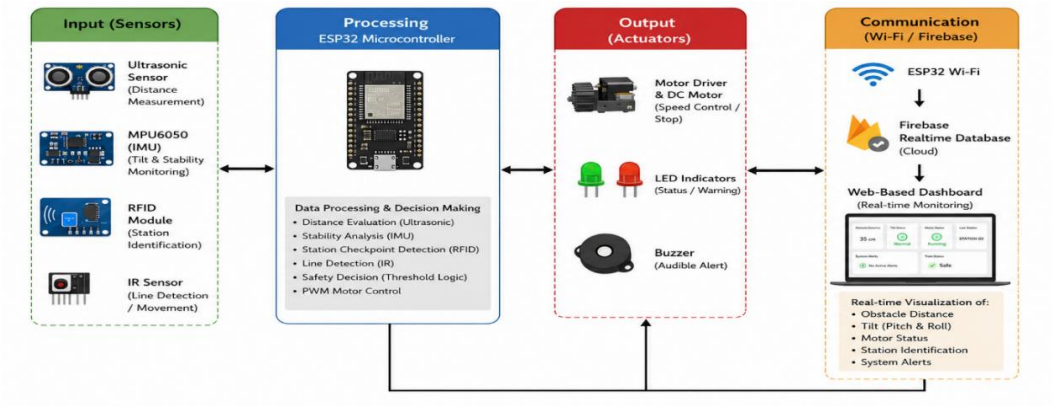

Figure2. 3System flow of the integrated ESP32-based railway safety system

2.6 Summary

This chapter reviewed the theoretical and existing technologies related to railway safety systems. Existing technologies such as sensors, RFID modules, ultrasonic detection, Firebase-based communication can improve train monitoring, collision prevention and automated safety response. However, many existing systems focus on individual technologies, rely heavily on advanced infrastructure or lack automated control and real-time communication features.

The review also showed that Zimbabwe's railway system still faces challenges related to ageing infrastructure, manual signalling, delayed fault detection and limited automation. Recent derailments and train collisions highlight the need for improved monitoring and collision prevention systems that are affordable and suitable for local railway conditions.

The identified gaps justify the development of a low-cost system that combines MPU-based stability monitoring, RFID-based station identification, ultrasonic obstacle detection for redundant collision prevention, Firebase-based communication, dashboard-based monitoring and threshold-based PWM speed control. These concepts form the foundation of the proposed railway safety prototype.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

This section outlines how the embedded railway safety prototype was built and tested. Built around an ESP32 microcontroller, the setup links an ultrasonic sensor, MPU6050 IMU, RFID unit, IR detector, and motor controller into one working unit. Instead of separate functions, these parts work together - avoiding collisions, tracking balance, adjusting speed automatically, while feeding live updates to a browser interface. Architecture layout comes next, followed by choices in physical components and code structure. Thresholds for responses are set based on field conditions, with data flow managed through stable signaling paths. Creating the visual display involved step-by-step refinement, ending with hands-on checks to confirm each function behaved as expected.

3.2 Research Design and Methodology

A working model for railway safety, built at low cost, formed the core of this research. Built not through opinion gathering but through hands-on creation, its foundation lies in tangible output. Instead of relying on interviews or archived data, the work took shape in physical form. Through construction and repeated trials, function emerged under varied scenarios. Testing followed real operation, not theoretical assumptions. Functionality checks happened after assembly, ensuring alignment with original goals. Performance came from trial runs, measured against set targets. Design choices led directly to testable outcomes. Evaluation grew out of observed behavior during experiments. Success depended on measurable results, not abstract reasoning.

Beginning with what needed fixing, the creation of the railway safety setup moved step by step through clear stages. Earlier sections pointed out risks on tracks along with missing solutions - these became the starting point for shaping how the system should work. So, it had to stop crashes, track balance during movement, know where each train was, while feeding live updates into an online display. Not every idea made it in; only those tied directly to urgent operational needs stayed.

After establishing the system requirements, the overall system architecture was designed. Block diagrams and flowcharts were developed to show how the different components interact. During this stage, suitable hardware components were selected, including the ESP32 microcontroller,

MPU6050 IMU sensor, ultrasonic sensor, RFID module, IR sensor, motor driver, LEDs and buzzer. The role of each component was carefully defined to ensure proper system integration and operation.

The next stage involved circuit design and simulation. The circuit connections were designed using Proteus software to verify component interfacing, signal flow and power distribution. Although Proteus provided a useful environment for hardware validation, complete system simulation was limited because some ESP32, Wi-Fi and Firebase libraries were not available. Therefore, simulation was mainly used to confirm the correctness of circuit connections before physical implementation.

After running simulations, construction began on the physical model using chosen parts. At its core sat an ESP32 chip, linking every sensor and actuator. Detection of nearby objects relied on an ultrasonic device. Train balance checks were handled by the MPU6050 unit. Position tagging came through signals from an RFID reader. Guidance along paths depended on readings from an infrared sensor. The motor driver controlled the movement of the DC motors, while LEDs and a buzzer provided warning indications during unsafe conditions.

Software development was carried out using the Arduino IDE with C/C++ programming language. The software was designed to continuously collect data from the sensors, process the information and make safety decisions based on predefined thresholds. Obstacle distance measurements, train tilt angles and RFID location information were analysed by the ESP32 to determine the appropriate system response. When unsafe conditions were detected, the controller automatically reduced motor speed or stopped the train completely. Sensor data and system status information were also transmitted to Firebase Realtime Database through Wi-Fi for remote monitoring on a web-based dashboard.

After finishing the prototype, experiments began right away to check how well it worked. To examine function, researchers looked at how accurately obstacles were spotted, with attention also given to avoiding crashes. Monitoring tilt came next, followed by checking whether the robot could follow lines without deviation. Location data through RFID tags played a role too, while updates

flowed into Firebase constantly. Each outcome shaped understanding, helping measure consistency, speed of reaction, and overall usefulness within real-world rail environments.

This work builds on engineering design combined with hands-on experiments to create an affordable embedded system for rail safety. Following a stepwise path, it weaves together planning, simulated testing, physical setup, and real-world trials - balancing concept rigor with actual performance. Each phase feeds into the next without rigid separation, allowing adjustments grounded in observation rather than assumption alone. The overall methodology used in this study is summarised in Figure 3.1 below.

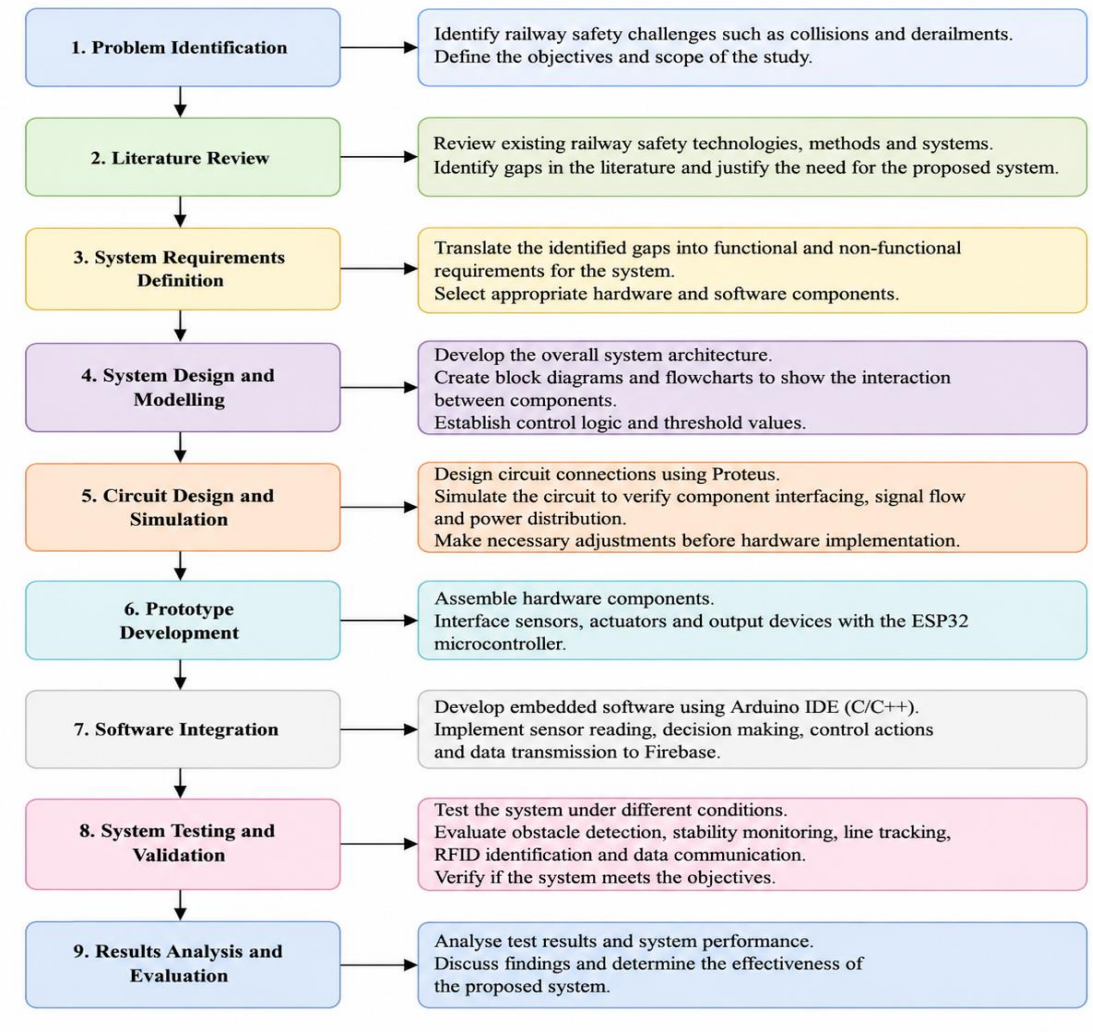

Figure3. 1 Overall Research Methodology

3.3 System Requirements Specification

This section defines all the required hardware and software components necessary to reproduce the prototype.

3.3.1 Hardware Requirements

The prototype system consists of the components which were chosen based on cost-effectiveness, availability, compatibility with embedded systems and suitability for real-time control applications.

1. Microcontroller Unit – ESP32 Development Board

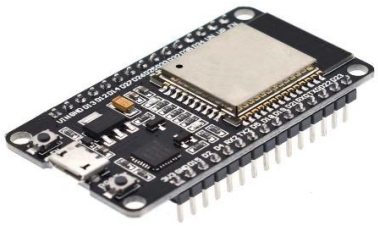

Figure3. 2 ESP32 Development Board

In terms of efficient control, the ESP32 can be considered the brain of the system. In particular, the device has two cores with the capability to work at the frequency of 240 MHZ. Built-in wireless capabilities allow for having Wi-Fi and Bluetooth connectivity on board. For external communications, GPIO pins can be used. Not only on/off but also pulse width modulation is possible due to the presence of specific PWM channels. Analog sensors can be connected to the inputs designated specifically for analogue-to-digital conversion (ADC). Information exchange is performed through the I2C, SPI, or UART protocols.

The ESP32 development board was taken as the controller for our railway safety system. It receives data from sensors and then takes decisions based on specific conditions required for the safety. The reason why we chose the ESP32 was the presence of a powerful processor, built-in Wi-Fi connectivity and communication protocols on board.

2. Inertial Measurement Unit (MPU6050)



Figure3. 3 MPU6050 IMU Module

Stability tracking on the train model relied on the MPU6050 unit. Built into one chip, it holds both a triaxial accelerometer along with a triaxial gyro. Motion details like shift speed, rotational rate, and lean position come from this device, helping assess operational safety. If leaning goes beyond set thresholds, intervention steps follow - slowing down or halting immediately - managed by the ESP32. Data moves between sensor and controller using I2C signaling.

3. Ultrasonic Sensor (HC-SR04)



Figure3. 4 Ultrasonic sensor

Obstacle detection relied on the HC-SR04 ultrasonic module instead of visual or infrared methods. From its position, it sends out high-frequency sound pulses that travel forward into space. When those pulses strike a surface, they bounce back toward the device at predictable speeds. Time elapsed during this round trip gets captured precisely by internal circuitry each cycle. With speed

known and duration measured, distance emerges through basic arithmetic operations. This calculated gap between train and barrier updates constantly without pauses or delays. An ESP32 microcontroller takes in these values moment by moment as conditions shift nearby. No gaps occur in observation while movement continues along the track ahead. Should detection occur inside the warning limit, velocity begins to decrease. Once that object crosses into critical range, braking activates without delay.

4. RFID Module (RC522-MFRC522 Based)



Figure3. 5 RFID Module

The RC522 RFID reader was used for train identification and location monitoring. RFID tags were placed at selected points along the prototype railway track to represent stations and checkpoints. As the train passes over a tag, the reader detects its unique identification number and sends the information to the ESP32. The controller then updates the train location and transmits the information to Firebase for display on the monitoring dashboard. The RFID system provides a simple and low-cost method of location identification within the prototype.

5. Four-Wheel DC Motor Chassis



Figure3. 6 Four- wheel Dc Motor Chassis

Four-wheel DC motor chassis was used to represent the motion of the train prototype. This is a combination of four geared DC motors attached to a stable base. The chassis serves the purpose of providing the physical motion required in the testing of obstacle detection, line tracking, and speed control. Four-wheel chassis helps in balancing and stabilization during the motion process.

6. Motor Driver Module (L298N Dual H-Bridge

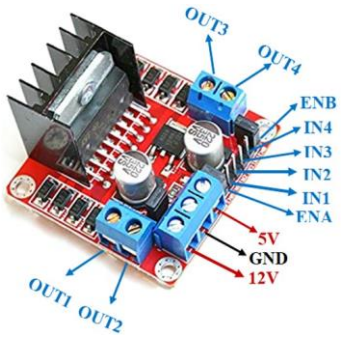

Figure3. 7 Motor Driver Module

One way to manage the four DC motors on the chassis is through the L298N dual H-bridge motor driver. From the ESP32, low-energy PWM signals travel to the module - then switched into stronger currents for the motors. Instead of connecting motors directly, this unit bridges the gap between tiny controller outputs and power-hungry hardware. When pulses arrive from the ESP32, they get transformed into usable voltage ranges that turn the motors effectively. Because of this shift in signal strength, speed stays more stable - even when dodging obstacles.

7. IR Sensor

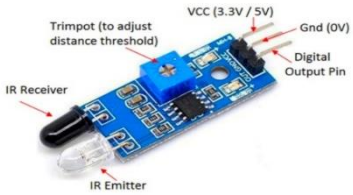

Figure3. 8 IR Sensor

The IR sensor is meant for detecting lines or tracks and helps the robot differentiate between the track line and other surfaces around it. It helps in guiding the locomotion of the train model in such a way that it stays on the intended track.

8. Alert Indicators (Buzzer and LED)



Figure3. 9 Buzzer



Figure3. 10 LED indicators

The buzzer and LEDs provide real-time feedback on system status and safety conditions. The buzzer generates audible alerts during critical events such as obstacle detection or tilt conditions, while LEDs indicate system states such as normal operation, warnings or connectivity status. These components enhance system usability and monitoring.

9. Power Supply System

In order to ensure the smooth operation of the prototype under any changing conditions, a constant electric supply is needed by the power module. In this design, there is a controlled DC power source to deliver necessary electric energy to each element - a brain chip, detectors, and movement controller. As the main processor works at 3.3V, other components, namely the motion tracker and the tag reader, must have their voltage lowered for their safe performance. Otherwise, without proper control of electric currents, some sensitive elements may become damaged or give incorrect information.

On the contrary, a higher voltage and current are required to power the L298N motor driver and DC motors, and usually they are powered by the second power source in the form of a battery. The isolation of the motor power from the logic level reduces electrical noise and voltage drop that can affect the microcontroller. Voltage regulators and filters can be used in order to keep the power supply pure and stable, particularly while motor starting when the current is high.

The power supply design plays an important role in system reliability and safety.

3.3.2 Software Requirements

The software part of the system was created using software development tools that enable embedded software development, database connectivity and remote monitoring features. The selection of software development tools has been done based on simplicity, availability and compatibility with the ESP32 microcontroller.

Arduino IDE



Figure3. 11 Development environment (Arduino IDE)

Programming of the ESP32 occurs using the Arduino Integrated Development Environment (IDE) that performs software editing, compiling and transfer onto the board. This software makes coding in C/C++ simpler but provides access to additional features – libraries handling RFID modules, network connections and sensor readings. Its main components consist of two types of operations one executes once when the program starts and another is continuously repeated. Because of such, structure the sensor readings occur regularly and actions are carried out instantly. The real time processing ability is achieved because of repeated actions within the infinite loop. At each cycle new conditions are checked and appropriate actions are taken depending on them. The serial monitor functionality that allows observing the system behaviour (sensor readings) is included into the IDE functionality and can be used for debugging during programming process. Easy to use,

flexible and supported by active community this environment can be used for fast prototyping and implementation of the proposed railway safety system.

Firebase Realtime Database

The tilt angle, distance of obstacles, train status, and movement of RFID were transmitted to the Firebase Realtime Database through Wi-Fi from the ESP32. The cloud was used for storing as well as transferring the operational data. Coordinating the physical model and the monitoring interface was done effortlessly through synchronisation. The update would reflect immediately due to the seamless integration process.

Web-Based Dashboard

The web dashboard was created in order to monitor the condition of the trains in real time. The dashboard shows the data collected from Firebase, which include the position of the trains, obstacle detections, stability data and warnings.

Proteus Design Suite

Proteus software was employed during the design process to develop circuit diagrams and do simulations of the hardware interfaces. This software assisted in confirming component interfacing and circuitry design prior to actual implementation. Despite the inability of some advanced features of the ESP32 and Firebase software to be simulated in Proteus, the latter proved to be very useful.

Embedded Control Software

The embedded software running on the ESP32 was responsible for reading sensor data, processing information and making safety decisions. The program continuously monitored obstacle distance, train stability, RFID locations and line tracking information. Based on predefined thresholds, the controller automatically adjusted motor speed, activated warning devices and transmitted data to Firebase for remote monitoring.

3.4 System Architecture / Block Diagram

A network of sensors forms the base layer, feeding data into a central processor that guides responses across subsystems. While one part tracks conditions on board, another links with ground

stations using secure channels. As situations unfold, decisions trigger without delay thanks to built-in logic rules. Instead of relying on human input, actions follow pre-set patterns tied to incoming signals. Real time updates flow outward even as internal checks confirm accuracy. Safety gains emerge not from single features but how components interact under stress.

From sensors, data flows into the system right away. Distance tracking happens through constant readings by the ultrasonic module - this keeps the train clear of obstructions. Movement shifts and tilting get recorded via the MPU6050, giving clues about unstable travel states. Position recognition emerges when the RFID unit picks up signals from markers located at stops and control zones. Following the intended route depends on the IR sensor spotting a guiding line meant for directional alignment.

From each sensor, data flows into the ESP32 microcontroller - this chip serves as the brain of the setup. Once signals arrive, the device checks them against set safety limits. Should an object appear too close, slowing begins automatically. Only when danger draws nearer does full halt occur. Much like that, sudden angle changes caught by the MPU6050 trigger protective steps. Prevention of tipping guides every reaction taken.

From the ESP32, signals pass to the L298N chip - this one handles how fast the DC motors run by adjusting pulse width. Movement changes happen like that: speed up, slow down, halt, all based on what the system senses around it. When danger shows up in the readings, lights flash and sound sounds. Warnings appear without delay, seen through glowing diodes, heard as beeps. The whole response ties back to real-time inputs, keeping reaction sharp.

From afar, someone can watch how the train prototype behaves thanks to live updates sent via the ESP32's native Wi-Fi link. Instead of staying onsite, observers access details like proximity alerts, position shifts, angle changes, and caution flags pulled straight from Firebase. Stored instantly, these values feed into an online interface that reflects current system behavior. Because data flows continuously, response becomes faster even when no one is near the physical model.

The integration of sensing, processing, control and communication functions allows the system to respond automatically to potential hazards while also providing real-time monitoring capabilities.

This architecture improves system reliability and demonstrates how low-cost embedded technologies can be combined to enhance railway safety.

The interaction between these subsystems forms the complete embedded railway safety system shown in Figure 3.12.

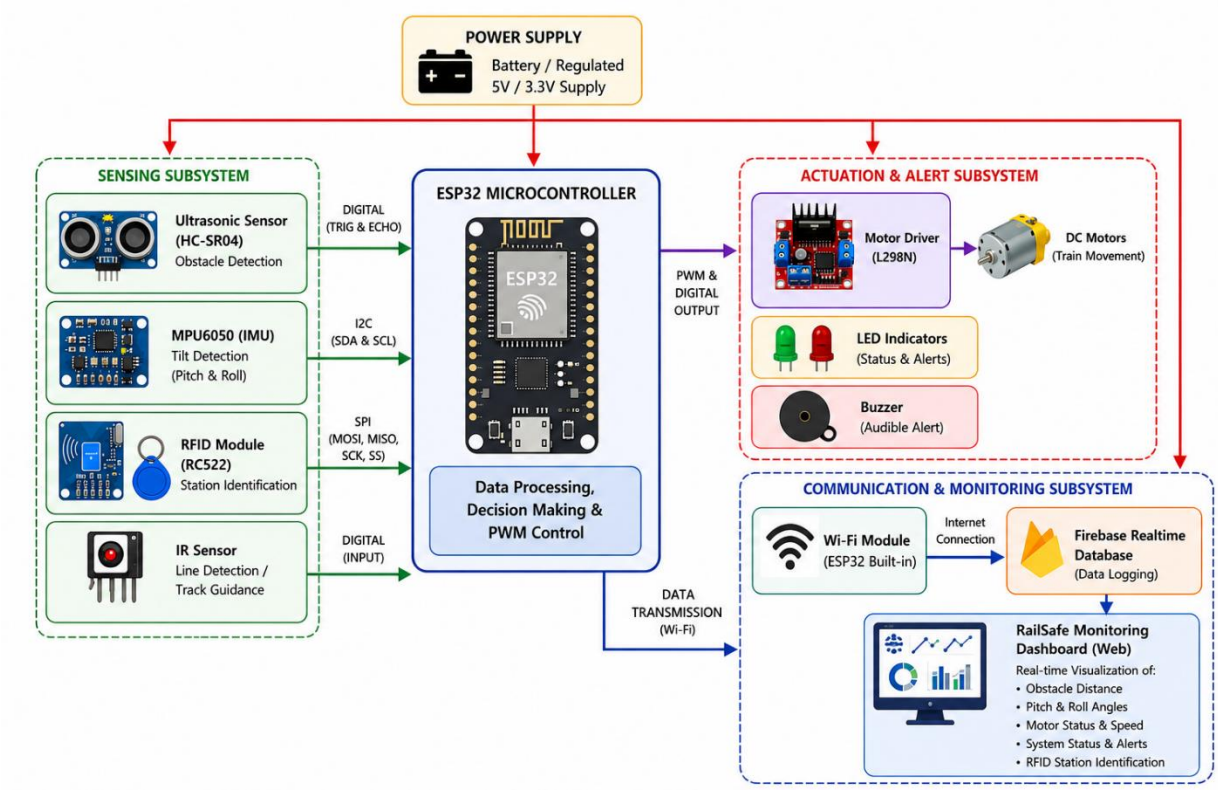

Figure3. 12Block diagram of the system

Signal Flow Explanation

Data flows from sensors >> ESP32>> decision logic>> actuators >> Firebase>> Dashboard

The ESP32 acts as the central unit coordinating all operations.

3.4.1 System Thresholds and Response Parameters

The automatic safety decision was implemented through the establishment of preset threshold values for the obstacle detection and stability of the train. Such values were set depending on the

working speed of the train prototype and time required for the reaction to the obstacles or derailments.

Usually, in most cases, the train will move at a certain speed without any stops in case there is no obstacle within 30 cm. Rather than depending on the stopping of the train, the use of an ultrasonic sensor for the measurement of the distances between the objects is utilized. In this case, the selected value (30 cm) was chosen considering that the selected value is sufficient for taking necessary actions in case any threat emerges. The deceleration process starts immediately the distance falls below the selected value.

In case the detected distance is less than 30 cm, ESP32 automatically decreases the speed of the motor by decreasing the duty cycle of PWM signal sent to the motor driver.

However, when the distance of the obstacle reduces further and becomes 15 cm, the safety zone is entered by the prototype. At this level, the ESP32 sets the speed of the motor at zero resulting in the complete stop of the train. The 15 cm distance was chosen since the prototype will be able to stop safely without coming into contact with the obstacle. Warning signs including LEDs and buzzer are triggered by the prototype at this level to warn users of the dangerous situation.

In case of train stability measurement, the MPU6050 sensor measures tilt angles. When the tilt angle is 10°, the prototype detects the abnormality and triggers the warning sign. The 10° value of tilt was chosen since it indicates the normal situation of the prototype during its operation.

When the tilt angle exceeds 25°, the prototype interprets the tilt as the potential risk of train derailment and takes the action by triggering a warning and stopping the train. The threshold value of 25° provides a solution for the early detection of abnormality of train stability while preventing possible false alarms during normal movement of the train.

Table 3.1 summarises the threshold values and corresponding system responses used in the prototype.

Table3. 1System Thresholds and Response parameters

Parameter	**Threshold Value**	**System Condition**	**System Response**
Obstacle distance	>30cm	Safe	Train moves at normal speed
Obstacle distance	</= 30cm	Warning	Train speed reduced
Obstacle distance	</= 15cm	Critical	Train stopped, LED and buzzer activated
Tilt angle	$< 10^{o}$	Normal	Train continues operating normally
Tilt angle	10° -24°	Warning	Warning alert generated
Tilt angle	>/= 25°	Critical	Train stopped, LED and buzzer activated

3.5 System Flowchart

System flow chart represents the steps of operation that are implemented in the railway safety system prototype. First of all, power must be delivered to the system for the ESP32 microcontroller to initialise all sensors and communication devices including ultrasonic sensor, MPU6050 IMU, RFID reader, IR sensor and Wi-Fi.

After the initialisation step, ESP32 constantly checks all sensors and receives the readings from them. Ultrasonic sensor detects the distance between the train and any obstacle in front of the train. In case if the detected distance is more than 30 cm, train moves with a normal speed. But if the distance becomes less than 30 cm, ESP32 slows down the motor speed to enable safe deceleration.

And if the distance becomes 15 cm or lower, then the controller stops the train and starts working of the LED and buzzer warning system.

In parallel with the ultrasonic sensor, MPU6050 constantly controls the pitch and roll angles of the train. If the angle does not exceed 10°, then everything is fine. But if the detected tilt angle of train exceeds 25°, the ESP32 detects an unstable state of the train and stops it.

The RFID subsystem continuously checks for RFID tags placed at stations and checkpoints. Whenever an RFID tag is detected, its unique identification number is read and processed by the ESP32. The corresponding location information is then sent to the Firebase Realtime Database and displayed on the monitoring dashboard.

Although invisible to the eye, infrared light helps detect surface changes. Emission happens first, then reflection determines what follows next. Surfaces play a key role - white returns much of the signal, whereas dark tones pull it in. Detection relies on contrast like this, nothing more complex. What results is a constant reading shift near edges or boundaries. Processing comes after sensing; decisions emerge from tiny voltage differences. Movement adjusts based on those real-time inputs without delay. Direction changes happen smoothly when contrasts switch abruptly. This entire loop repeats rapidly during operation. Path following works because feedback stays consistent.

All operational data, including obstacle distance, tilt status, train location and warning events, is transmitted to Firebase through the ESP32's Wi-Fi connection. The data is then displayed on the web-based dashboard for real-time monitoring. This process continues repeatedly while the system remains powered, allowing continuous monitoring, automatic safety response and remote supervision of train operations

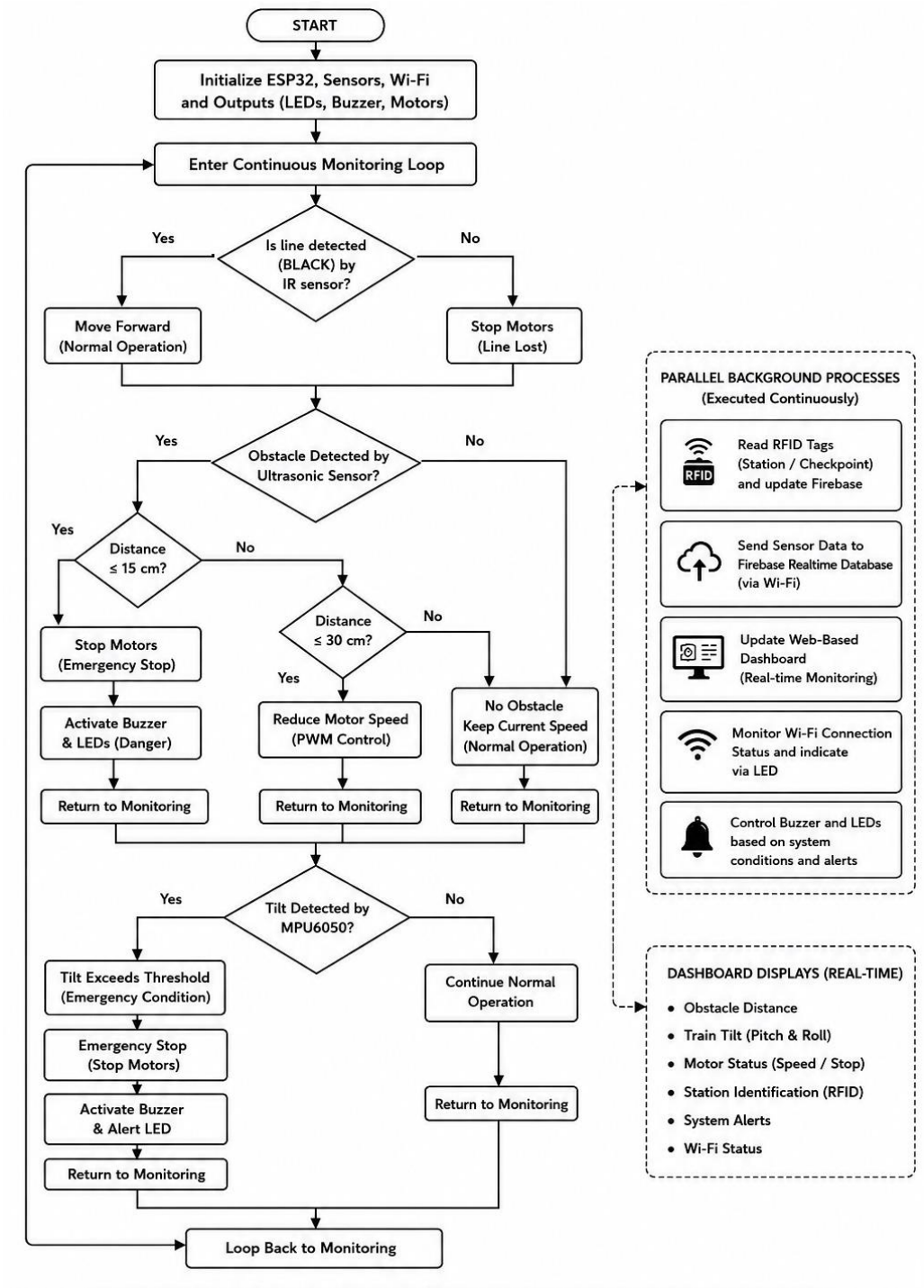

Figure3. 13 System Flowchart

3.6 System Design and Implementation

3.6.1 Hardware Design

Communication paths follow the planned circuit design, linking every hardware part to the ESP32 microcontroller. Instead of universal connections, each sensor links via a tailored protocol matching its function. Though it relies on high-speed transfers, the RFID unit exchanges data with the ESP32 by way of SPI. Meanwhile, tilt and movement readings stream from the MPU6050 using I2C signaling. Distance sensing happens when the ultrasonic device fires pulses through dedicated digital pins. On the other hand, the IR detector sends basic on-off feedback to spot lines. Motor actions respond accurately because pulse-width modulated outputs drive the controller chip.

3.6.2 Software Design

This application is arranged into modules for easy comprehension and system efficiency. This program has various modules that perform specific functions in the system. This includes reading the input from the sensors, control functions, communication functions, updating of the dash through the Internet and control of actuators such as motors and indicator lamps. This program runs in a continuous loop for real-time processing of the input from the sensors and changing the train's behaviour in real-time.

3.6.3 Algorithm Design

The system uses a threshold-based algorithm:

If tilt angle > threshold >> Stop the motors

If distance <=15cm >> Stop

If distance <=30cm >> Slow down

Else,

If Infrared detects line>> Move Forward

If No line detected >> Stop

3.6.4 Code Implementation

The system is implemented using embedded C on the ESP32.

Code snippet 3.1: Sensor initialisation (setup function)

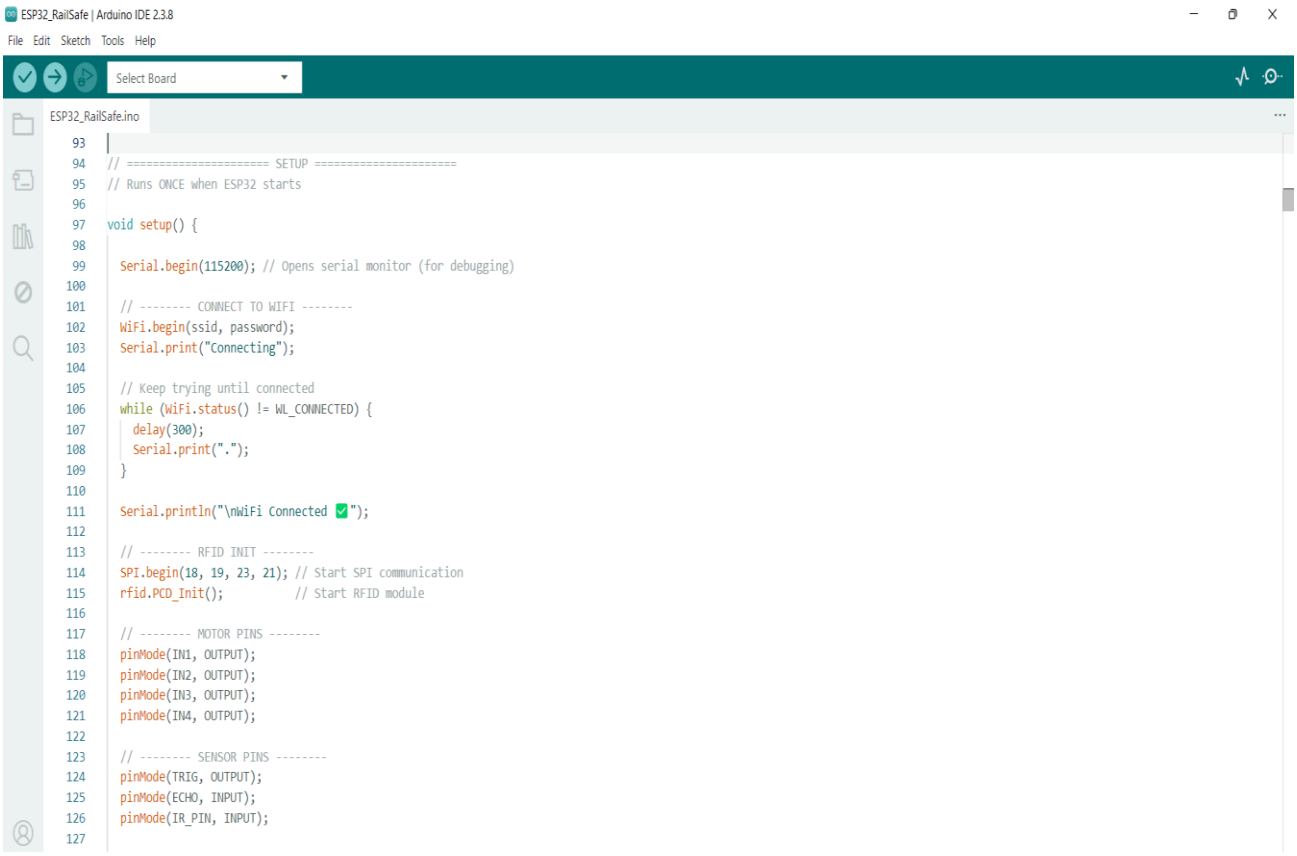

Figure3. 14 Sensor initialisation

The initialization of all sensors, communication modules and outputs is done in the initialization part of the code illustrated in Figure 3.14. The ESP32 initiates communication with the sensors and makes sure that everything is set up for real-time operation at the time of system start-up.

Code snippet 3.2: Distance Measurement function

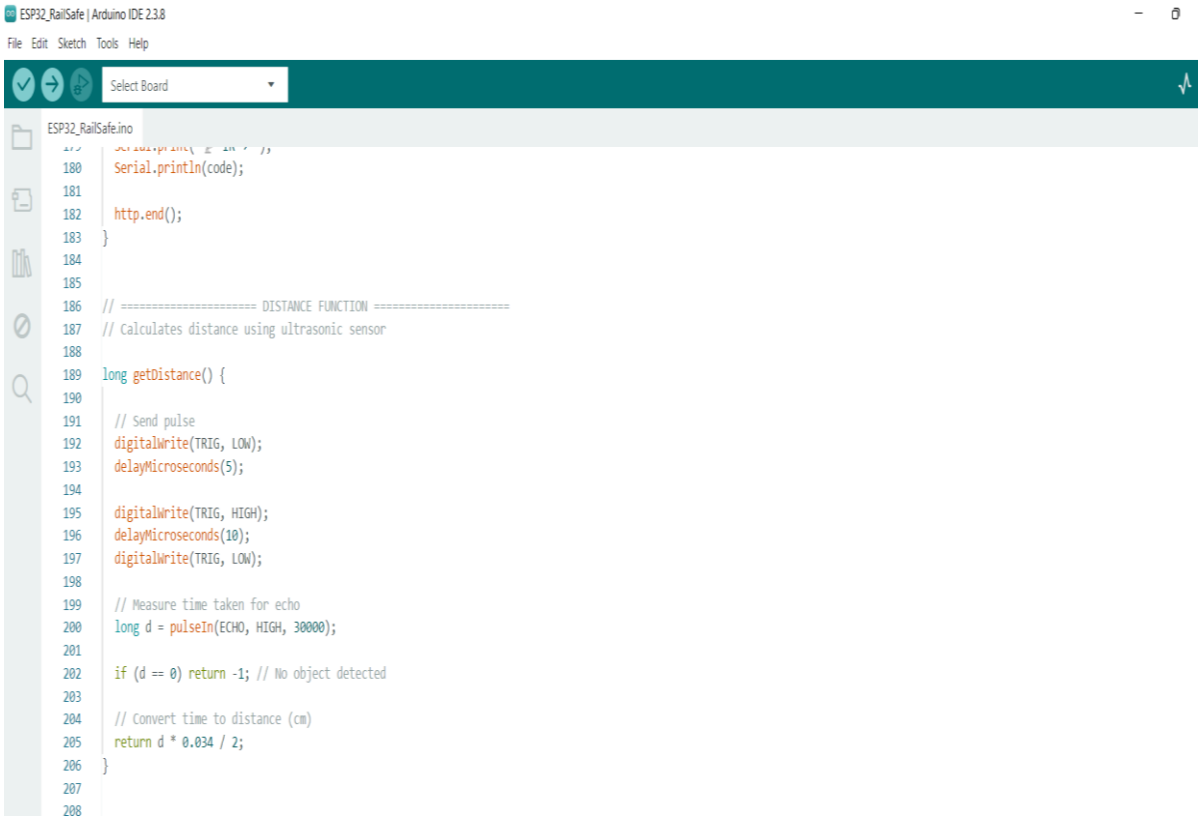

Figure3. 15 Distance function

Figure 3.15 presents the ultrasonic sensor distance measurement function used for obstacle detection. The function calculates the distance between the train and an object ahead using echo return time. The measured value is then used by the ESP32 to determine the appropriate safety response.

Code snippet 3.3: Motor Control Using PWM

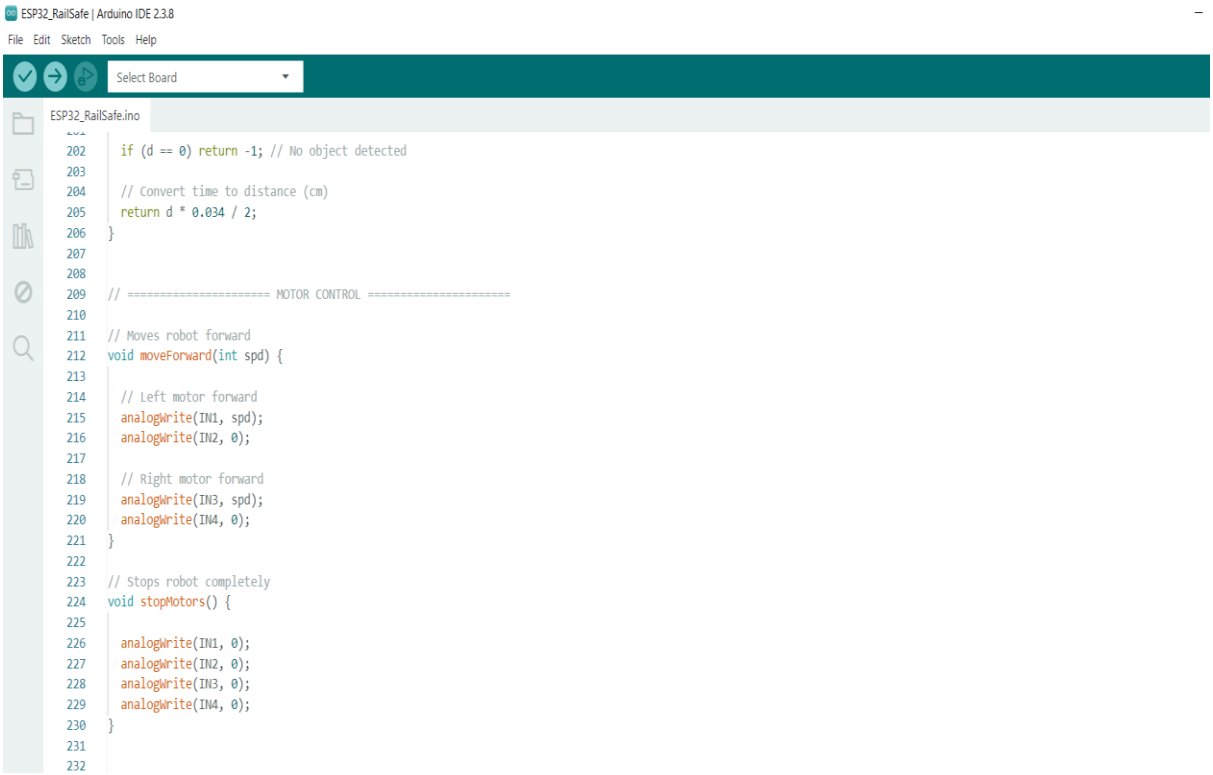

Figure3. 16 Motor Control

Figure 3.16 shows the implementation of the PWM motor control module in the ESP32 program. This control module regulates the speed of the motors based on the distance from obstacles and the condition of the system. It allows for gradual slowing down during warnings and stopping in critical conditions.

Code snippet 3.4: RFID Location Detection

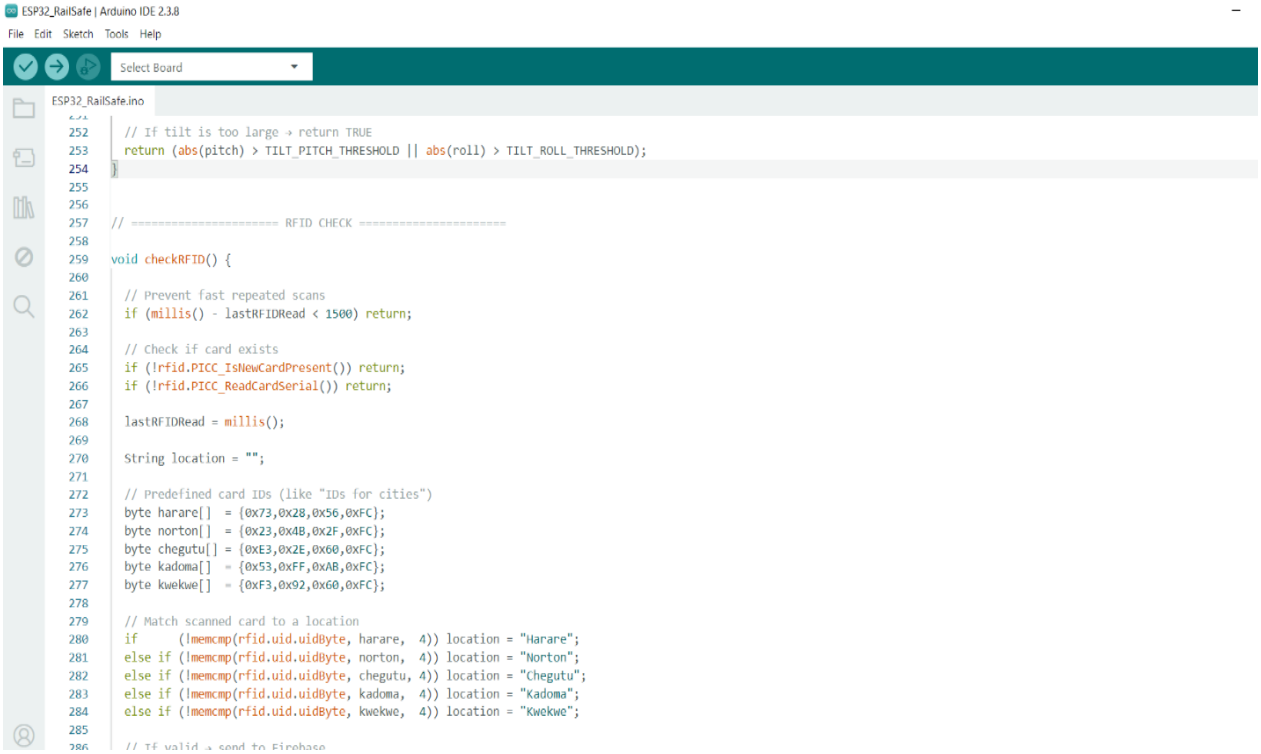

Figure3. 17 RFID Location Detection

In Figure 3.17, the function that is used for identifying station and checkpoints using RFID technology has been provided. If an RFID is detected, ESP32 will detect RFID tag information, and will update the location status in the system. The data will be sent to Firebase via the dashboard.

3.7 Simulation Using Proteus

Prior to the implementation of hardware, a model and partial simulation of the hardware was carried out through the use of Proteus Design Suite software to confirm the circuitry design and the overall system design.

It should be noted that full simulation of the system's functionality could not be performed due to the lack of compatibility of some ESP32 library functions with Proteus. Such library functions as Wi-Fi. h, HTTP Client. h, MFRC522. h and MPU6050. h which plays an important role in communication and interfacing of various sensors could not be simulated by the software.

However, despite this restriction, the simulation was used to validate pin configuration, sensor interfacing and the connection of the motor drivers to the microcontroller.

In order to compensate for this shortcoming, full testing of the system was conducted using the physical model of the device, which supported the ESP32 microcontroller and all required libraries.

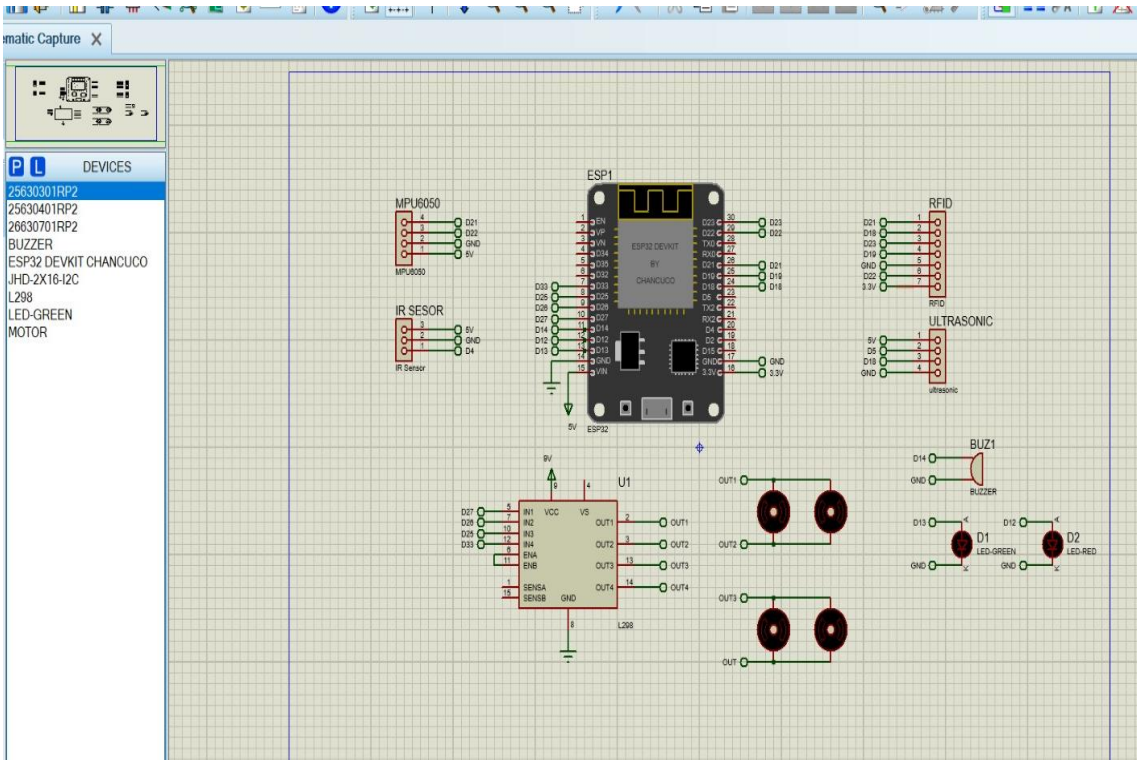

Figure3. 18 Simulation Layout

3.8 Prototype Development

The prototype of the design was developed using physical components to test the functionality of the system in real-life environment. The development of the prototype was done following the circuit and system architecture that were designed for the system.

3.8.1 Assembly

During assembly, all electronic components were carefully mounted onto the train chassis in appropriate positions to ensure stability and proper operation. The wiring process was carried out according to the circuit design, ensuring correct connections between the ESP32, sensors, motor

driver and power supply. Care was taken to maintain secure connections and reduce wiring errors that could affect system performance.

3.8.2 Operation

While operating, sensors keep checking nearby changes to gather live details like how far objects are, angle shifts, and movement path. Data flows into the ESP32 chip, which runs preset rules to decide what actions follow. Speed and turning get fine-tuned using pulse signals sent by the processor to each motor. If something unusual occurs, warning lights flash alongside sound cues to show issues or critical situations. Information streams constantly to an online database called Firebase, appearing instantly on a browser screen meant for tracking behavior and reviewing patterns.

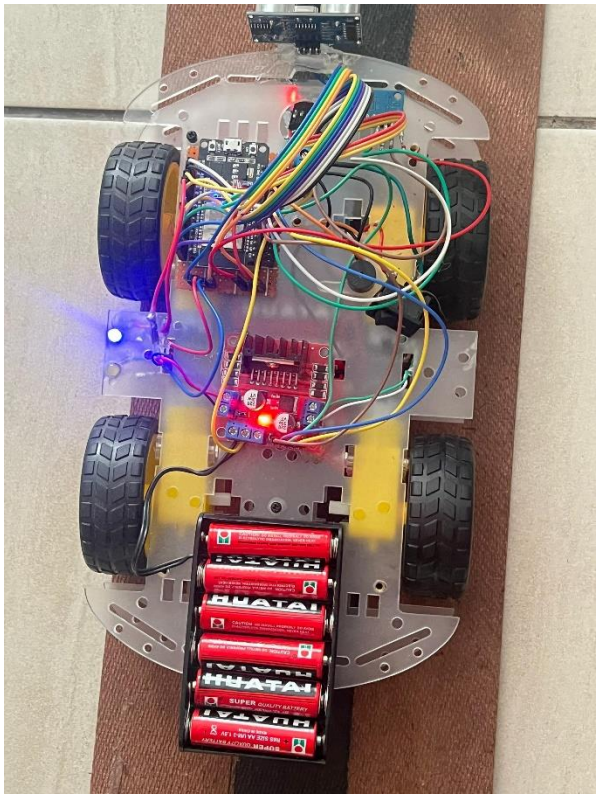

Figure3. 19 Physical prototype image

3.9 Testing and Validation

Various tests were conducted on the system in order to ensure that everything is working perfectly well. First, there was the obstacle detection test where the system was analysed to determine whether it could detect obstacles in its path and consequently slow down or stop as required. This confirmed the reliability of the distance-based control functions.

During the tilt detection test, the system was analysed to check whether it was able to detect any abnormal tilts from the train. When the sensors detected any unusual tilting, the system automatically initiated an emergency shut off mode hence ensuring that the safety measure was working effectively.

Also, the RFID system was tested in order to ensure that it was able to detect the tags and collect data about the train's location effectively.

Finally, the system was put to a communication test in order to confirm that data is being uploaded to Firebase without any error.

Table3. 2 Preliminary Test Results

Test Case	**Input Condition**	**Expected Output**	**Status**
System initialisation	Power ON	All modules initialise successfully	Successful
Wi-Fi connectivity	Available Network	Successful connection+ LED indication	Successful
RFID detection	RFID Tag scanned	Location identified and sent to Firebase	Successful

Ultrasonic (Stop)	Distance</= 10cm	Motors stop, LED and buzzer activated	Successful
Ultrasonic (Slow down)	15cm< Distance< 30cm	Speed reduced (PWM control)	Successful
Ultrasonic (Clear path)	Distance> 30cm	Normal operation continues	Successful
IR Line detection	Black Line Detected	Train moves forward	Successful
IR line loss	White surface detected	Train stops	Successful
Tilt Detection	Tilt exceeds threshold	Emergency stop + alerts	Successful
Firebase Communication	Data transmission triggered	Data successfully uploaded	Partially successful
Dashboard Monitoring	Sensor data generated	Dashboard updates and displays data correctly	Successful

The Firebase communication was partially successful because its performance depended on the availability and stability of the internet connection. During testing, the system successfully transmitted data to the Firebase Realtime Database and displayed information on the dashboard. However, occasional network interruptions and variations in signal strength resulted in delayed updates. Despite these limitations, the railway safety functions continued to operate correctly because all safety-critical decisions, such as speed reduction and emergency stopping, were executed locally by the ESP32 microcontroller.

3.10 Ethical Considerations

Despite lacking human involvement, ethics and safety shaped decisions made while building the setup. Throughout creation, care was applied to electrical practices so harm or part failure could be avoided. Voltage levels stayed inside manufacturer guidelines at every stage, preventing strain on parts. Reliability emerged naturally when boundaries set by producers were respected without exception.

3.11 Summary

This chapter has detailed the methodology used in designing, simulating and implementing the railway safety system. The integration of sensing technologies, embedded control using PWM Firebase communication and a web-based dashboard provides a reliable and cost-effective solution for real-time railway safety monitoring. The methodology ensures reproducibility and aligns with engineering best practices for embedded system design.

CHAPTER 4: EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Introduction

This section covers how the embedded railway safety and collision avoidance prototype was built, tested, while showing experimental outcomes alongside performance review. Testing focused on checking if the system could detect obstacles, prevent collisions, monitor train balance, identify positions via RFID, along with live tracking using a web interface. Findings appear through images of the device, screen captures of the dashboard, charts and visual data plots. Performance across varied operational scenarios gets examined here too, measuring success against original goals. Whether targets were met comes under scrutiny within this discussion.

4.2 System Implementation Results

The developed railway safety prototype was successfully assembled and tested using embedded hardware components such as the ESP32 microcontroller, HC-SR04 ultrasonic sensor, MPU6050 IMU, RFID module, IR sensor, motor driver and DC motors. The system was first evaluated through simulation and later implemented as a physical prototype for experimental testing.

Although simulation was attempted using Proteus software, full system simulation could not be achieved because some ESP-32 related libraries and components, particularly the MPU6050 and RFID modules, were unavailable in the simulation environment. As a result, only part of the obstacle detection subsystem could be demonstrated through simulation while the remaining functions were verified using the physical prototype.

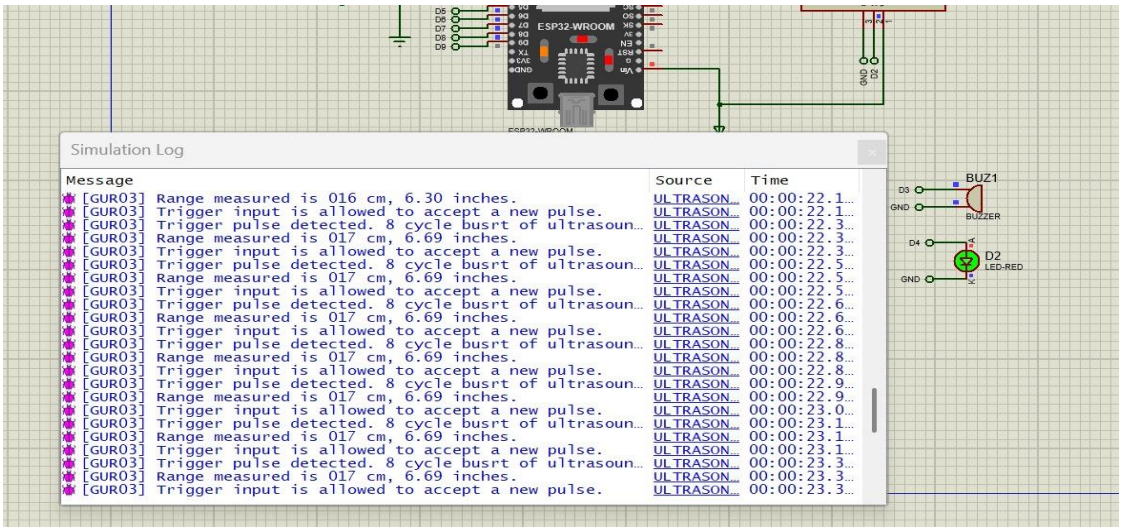

Figure4. 1 Ultrasonic obstacle detection simulation results showing distance measurements generated during Proteus simulation

The simulation log in Figure 4.1 below shows the ultrasonic sensor continuously measuring obstacle distances. Distance readings between 16cm and 17cm were successfully detected, confirming that the obstacle detection algorithm and sensor triggering mechanism operated correctly during simulation. However, complete simulation of the ESP32, MPU6050 sensor and RFID subsystem was limited by unavailable component libraries.

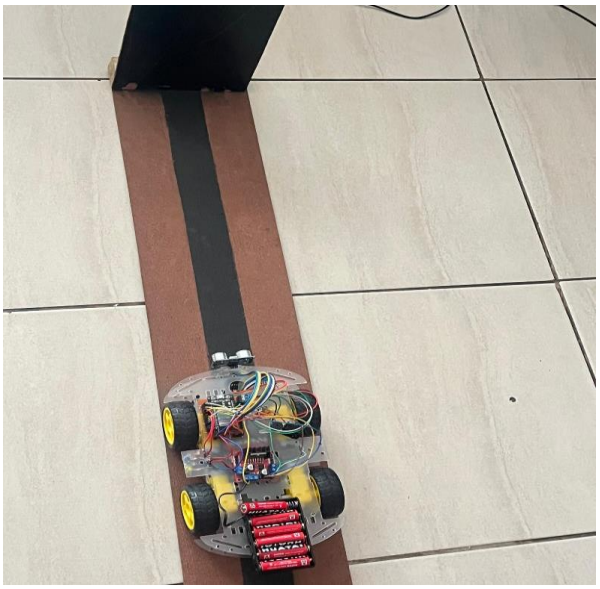

Figure4. 2 Complete Prototype

Figure 4.2 shows the complete embedded railway safety prototype used during experimental testing. The prototype integrates all hardware components required for obstacle detection, train stability monitoring, RFID location identification and wireless communication. The successful assembly of the prototype confirmed that all the system components could operate together as a single embedded railway safety platform.

A web-based dashboard was developed and connected to Firebase Realtime Database to provide remote monitoring of train operations. The dashboard displays sensor readings, train status and safety alerts in real time.

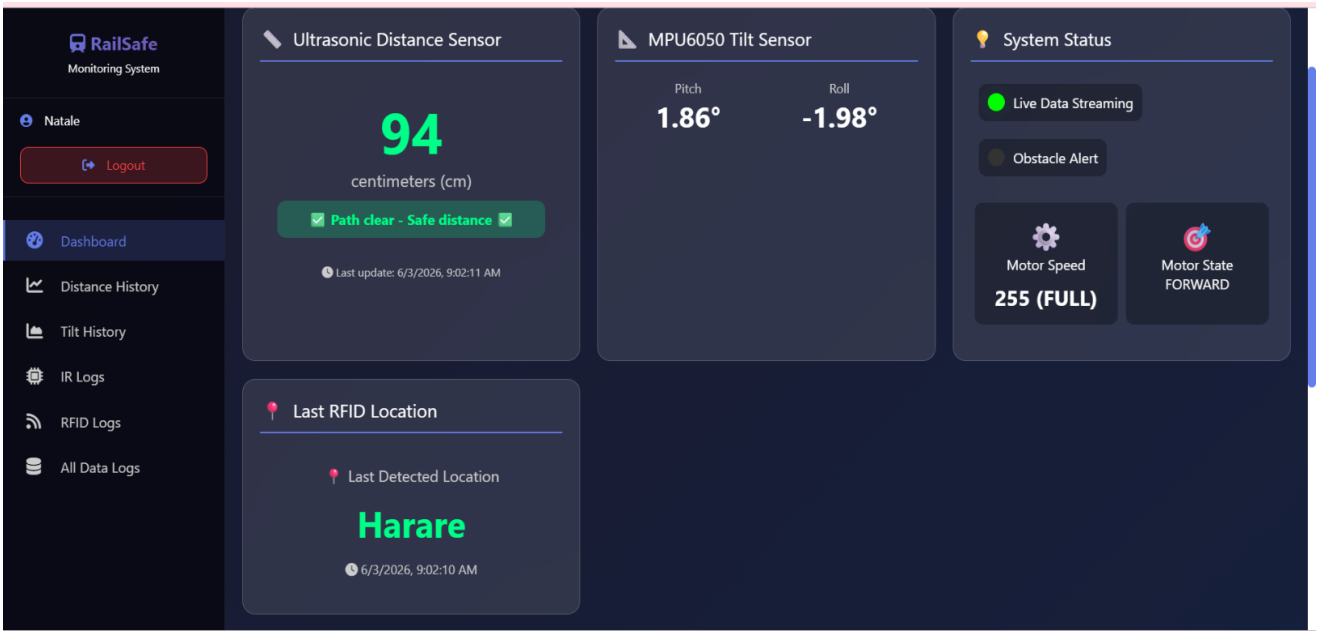

Figure4. 3 Dashboard Home page

Figure 4.3 shows the dashboard displaying obstacle distance measurements, pitch and roll angles, RFID location information, motor speed and safety alerts. This allows users to monitor the condition of the train remotely through a web interface.

The dashboard was also tested under obstacle detection conditions to verify whether warning messages and emergency responses could be displayed correctly.



Figure4. 4 Dashboard Showing Critical Obstacle

Figure 4.4 shows a critical obstacle condition where the measured distance was 8cm. Since the distance was below the critical threshold of 15cm, the system stopped the motors automatically and displayed an emergency warning message on the dashboard.

Physical testing was also conducted to verify that the train prototype responded correctly when obstacles were placed on the track.

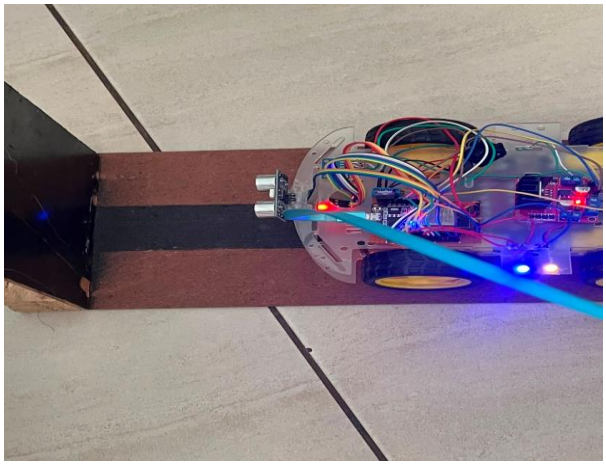

Figure4. 5 Prototype stopped by obstacle

Figure 4.5 shows that the prototype successfully detected the obstacle and responded according to the predefined thresholds. The yellow LED was illuminated when the obstacle was first detected within the warning threshold, indicating a caution condition and reduced train speed. When the obstacle reached the critical threshold, the train performed an emergency stop. This confirms that the collision prevention mechanism operated correctly under actual testing conditions.

The warning threshold was tested by placing an obstacle within the speed reduction zone.

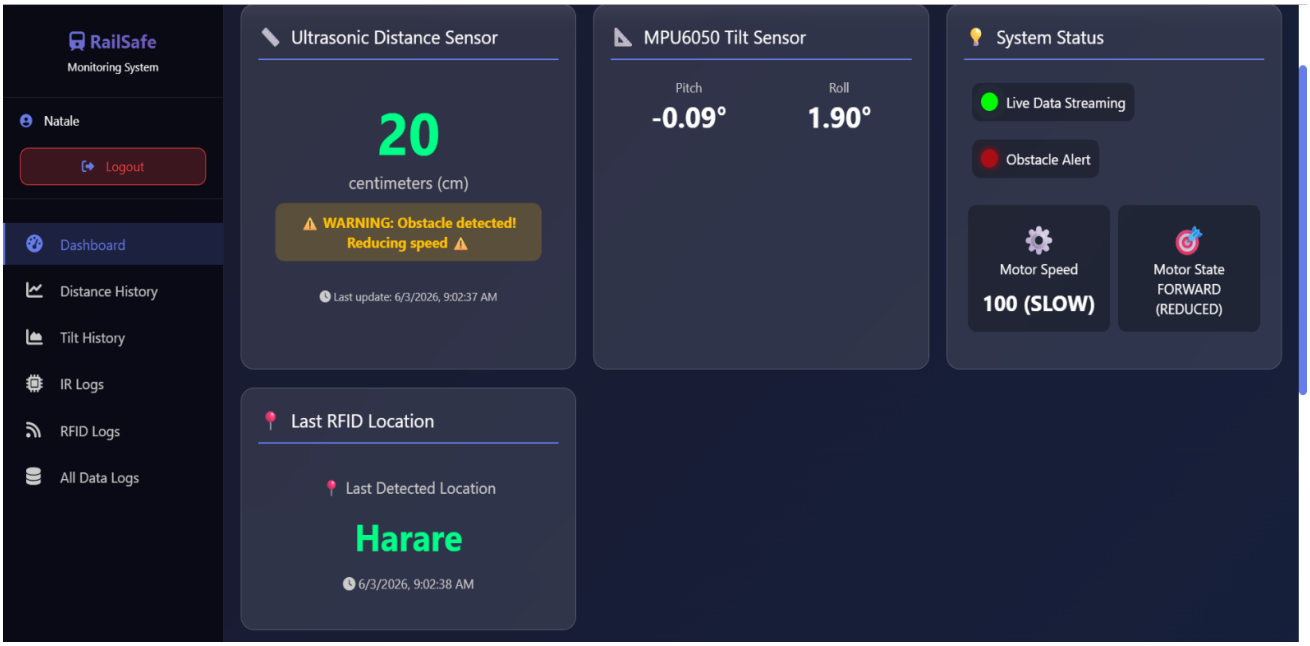

Figure4. 6 Reduced Speed Dashboard

Figure 4.6 shows when the dashboard is showing reduced speed as a warning alert. When the obstacle distance was between 15cm and 30cm, the system reduced motor speed using PWM control while allowing the train to continue moving safely.

The system was also tested under normal operating conditions where no obstacle was present ahead of the train.

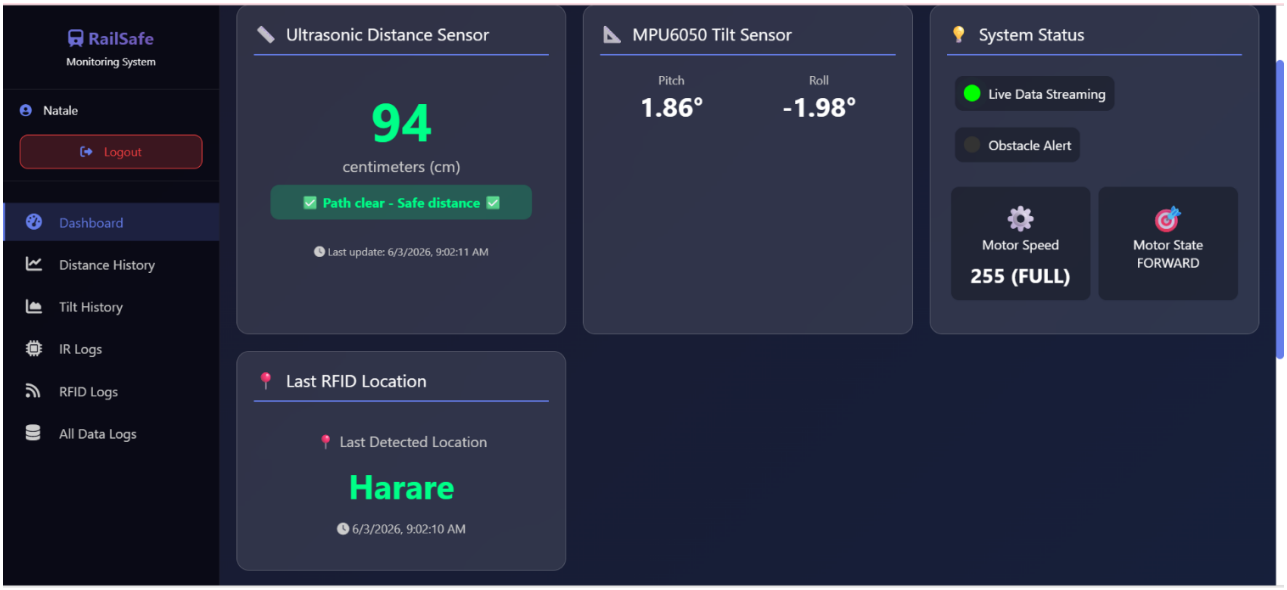

Figure4. 7 Clear Path Dashboard

Figure 4.7 illustrates when the measured distance had exceeded 30cm, the train maintained normal operation and full motor speed. No warning messages were generated because the track ahead was clear.

4.3 Data Presentation

This section presents the experimental data collected during testing of the railway safety prototype. The results are presented using tables and graphs generated from the dashboard data and experimental observations.

Obstacle detection logic was first evaluated through simulation to verify the warning and emergency thresholds. The results obtained are shown in Table 4.1.

Table 4. 1 Simulation Obstacle Detection Results

Time (s)	Dist (cm)	Zone	Motor	LED	Buzzer
0.07 – 2.84	35	Full speed	Full forward	OFF	Silent
2.94 – 3.26	34	Full speed	Full forward	OFF	Silent
3.35 – 3.78	33	Full speed	Full forward	OFF	Silent
3.87 – 4.08	32	Full speed	Full forward	OFF	Silent
4.18 – 4.39	31	Full speed	Full forward	OFF	Silent
4.48 – 4.66	30	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
4.81 – 4.98	29	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
5.13 – 5.31	28	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
5.46 – 5.78	27	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
5.94 – 6.12	26	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
6.27 – 6.60	25	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
6.75 – 7.08	24	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
7.24 – 7.41	23	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
7.56 – 7.74	22	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
7.89 – 8.21	21	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
8.37 – 8.54	20	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
8.70 – 9.03	19	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
9.18 – 9.51	18	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
9.67 – 10.00	17	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
10.15 – 10.33	16	Slow zone	Half speed (toggle)	Pulsing ON 60 ms	1000 Hz, 60 ms pulses
10.48	15	STOP	STOPPED	3x flash 150 ms	2000 Hz, 3x 150 ms bursts
11.23	14	STOP	STOPPED	3x flash 150 ms	2000 Hz, 3x 150 ms bursts
11.98	12	STOP	STOPPED	3x flash 150 ms	2000 Hz, 3x 150 ms bursts
12.73 – 14.99	11	STOP	STOPPED	3x flash 150 ms	2000 Hz, 3x 150 ms bursts

When distances stayed beyond 30 cm, the system marked them as safe, so normal operation continued without interruption. Although obstacles approached gradually, the detection mechanism activated only upon crossing into the warning range. Because the logic followed preset safety limits, responses matched expected behavior under varied test conditions. Even before building the actual model, the virtual tests verified correct function of internal decision rules. Once proximity

dropped below threshold, preparation for intervention began without delay. Since outcomes aligned with design goals, confidence in the algorithm increased noticeably. With each trial, the link between distance changes and system reaction became more evident. After repeated runs, error risks in real-world trials decreased significantly due to early validation. While simulated, the environment still reflected realistic response demands accurately. Only when inputs triggered defined zones did output states shift accordingly.

Table 4. 2 Obstacle Detection Results

Time (s)	**Distance (cm)**	**Zone**	**LED condition**	**Buzzer Condition**
0	45	Safe Zone	OFF	OFF
1	38	Safe Zone	OFF	OFF
2	32	Safe Zone	OFF	OFF
3	29	Warning Zone	Yellow LED ON	ON
4	25	Warning Zone	Yellow LED ON	ON
5	20	Warning Zone	Yellow LED ON	ON
6	15	Warning Zone	Yellow LED ON	ON
7	10	Critical Zone	Yellow LED ON	ON
8	8	Critical Zone	Yellow LED ON	ON
9	5	Critical Zone	Yellow LED ON	ON

It becomes obvious that there is a noticeable inverse proportion between obstacle distance and train speed. As the obstacle got closer, the system automatically decreased the motor speed until reaching the critical obstacle distance of 15 cm when the system came to a stop. The obtained results prove that the proposed control algorithm works fine and that the system is capable of adjusting itself according to the changes in environment conditions.

There are no deviations from the expected course of events in the data, which means that the measurements conducted by the ultrasonic sensor are accurate enough for the given experiment. Reduction of the motor speed before coming to an emergency stop is crucial for decreasing the mechanical stress on the motor as well as increasing the safety of the process. Thus, the efficiency of the proposed collision prevention method is proven in the experiment.

The inverse proportion between obstacle distance and train speed is analysed to check the efficiency of the collision prevention mechanism.

The relationship between obstacle distance and train speed was analysed to evaluate the effectiveness of the collision prevention mechanism.

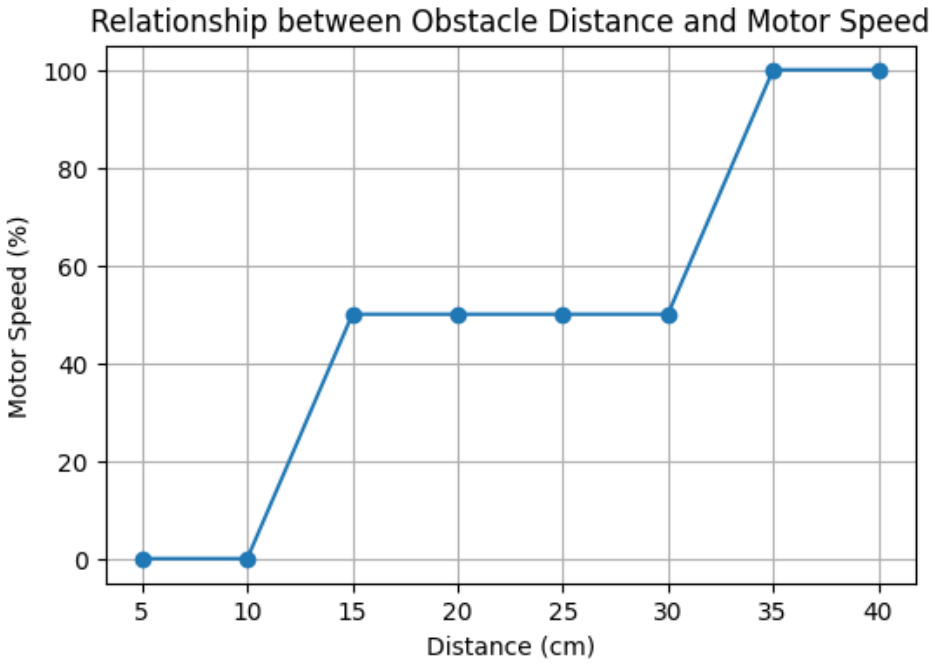

Figure4. 8 Distance vs Motor Speed Graph

The diagram above proves that motor speed has stayed the same as obstacle distance was higher than 30 cm, which confirms that the control system has been able to recognize the safe working conditions. With the approaching warning threshold, the speed has been reduced gradually as opposed to instantly dropping. The above tendency can be explained by the fact that PWM control had been programmed for gradual reduction of speed for improving stability and comfort of passengers in real railway conditions.

The moment when the controller starts reacting to the presence of obstacles on the way can be seen in the change of the slope of the graph near the warning threshold. It should be noted that there are no unusual spikes in the graph, which means the smooth functioning of the sensor and the motor control system.

Table 4. 3 MPU6050 Tilt Monitoring Results

Test No.	**Pitch Angle(º)**	**Roll(º)**	**System Condition**	**System Response**
1	2	5	Normal	Train continued moving normally
2	3	10	Normal	Train continued moving normally
3	3.44	13.96	Warning	Warning message displayed
4	5	18	Warning	Alert LED activated
5	8	26	Critical Tilt	Emergency stop activated
6	4.05	10.29	Warning	Warning message displayed
7	-3.71	3.14	Normal	Train continued moving normally

8	-11.46	19.28	Warning	Alert LED activated
9	-5.88	47.34	Critical	Train stopped and alerts activated

The results show that the system was able to distinguish between normal operating conditions and unsafe tilt conditions. Small tilt angles produced no intervention because they represented normal train movement. As the tilt angle increased, the system generated warning responses before eventually initiating an emergency stop at critical values.

The trend suggests that the MPU6050 provided reliable orientation measurements across the tested range. A small variation between successive readings was observed, which is expected due to sensor noise and normal movement of the prototype. However, these variations did not affect the overall decision-making process. Early detection of excessive tilt is important because derailment events often develop progressively rather than instantaneously. The results indicate that the monitoring system can provide sufficient warning before a dangerous condition becomes critical.

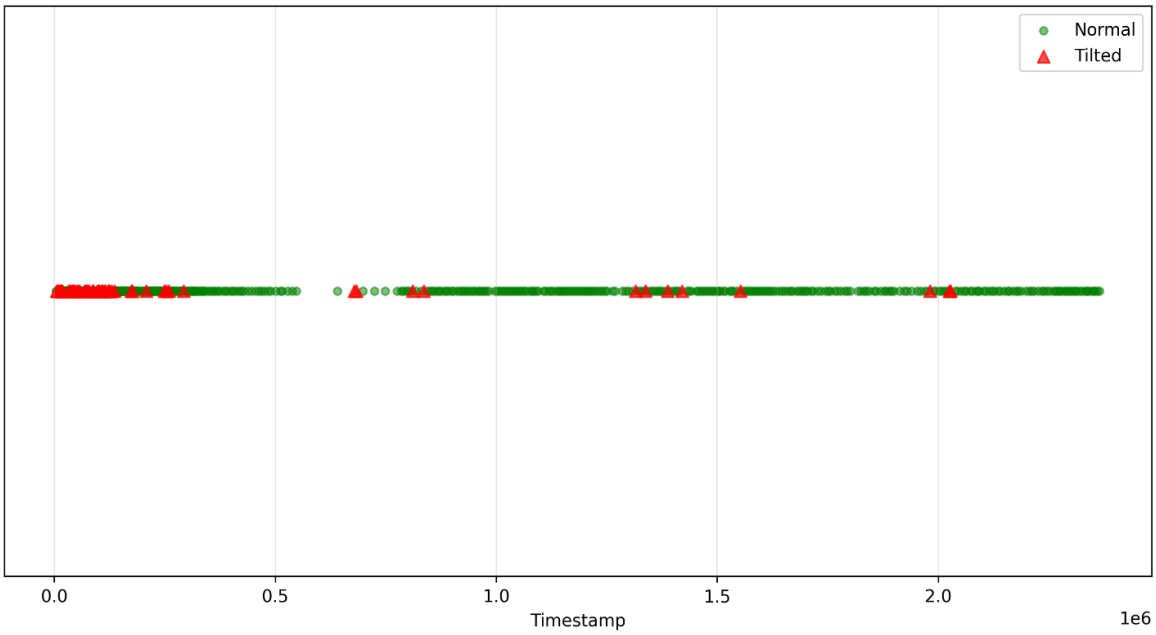

Figure4. 9 Tilt Sensor Events Timeline

Based on the timeline, most of the readings were within the operational ranges, thus indicating that the prototype had a relatively high level of mechanical stability during testing. A small number of events reached the caution or critical zones. This means that dangerous conditions occurred rarely, implying that the train was designed to be mechanically stable.

Some occasional high readings for tilt angles could have been caused by changes in the rail conditions. In practice, such deviations are common and show the need for constant monitoring of such parameters, which, in turn, proves that the stability monitoring subsystem is able to prevent possible derailments.

Pitch and roll angle measurements recorded during testing were analysed to observe train stability behaviour.

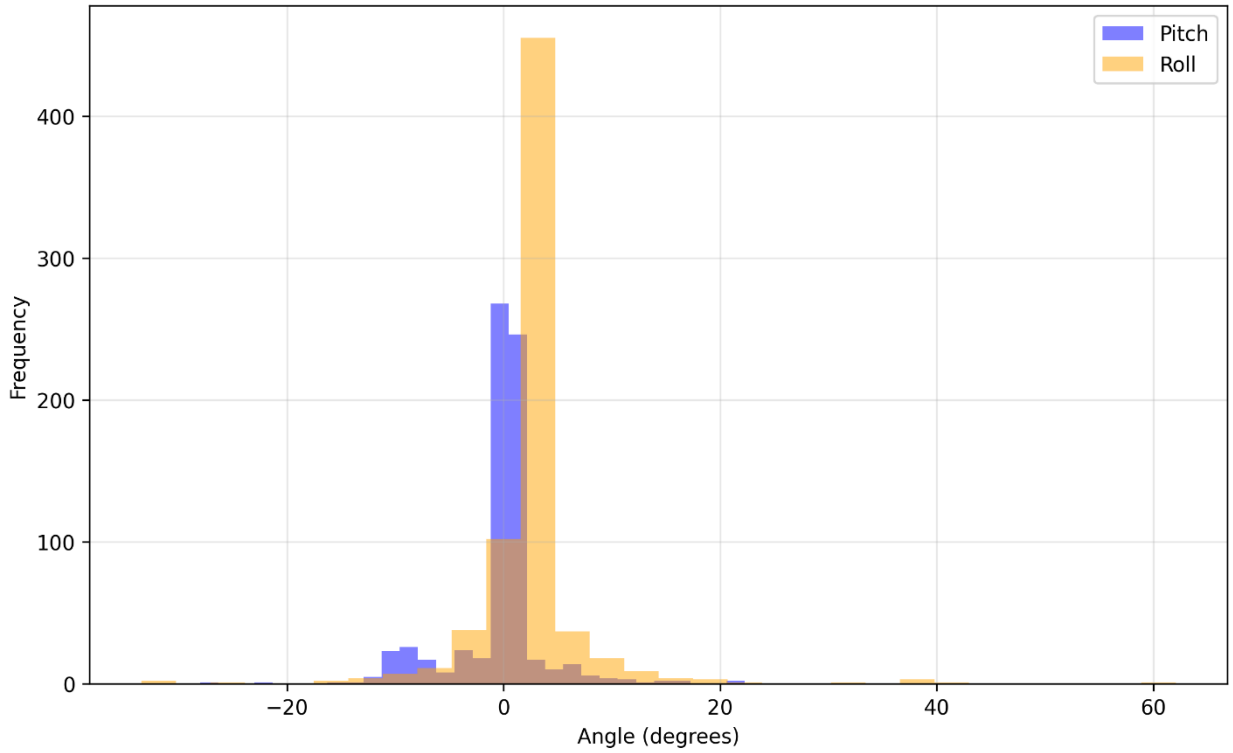

Figure4. 10 Pitch and Roll Distribution

The distribution of pitch and roll measurements shows a strong concentration around lower angles, indicating that the train spent most of its operating time in a stable condition. As the angle

increased, the frequency of occurrences decreased significantly. This pattern is expected because excessive tilt conditions are abnormal events rather than normal operating states.

The absence of a large number of readings near the critical threshold suggests that the prototype maintained good balance throughout the testing period. This result demonstrates that the monitoring system can effectively differentiate between routine motion and potentially dangerous instability. Such capability is essential for reducing false alarms while still maintaining high safety standards.

RFID performance was evaluated by placing tags at different checkpoints along the railway track.

Table 4. 4 RFID Station Identification Results

RFID Tag ID	**Assigned Station**	**Detection Status**	**Dashboard Update**
TAG001	Harare	Detected	Successful
TAG002	Norton	Detected	Successful
TAG003	Chegutu	Detected	Successful

The RFID sub-system managed to detect the tags consistently throughout all the testing locations, meaning effective communication between the RFID reader and the deployed tags. This shows that the chosen reading range and positioning of tags was appropriate for the operating conditions.

There were no major problems encountered during the testing process. The success in identifying all checkpoints indicates that the RFID system is ideal for train tracking. This will ensure the effectiveness of traffic management and scheduling because of the availability of precise location data for railway trains.

The frequency of RFID detections recorded at different locations is shown in Figure 4.11.

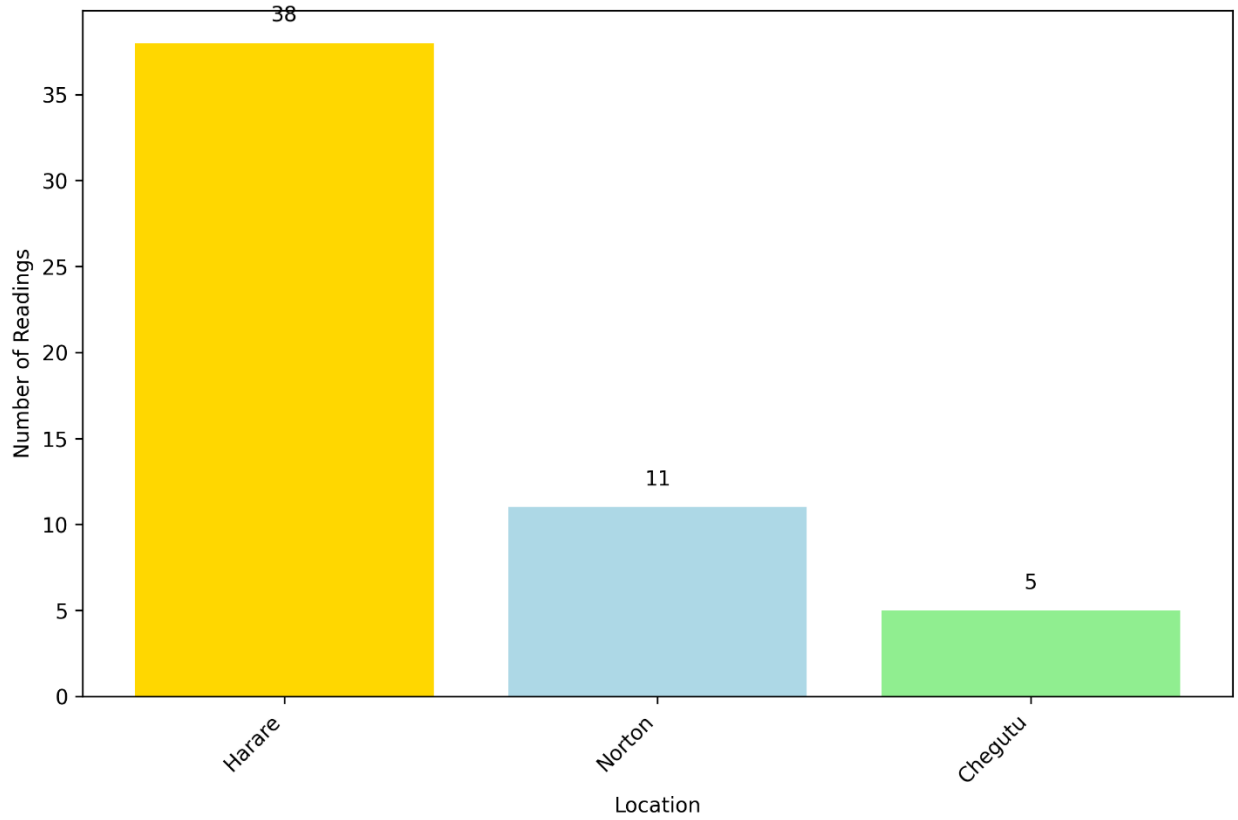

Figure4. 11 RFID Location Distribution

The frequency of RFID detections is different from place to place, owing to variations in the movement pattern of the train while testing. Places with a greater number of detections denote the places at which the train stayed or moved through more often. These discrepancies are natural and do not signify any error in the system.

The crucial point here is that all checkpoints have been detected. This ensures track coverage and no locations are left undetected. The implication for the engineers is that the RFID subsystem is capable of continuous location tracking, which is essential in a monitoring system for railways today.

The sequence of RFID detections over time was also studied.

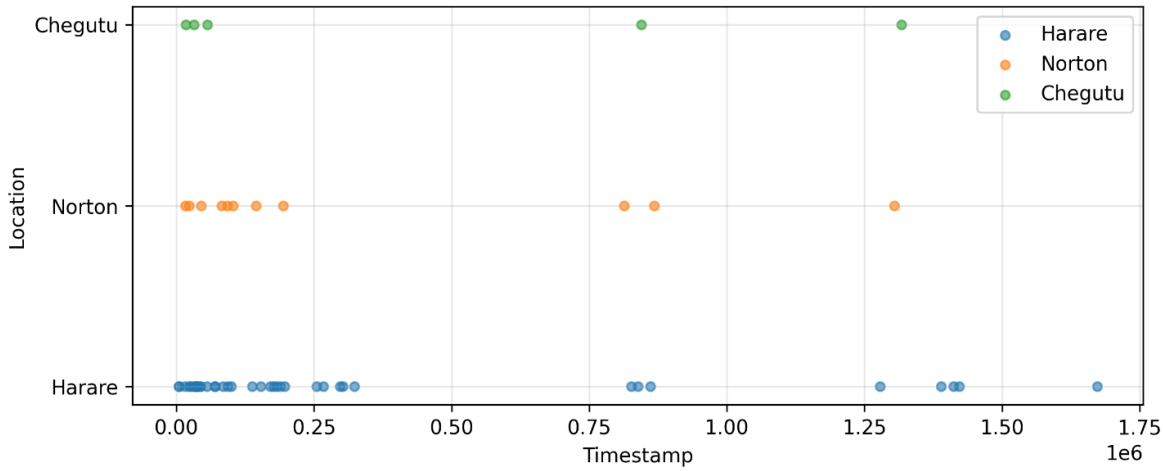

Figure4. 12 RFID Location Timeline

The RFID timeline shows the order in which the checkpoints have been detected in transit by the train. The systematic recording of the locations clearly shows that the system was working effectively in tracking the movements of the train from one station to another. There were no anomalies in terms of unexpected location recordings, showing that the RFID sub-system was performing effectively.

The IR sensor readings were analysed to evaluate track- following performance.

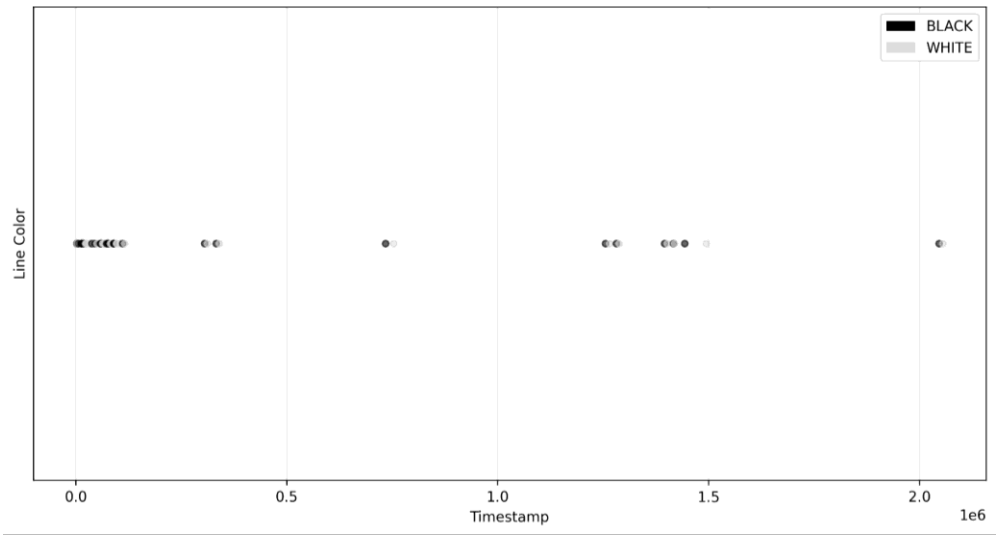

Figure4. 13 IR Sensor Timeline

The findings reveal a clear demarcation between the detection of black and white surfaces. This phenomenon happens due to the increased absorption of infrared light by the black surface, compared to the reflection of infrared light by the white surface. The variation in reflected light intensity helps to differentiate the line of the track from the rest of the surfaces.

Small variations in the readings from the sensor could have resulted from the variations in ambient light intensities or surface texture. Nevertheless, such small variations were not significant enough to interfere with the line-tracker's accuracy. It is important to ensure that accurate detection of the lines takes place since any mistakes in path tracking might cause navigation errors.

Distance information from the dashboard was analysed to examine obstacle detecting capability.

Distance measurements stored in the dashboard were analysed to evaluate obstacle monitoring performance over time.



Figure4. 14 Distance History Graph

The obstacle distance graph displays the changes in obstacle distances over time during the operation. Intervals with a falling distance represent cases when obstacles were added to the path of the train. Quick reaction of the system at such intervals proves the efficiency of the obstacle detection system. High values of distances mean a safe state of the system when there was no threat of collision.

ESP32 Validation Tables

Table 4. 5 ESP32 Calibration and Operating Thresholds

Component	**Parameter monitored**	**Normal range/ state**	**Warning threshold**	**Critical threshold**	**ESP32 action**
HC-SR04 Ultrasonic Sensor	Obstacle distance	>30cm	16-30 cm	</= 15cm during testing	Reduce speed in warning zone; stop motors, activate buzzer and LED in critical
MPU6050 IMU	Pitch/ Roll angle	0-10° typical stable operation	+/- 10°	+/- 25°	Continue motion in normal state; raise warning or stop train when unsafe tilt is detected
RC522 RFID Module	Station tag detection	Valid tag read	-	Missed/ invalid tag	Update train location on dashboard when valid tag is detected
IR Sensor	Track/ line state	BLACK line detected	-	WHITE surface/line loss	Continue motion on black line; stop or

					correct motion when line is lost
ESP32+ Wi-Fi	Data transmission	Normal logging	Delay in updates	Loss of network	Local safety decisions still continue even if internet is unavailable

Table 4.5 provides the information about the safety guidelines and automatic reactions performed by the ESP32 controller according to the results of the readings of various sensors. The obtained calibration values helped to identify the operational thresholds utilized by the ESP32 controller in order to implement safety procedures while working with the system. These selected thresholds provided a clear distinction between safe, warning, and dangerous states. Such a distinction helped to minimize any chances of confusion when dealing with the change in sensor readings.

The obstacle detection thresholds helped to provide enough time for the decrease in the speed before the emergency stop procedure was implemented. Likewise, the thresholds of the train's tilting helped to differentiate between regular operations of the train and dangerous situations.

Table 4. 6 Summary of logged data

Sensor / Module	**JSON log name**	**Number of records**
Ultrasonic sensor	Distance_ logs	514
IMU sensor	Tilt_ logs	700
RFID module	Rfid_ logs	54
IR sensor	Ir_ logs	76

Table 4.6 is the most concise table describing the data stored by the four sensors and modules. It links each piece of hardware with the name of the respective JSON log file and the total number of collected data entries. The logged data revealed that the system was collecting information from the sensors at all times during the experiment. Numerous entries were gathered using the ultrasonic sensor and MPU6050 since there was constant monitoring of the obstacles and train stability.

The majority of time spent on testing had stable connections between the sensors, ESP32 and Firebase, as proved by the amount of collected data. Because of such data flow, it was possible to analyse how the system behaved under various conditions.

Table 4. 7 Ultrasonic sensor validation results

Metric	**Value**
Total distance records	514
Minimum measured distance	4cm
Maximum measured distance	309cm
Mean distance	65.75cm
Median distance	72.0cm
Approximate median logging interval	5027ms

The performance of the ultrasonic sensor is presented in Table 4.7 and was evaluated according to 514 readings. According to the validation results, the ultrasonic sensor proved to be efficient in measuring the distance within the selected range of values. The obtained values correlated with the expected dependence in such a way that lower distances led to higher system interference while greater distances ensured the normal operation of trains.

The stability of measurements can be observed during all tests; there were no considerable changes in the measurement values. Minimal deviations from the predictions can probably be explained by the environment, including the reflection of light from objects or the position of objects. The effectiveness of the sensor in preventing accidents is quite high, at least within testing conditions.

Table 4. 8 Distance Zone Classification

Distance zone	**Threshold used**	**Number of records**	**Percentage**	**Expected ESP32 response**
Safe zone	>30cm	397	77.2%	Normal operation
Warning zone	15-30cm	25	4.9%	Speed reduction

Critical zone	</= 15cm	92	17.9%	Emergency action/ stop logic

Table 4.8 categorises the obstacle detection outcomes based on the safety thresholds employed in the prototype. From the classification results, 77.2% of the measurements recorded were within the safe zone, while a smaller portion reached the warning and critical zones. It is evident that the train was operating in safe conditions for most of the test time.

The low percentage of warning-zone measurements means that obstacles stayed within the speed-reduction zone for short periods. However, the percentage of the critical zone was 17.9%, which signifies testing of the emergency braking. The findings indicate that the ESP32 classified the obstacle distance in line with the defined thresholds and triggered the desired actions. Distances exceeding 30 cm allowed normal operations, 15-30 cm led to speed reduction, and distances at 15 cm and below led to emergency stopping.

Table 4. 9 MPU6050 Validation Summary

Metric	**Pitch**	**Roll**
Number of records	700	700
Minimum value	-28.02^0	-33.44^0
Maximum value	22.29^0	62.09^0
Mean value	-0.28^0	2.61^0
Median value	0.32^0	2.83^0

Table 4.9 displays the statistical analysis of the readings taken of the pitch and roll. From the statistical results, both pitch and roll readings stayed mostly centred at smaller mean values, which suggests that the train prototype operated steadily during most of the tests. Also, the closeness of the median value to zero shows that the tilts have been rare.

Despite the fact that maximum values were higher than the operating ranges, they were achieved intentionally in order to test the system while in unsafe conditions. This proves that the range of variation between minimum and maximum values shows the ability of the sensor to detect small as well as large changes in the train's position.

Table 4. 10 Tilt Classification Results

Tilt condition	**Threshold**	**Number of records**	**Percentage**	**Interpretation**
Normal	$<15^0$	677	96.7%	Stable train condition
Warning	15^0 to $<25^0$	14	2.0%	Potential instability; caution required
Critical	$>/= 25^0$	9	1.3%	Unsafe tilt; emergency stop condition

Table 4.10 divides the tilt values detected into normal, warning and critical categories. It appears from the classification outcomes that 96.7% of all detected tilt values fell into the normal operation category. This implies that the train prototype had stable mechanical properties during the majority of the experiment.

Only 2.0% of tilt values have fallen into the warning zone, and 1.3% into the critical one. The above percentages can be expected because the unsafe conditions were deliberately created only during particular experiments. Therefore, it is obvious that the monitoring system distinguished safe and unsafe operational modes of the train effectively. Moreover, the low number of critical incidents means that the emergency stopping occurred during unsafe situations only

Table 4. 11 RFID Station Detection Statistics

Detected station	**Number of detections**	**Percentage**
Harare	38	70.4%
Norton	11	20.4%
Chegutu	5	9.3%

Table 4.11 presents the RFID detection results recorded during testing. The RFID results show that Harare recorded the highest number of detections, accounting for more than two-thirds of all RFID events. This trend suggests that the train either spent more time near this location or passed through it more frequently during testing.

The lower number of detections recorded at Norton and Chegutu does not indicate reduced system performance but instead reflects the train movement pattern during the experiment. Importantly, detections were successfully recorded at all configured stations. This confirms that the RFID subsystem maintained complete checkpoint coverage and provided reliable location identification throughout the testing process.

Table 4. 12 IR Sensor Validation Results

IR sensor state	**Number of records**	**Percentage**	**Expected train action**
BLACK	32	42.1%	Train allowed to move
WHITE	44	57.9%	Train stops/ line lost condition

Table 4. 12 Overall ESP32 System Validation the results acquired from the IR sensor while carrying out line-following experiments. From these results, it is evident that the IR sensor performed successfully in detecting either BLACK or WHITE surface conditions during the tests. More WHITE surface detections were recorded compared to BLACK, implying that there were more instances where line loss conditions occurred during the test process.

The distinct difference between the two cases demonstrates that there was adequate contrast between the reflected infrared signals for proper line detections. Though the WHITE cases are more than the BLACK cases, the IR sensor has performed successfully and detected both surface conditions properly. It can be concluded that the IR sensor can effectively guide the trains.

Table 4. 13 Overall ESP32 System Validation

Subsystem	**Evidence from Firebase JSON file**	**Validation outcome**
Ultrasonic obstacle detection	514 distance records, including safe, warning and critical zones	Functional
IMU stability monitoring	700 tilt records with pitch, roll and tilt-flag status	Functional
RFID station identification	54 station detection logs across3 stations	Functional
IR track detection	76 line-state logs for BLACK and WHITE states	Functional
Integrated safety logic	Logged values align with threshold-based system behaviour described in document	Functional at prototype level

Table 4.13 is the summary of the performance of all major subsystems incorporated into the prototype. Validation outcomes show that all major subsystems have functioned successfully being combined in a single railway safety platform. The data generated from the ultrasonic sensor, MPU6050, RFID module and IR sensor have been validated since their behaviour has fully corresponded to the expectations from the system.

There have been no failures of any of the subsystems that could indicate problems in the integration process since all the sensing, control and communication processes have worked successfully. Though some delays have occurred in the process of updating the dashboard because of the constraints in networking, this did not influence safety-critical tasks as all decision-making processes were performed locally using the ESP32.

A combined dashboard analysis was generated to summarise the collected sensor data.

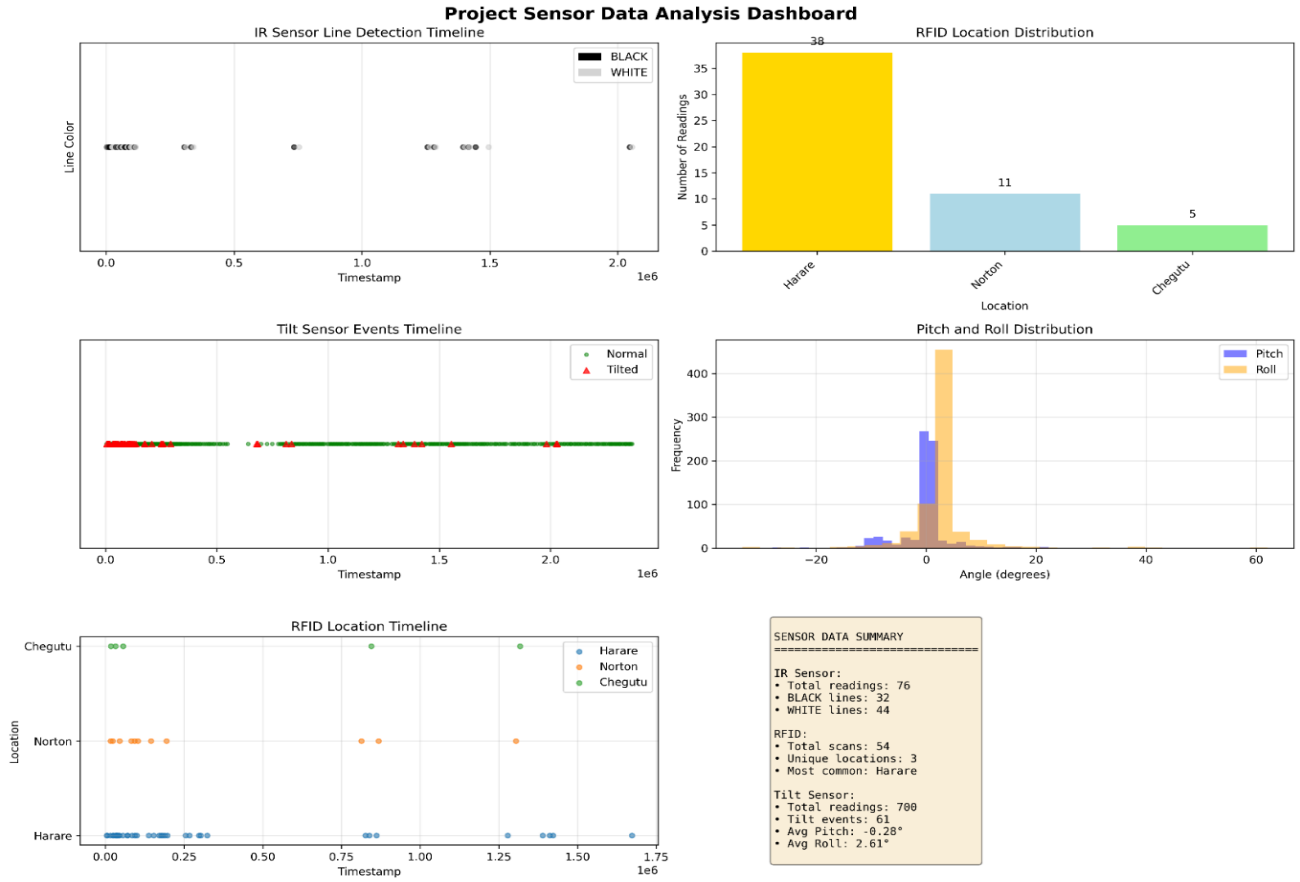

Figure4. 15 Sensor Data Analysis Dashboard

For the entire period of the test procedure, new information kept coming in without any break. This is a clear indication of the effectiveness of the embedded hardware's connection to the online database system. The information updates showed up in real time right after leaving the ESP32 module. The performance of the system remained constant throughout. Communication worked consistently in all the trials. Information came in effectively each time it was sent.

It is worth noting that there were some lags witnessed during times of unreliable internet connectivity. The delays did not have any effect on the functionality of the safety features since the obstacle detection, tilt monitoring and motor control were performed locally in the ESP32 chip. This is because the findings indicate that the availability of the communication infrastructure is a

major challenge in cloud monitoring systems. Therefore, safety critical operations should continue to be performed locally, with cloud only handling monitoring and data logging.

4.4 Analysis and Interpretation

Objective 1: Obstacle Detection and Collision Prevention

The first objective was to incorporate the ability to detect obstacles and prevent collision by the use of ultrasonic detection and speed regulation by threshold control. As depicted in Table 4.1, Table 4.2, and Figure 4.8, the system was able to detect the obstacles and react based on the set threshold levels. When the obstacle distance came to 30cm, the speed of the train reduced and a warning signal was triggered. At 15cm obstacle distance, the train stopped itself and the warning signals were triggered.

Objective 2: Train Stability Monitoring

The second goal of the experiment was the detection of unsafe tilt conditions by monitoring train stability through the use of the MPU6050 sensor. According to Table 4.3 and Figures 4.9 and 4.10, it can be concluded that the system was able to monitor the angles of rotation in roll and pitch. When there were abnormal tilt values, warnings were shown on the dashboard; critical tilt condition resulted in an emergency stop.

Objective 3: RFID-Based Station Identification

Objective number three involved RFID based station identification and checkpoint monitoring for train location referencing. Table 4.4, in conjunction with Figure 4.11, reveal that the RFID tags were successfully detected at various checkpoints. The detected locations were then transferred to Firebase and displayed on the dashboard. This indicates that the RFID subsystem successfully performed station identification and train location referencing.

Objective 4: Web-Based Dashboard Monitoring

Objective number four was to create a dashboard on a website which would be linked to Firebase for visualisation in real-time of the train status, sensor readings, and warning alarms. As can be seen from the screenshots in the dashboard shown in Section 4.2, the following parameters were

successfully visualised in real-time: obstacle distance, train status, tilt status, RFID readings, and warning alarm statuses. This is an indication that communication between the ESP32 and Firebase was successful.

Overall System Performance

From the above findings, it is clear that the combination of the subsystems was successful in working together as one. The prototype showed automatic collision prevention, stability monitoring of the train, station detection, and dashboard monitoring in one single embedded system. Therefore, the findings indicate that the whole project was successful.

4.5 Discussion of Findings

The results obtained from the prototype testing are in agreement with the literature review conducted in Chapter 2.

Even though small, MPU6050 IMU worked effectively as observed in the results achieved by Song and colleagues in 2022and two years prior in the study by Zhou. The vibration pattern as well as the angular change was keenly monitored throughout the process. Wherever there was an angle change beyond the predetermined limit, there were alerts issued immediately. Such alerts reflect how warnings are made in stressful situations. Alerts come automatically once there is physical evidence. Safety measures were automatically implemented where there were angle deviations beyond the critical points.

The ultrasonic sensor results also support (Kumar, et al., 2022), who explained that ultrasonic sensing provides reliable short-range obstacle detection for collision prevention applications. The prototype successfully detected obstacles, reduced speed at the warning threshold and stopped at the critical threshold.

The RFID checkpoint monitoring results agree with the findings of (Aditya, et al., 2022), who demonstrated that RFID technology can provide affordable and reliable train identification and location referencing in railway systems. The prototype successfully identified RFID tags placed at different checkpoints and updated the location information accordingly.

The web-based dashboard integrated with Firebase successfully displayed real-time train information, sensor readings and safety alerts. This supports studies by (Roy & Dey, 2020), which highlighted the growing use of IoT-based monitoring platforms in embedded systems. The dashboard provided a simple way of monitoring train status remotely without directly accessing the hardware.

While most earlier studies concentrated on hazard detection and warnings, the proposed solution involved the integration of obstacle detection, tilt detection, RFID location sensing, automated speed control using PWM, and dashboard-based monitoring in a single inexpensive device.

This solution enhanced automation of the process and minimized the need for manual intervention. The study also attempted to solve problems encountered in the railway system of Zimbabwe through the use of inexpensive components, modularity, and infrastructure independence.

4.6 Summary

This chapter presented the implementation, testing and experimental analysis of the proposed embedded railway safety and collision prevention prototype.

The results showed that the system successfully performed obstacle detection, train stability monitoring, RFID checkpoint identification, PWM-based speed regulation and real-time monitoring through a web-based dashboard integrated with Firebase.

When danger appeared, slowing down happened without help - then stopping followed. Warnings showed up as sounds and lights at once. Readings from sensors reached the screen smoothly. Train details updated live where staff could watch far away.

Despite its early stage, the system shows promise as an accessible method to enhance rail safety during testing phases. What follows explores outcomes drawn from the study, alongside boundaries encountered and possible paths forward for refinement.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Summary of the Study

This work looked into building a railway safety prototype, relying on affordable embedded tech. Though centered on collision avoidance, it also explored automation in tracking trackside obstacles. Because trains face risks beyond human oversight, systems that watch stability matter just as much. Where speeds shift unexpectedly, smart controls adjust without delay. Remote supervision happens all the while, feeding data as events unfold. While hardware stays minimal, functions combine to reduce failure points across operations.

A first-stage model brought together multiple electronic parts and code modules within one rail safety setup. At its core, an ESP32 chip acted as the main brain - gathering inputs from sensors, judging risks, then triggering responses. Train balance and lean were tracked using an MPU6050 motion detector. Obstacles ahead got spotted through sound waves bounced off them by a distance-measuring module. For recognizing stops along the route, radio signals linked to tags placed at stations provided location cues. Light-sensitive circuitry helped follow track markers, guiding movement based on contrast changes seen beneath the vehicle.

To support remote monitoring, a web-based dashboard connected to Firebase Realtime Database was developed. The dashboard provided real-time visualisation of train status, sensor readings and safety alerts. Firebase also enabled communication between the prototype and the monitoring platform, allowing operational data to be viewed remotely.

The prototype functioned based on predefined safety threshold levels. In case of any detected unsafe situations, the system automatically took action through motor deceleration and full train stoppage. Additionally, the system generated visual and audible warnings of any warning or emergency situation.

The tests and evaluations conducted revealed that the prototype effectively conducted obstacle detection, line following, tilt detection, RFID station identification, PWM speed adjustment and dashboard monitoring. The prototype was therefore able to respond to various operating conditions and had reliable interaction between sensing, control and communication processes.

This study makes contributions to railway safety literature through its demonstration of the integration of affordable embedded technologies into one platform capable of conducting multiple safety operations. The results reveal that affordable embedded systems coupled with web-based monitoring can provide practical railway safety solutions for railway environments such as Zimbabwe.

5.2 Achievement of Objectives

The objectives of the study were successfully achieved through the design, implementation and testing of the proposed railway safety system.

One goal aimed at building a way to detect barriers and avoid crashes by combining ultrasound technology with speed limits set in code. Success came through clear results during testing. As the train moved, readings from the sound-based sensor fed live data to the main processor. That chip, an ESP32, made decisions based on preset safe distances written into its logic. Whenever something approached too closely, slowdown began automatically past a certain point. Complete halt occurred only once the object drew within fifteen centimeters. Movement paused until clearance returned beyond that limit.

The second objective was to monitor train stability and detect unsafe tilt conditions using the MPU6050 sensor. This objective was also achieved successfully. The sensor continuously measured train orientation and enabled the system to identify abnormal tilt conditions. When critical tilt values were detected, warning indicators were activated and the train was stopped automatically to reduce the risk of derailment.

Thirdly, the third objective involved integration of RFID based station identification and check-point monitoring systems. This objective was successfully achieved by incorporation of RFID tags located at different points along the railway track. This was able to identify the check-points and update train locations through operation process, thereby validating the efficacy of RFID technology in location referencing.

The fourth objective involved creation of a web-based dashboard with Firebase for real time visualisation of train information, sensors readings and safety alerts. This objective was

successfully achieved. The dashboard was capable of displaying information such as obstacle distances, tilting data, train information, RFID location and system alerts. This made the operations more efficient as well as making the information available for the users in real time.

In summary, the study successfully combined sensing, monitoring, communication and intelligent control functionalities into one embedded railway safety prototype. Achievement of the above stated objectives is an indication of the feasibility of application of low-cost embedded technologies in improving railway safety.

5.3 Limitations

While the prototype functioned well during testing, there were some limitations that were found during the course of the study.

For the testing purposes, a small-scale railway prototype was used instead of a full-scale railway system. Railway systems have to work under certain conditions which include increased speed, increased distance travelled, different weather situations, and more communication needs. These conditions were difficult to emulate during this study.

The monitoring system based on the Firebase service which required a stable Wi-Fi connection. During the tests, there were some interruptions with the Wi-Fi network, which caused some delay in the dashboard updating process. This issue influenced only the speed of data visualisation since the safety-related functions worked properly due to local processing by the ESP32 microcontroller.

GPS technology was not fully implemented in the prototype. Even though GPS can track train movements continuously over great distances, it is not practical to implement the technology in an indoor setting like the one used in the prototype tests. GPS units normally need satellite communication as well as greater spaces in order to obtain accurate positioning information.

In addition, the research was mainly concerned about railway safety in terms of the prototype and did not look at advanced technologies such as railway traffic management systems, centralised signalling system, artificial intelligence or predictive maintenance algorithms which can be used to improve railway safety.

However, despite the constraints noted above, the prototype successfully showcased the use of embedded sensing and control technologies in railway safety and collision prevention.

5.4 Recommendations for Future Work

Future studies should focus on extending the capabilities of the proposed railway safety system through the integration of more advanced monitoring, communication and control technologies.

It would be beneficial to use GPS technology in the system of monitoring. It has been chosen to apply RFID technology in this work because it was better to implement a prototype using this technology and it could reliably identify the position of stations and checkpoints. Nevertheless, GPS technology allows providing information about the position of the train.

Future railway safety systems will be greatly helped by integrating the technology of RFID with that of GPS. While the former will remain responsible for providing accurate identification of stations and checkpoints, the latter will be responsible for the tracking of trains throughout the railway line. Integration of both technologies will result in improvement in terms of location recognition, train tracking and monitoring of operations.

Tests should also be done on bigger railway models or in real railway environment. This test will enable an understanding of how well the systems perform in a practical environment with greater speeds, communication distance and railway operations.

Reliability in communication can be achieved through the use of GSM, LoRa or any other long-range communication technology. These will offer better communication in cases where there is lack of internet connection.

More advancements might also be considered, such as developing mobile monitoring apps, integration with railway signalling systems, and use of AI technologies for predictive fault detection and safety analysis. Such advancements will lead to improved intelligence of the system, increased efficiency, and better proactive railway safety management.

Moreover, future research needs to look into ways of enhancing the performance of the system under harsh environmental conditions and in the absence of communication to maintain its uninterrupted operation in real railway environments.

5.5 Chapter Summary

This chapter presented the summary of the study together with the achievement of objectives, limitations and recommendations for future work.

Although built on affordable components, the system managed to detect obstacles while also tracking how steadily trains moved along tracks. Instead of relying on expensive hardware, it used RFID tags at stations to recognize location automatically. As speeds changed, controls adjusted without human input thanks to pre-set rules. Data flowed constantly into a web interface powered by Firebase, making updates visible in near real time. Because all pieces worked together, the test showed embedded systems could handle critical safety tasks reliably. Even basic electronics, when combined well, supported alerting, regulation, and oversight across distances.

The tests revealed effective responses to hazardous situations by applying preset safety limits, at the same time delivering actionable data via a real-time dashboard. Despite some drawbacks - mainly tied to the small-scale model and reliance on stable connections - the setup met core goals, proving consistent behavior under evaluation.

Despite limitations, results indicate basic electronics combined with online tools may help monitor rail conditions affordably. Evidence supports further exploration into scalable methods for enhancing train safety where infrastructure is limited.

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