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Next-Gen Railway Crossings with IoT Solutions for Enhanced Safety and Control

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Abstract
Unmanned level crossings particularly at the railway crossing are very dangerous, and cause accidents, which are normally caused by human oversights. This study provides an IoT-based railroad crossing system, which can improve safety using a combination of the NodeMCU, vibration sensors, and Firebase to control the gates in real time. In contrast to the manual or semi-automated systems used in the past, our solution exploits the use of wireless data transmission to monitor a train that is heading towards or leaving as well as automate the operation of the gates. The system will comprise three interconnected nodes namely two vibration sensor nodes that will be located at strategic points along the track and a gate node that has the leadership of a servo motor, a buzzer and LED indicators. Sensor data of the presence of a train is sent to the gate node when it has been recognized by the firebase, which closes the gate automatically and sends alert notifications. When the train takes off, the second sensor is utilized to open the system again. Our scalable, low-cost and real-time solution is expected to dramatically decrease the number of accidents in on coming trains, as well as offer a very efficient and IoT-based alternative to the traditional gate control systems.

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1 Introduction
The railway is an essential lifeline and a very popular mode of transport all over the world. It is nowadays a part of daily routine, yet any little malfunction in its mechanism might lead to disastrous incidents, cost of precious human lives, and serious injuries [22]. The reliance on the human collaboration to open or close level crossing gates is one of the biggest problems in railway systems where any failure can lead to unavoidable tragic outcomes. This project will help to overcome these problems by eradicating human errors and accidents avoidance via an automated system [25].

Although people may think that railway signaling is as old as the history of the world, it has undergone transformations into automatic signaling, which contributes to the security of passengers and their efficiency. The automatic signaling also insures even speeds, lengths, and schedules of trains and helps decrease accommodation. In most countries, they are embracing modern technologies such as self-driving railway signaling to enhance the quality of transit even more. But in Pakistan, where railway stations are very common, and trains are used as one of the major means of transportation by most people, the old systems and life endangering problems disrupt the dependability of the railway systems [24]. The inefficiency and safety of the railways is due to a shortage of technological advances and the continued use of manual processes that do not allow them to be a safe and efficient means of transportation [23].

The transportation is a key economic driver, which was emphasized by the World Bank. Though most third-world countries are slowly moving into the automated technologies, Pakistan continues to grapple with modern solutions in its railroads. Through proper measures of technology interventions, Pakistan will enjoy better standards of transportation, fewer accidents, and overcome the challenges of the economy. The advantages of automating the railway crossings are many, such as improved safety, lower risks to life, better accuracy in managing signals, elimination of train-pedestrian accidents and it can save time, lives and resources [3].

Moreover, automation can strengthen the economy of the country through the process of enhancing the local transportation infrastructure. Lack of staff and the absence of automated systems are often the cause of accidents in the railway crossings. According to the literature, different sensors have been used in smart railway crossings, which include IR, RFID, ultrasonic sensors, and CCTV cameras. Such systems however fail miserably because of their short range, lack of reliability, expensive nature and ecological limitations hence they are not befitting the Pakistani railway system [10].

As a solution to these challenges, the proposed project is the Internet of Things (IoT)-based one with a vibration sensor and the Node MCU Esp8266 to measure the distance between passing trains and crossing points accurately. The proposed system will substitute the present manual signaling system with an automated system, which will be safer, less susceptible to human error and costless, which will have long term benefits to the country [2].

The main aim of this project is to come up with an automated system of a railway crossing that improves on safety and efficiency whilst minimizing on human interference. A prototype that demonstrates the viability and efficiency of the innovative approach will be created based on the NCRA lab communication division. By leveraging automation, this project seeks to revolutionize railway crossings, mitigate accidents, and contribute to the country's economic and infrastructural development.

2 Literature Review

Sukenda s.t. and others started work on Vibration Sensor in 2020,and microcontroller mechanic signalling by initialising the sw-420 vibration sensor; after that Vibration Sensor records the data which will be generated by the train. That recorded data of sensor send to the microcontroller and LCD display the data. If the data of vibration cross the threshold, the led starts to glow and the sounds of buzzer starts, activating the relay and moving the mechanism on the mechanical signalling system. If no vibration data exceeds the predetermined limit, the led light illuminates and the buzzer alarm sounds [11], deactivating the relay and moving the mechanism on the mechanical signalling system. The vibration sensor will then execute vibration again. The opening and closing of the door will be done according to the threshold of Vibrating Sensor [4].

P llampiray et at J.phys introduce the ultrasonic gate control system for safe journey in 2021. The full setup has connected with the Arduino nano ATMEGAb28p and buzzer will be placed near Arduino. We will connect the external power supply with the Arduino, after that we wiil fix the toy train to its track. The train starts on track with the help of power supply. When the train comes nearer to the 1st ultrasonic sensor the crossing gate will be closed and if it reaches the 2nd one the gate will be open in this way automated railway gate has been mannered [5].

The automated railway system, as discussed by Rite S. Dhande et al., incorporates various techniques such as IR sensors and IoT technology. The study presents a system for managing unmanned gate crossings using FM communication. The proposed system integrates a microcontroller that processes signals from sensors to execute actions upon detecting a train's arrival. Specifically, when the train reaches the arrival point, the corresponding IR sensor detects its presence and communicates with the level crossing to close the gate [26]. Similarly, upon the train's departure, another IR sensor identifies the train leaving the area and triggers the level crossing to reopen the gate. This would be an efficient way of automating the functioning of unmanned level crossings in order to improve safety and effectiveness [6].

In 2021, Selvan et al. and others came up with an unmanned railway level crossing gate system. Their design uses real time application sensors which are designed to be calibrated in actual real time application where the movement of the train over a specified distance over the particular track activates the sensor. This stimulation produces a high-output signal which is distributed to the controller that allows automated operations [7].

"The Smart Unmanned Level Crossing Railway System" introduced by Ujjwal Kohli and Anmol Agarwal in 2016 is Indian-specific. The paper proposes a cost-saving and automated solution to unattended railway crossings. The system will computerize the operation of the railway barrier whereby a closing of the barrier will be detected when a train is coming by by using infrared sensors that are strategically positioned near the crossing. This will guarantee the safety of road users by minimizing road accidents and eradicating the inherent human errors in controlling the roads. The system also uses piezoelectric plates to collect energy that can be saved in a battery and used to run important elements such as the IR sensors and an LED display timer. The innovation is dealing with the issues of unattended level crossings in the nation [8].

Senthil Kumar and his team developed an ah robotically controlled railway gate system where they showed how it was done with the help of a technique flow diagram. The systems start with the identification of a train arrival, which is the sense of an ultrasonic sensor. On detecting the train, an alarm (buzzer) is set to notify the people at the vicinity that the train is coming as well as the gates to the railway are closing soon. [27]. One more ultrasonic detector analyzes the presence of obstacles at the crossing before closing. In case a car or an individual is spotted, the gates are held open a time of 15 seconds to give time to safely cross, the sensor then checks the area again [34].

These obstacles are calculated in centimeters that are determined by the width of the crossing to guarantee extra security. Once the barriers are installed, a different ultrasonic sensor would scan the area between the closed gates to ensure that there are no objects or people present between the gates [21]. If any are detected, a signal is sent to the train to stop. The system waits for two minutes (or an adjustable delay time) before rechecking for any obstacles. This process continues until the area is clear, allowing the gates to close securely. When the train departs, detected by a separate ultrasonic sensor, the barriers retract, and the gates reopen to resume normal operation [9].

To better understand the advancements in railway crossing automation, Table 1, provides a comparative analysis of existing studies. The comparison includes methodologies, technologies used, key features, and limitations. This summary highlights the strengths and weaknesses of each approach, allowing for a clearer understanding of the research gap and the need for an improved IoT-based solution.

System/Study	Response Time	Accuracy	Energy Consumption	Communication Latency
Sukenda S.T. et al. (2020)	Moderate	Moderate	Low	High
P. Llamipray et al. (2021)	Fast	High	Moderate	Moderate
Rite S. Dhande et al. (2021)	Moderate	High	Moderate	High (FM Communication)
Selvan et al. (2021)	Fast	High	High	Moderate
Ujjval Kohli & Anmol Agrawal (2016)	Moderate	Low	Variable (Energy harvesting dependent)	High
Senthil Kumar et al. (2021)	Fast	High	Moderate	Moderate
Proposed IoT-Based System (This work)	**Very Fast**	**Very High**	**Low**	**Very Low (Firebase communication)**

Table 1. Comparison of Existing Systems with Proposed IoT-Based System

3 Design and Methodology

The layout of the system follows the structure shown in Fig. 1. It includes three nodes placed along the track. Two nodes are of vibration sensor, node MCU, and one node is of servo motor, buzzer, node MCU, led (which will be at the gate) [12].

One node of vibration sensor will be put at the right-side meters away from gate and second node will be put at the left side meters away from gate [20]. When train arrives, the sensor detects the pulses of train and send data to the gate via node MCU via Firebase the data will be receive by the node MCU of gate node, and gate will be closed by servo motor[28]. When train departs the vibration sensor of the second node sends data through the node MCU by firebase which will be receive by node MCU of gate node and gate will open [13].

3.1 Design Specification

Any project requires a design definition; thus, our first goal was to develop the design specification, which required us to clarify the design requirements and goals. Our idea uses a Node MCU and a vibration sensor to regulate the track gate. To minimise accidents, the crossing gate controller model is built using a Node MCU and a vibration sensor. Because the train disaster occurred at an unmanned level crossing, it was caused solely by personnel's negligence. So far, we've only constructed three nodes of Node MCU and vibration sensor in our project, and our major goal is to deploy one node on the train and another on the track, with a third node at a crossing location. Such that it can detect and control the gate's operation In addition, we opted to provide a led and buzzer to warn of an incoming train [34].

3.1.1 NODEMCU ESP8266

Node mcu is an open source IoT platform with a cheap cost. We are tilizing three nodemcu to communicate the date wirelessly over firebase. NodeMCU combines node and mcu (micro controller unit). We can discover the accurate date by using node mcu that we set on different distances. It can be simply deployed wherever because of its inexpensive cost.

As shown in Fig. 2, Node MCU ESP8266 is a complete Wi-Fi network; it can run software applications or uninstall all Wi-Fi network features. When this device is mounted and used as the only application of the application processor, flash memory can be started directly from an external memory. The system will be improved, and

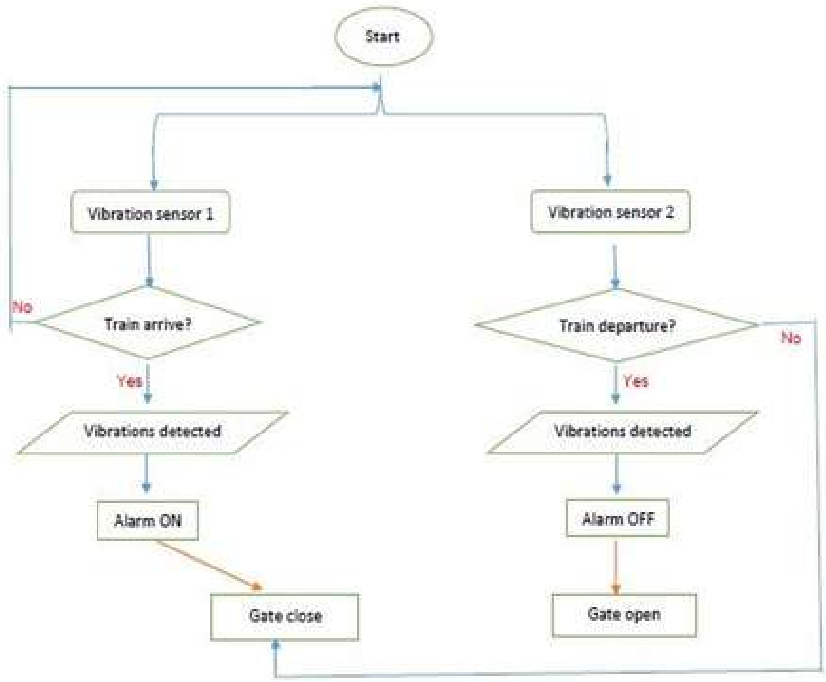

Figure 1. Flow chart of methodology

memory reduction will happen by the built-in cache memory [33].

It can be added this device to any project of microcontroller when the task of WiFi adapter will be supported by the wireless internet access, it has simple connection, only from the SPI / SDIO interface or the AHB bridge interface of the central processor. It has three modes: active mode, sleep mode and deep sleep type. The ESP8266 has 17 GPIO pins (0 to 16), however, you can only use 11 of them, because 6 pins (GPIO 6 to 11) are used to connect the flash memory chip.

3.1.2 Vibration sensor

A vibration sensor is a device that can monitor the quantity and frequency of the railway track vibrations. These data may be used to detect imbalances or other abnormalities in the asset and anticipate future failures [32].

As shown in Fig. 3,The module Vibration Sensor is based on the SW420 Vibration Sensor and locates the vibrations using the LM393 Comparator. The threshold can regulate the use of an on- onboard potentiometer. It is based on 2 conditions: it displays logic low when there is no vibration, and it displays logic high when some vibration is detected [31]. It has three pins:

- VCC: This pin powers the module with +5V
- GND: This pin provides ground power to module
- DO: Digital Out Pin for Digital Output

3.1.3 Servo Motor

Servo motors are a type of gear head motor that uses a potentiometer to provide feedback on the motor's position [16]. The gears of a servo's gearbox are connected to a potentiometer within the case, and the port is turned by the motor's rotation. The port is linked to a capacitor in a resistor-capacitor circuit (RC), and the motor is powered

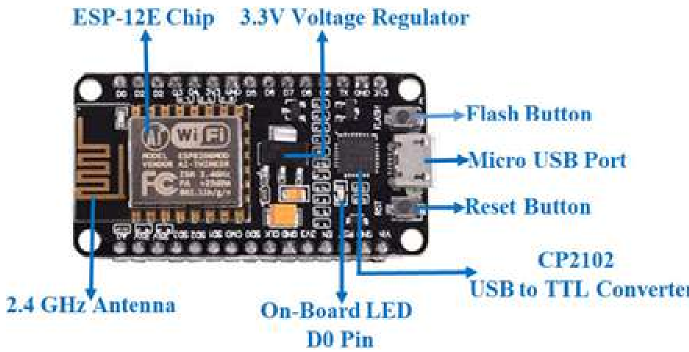

Figure 2. NODEMCU ESP8266 PIN CONFIGURATION

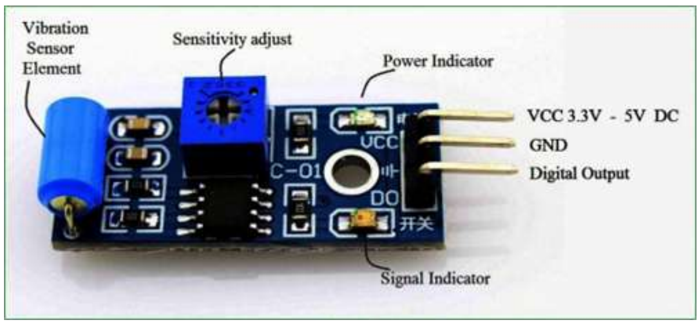

Figure 3. VIBRATION SENSOR PIN CONFIGURATION

by pulsing this RC circuit. When the motor rotates, the resistance changes. You may adjust the motor's position anywhere between 90 and 180 degree [28].

As shown in Fig. 4, It contains 3 types of pins [29]:

- Power wire: connected to 5V pin and having red color
- GND wire: connected to the GND pin and having a black/brown color
- Signal pin

As shown in Fig. 5, the pin configuration of the servo motor is clearly illustrated.

3.1.4 Buzzer

A buzzer, often known as a beeper, is a signaling device that is used in a variety of home and industrial applications to notify an occurrence. At level crossings, we utilized a buzzer. When the track node detects a train, it beeps to alert us that one is approaching [27].

3.1.5 Power Supply

A power supply is essential for everything to function. As a result, we utilised a V battery, whose primary duty is to deliver sufficient power to our motor and other equipment in our project so that it may work correctly without being harmed or overheated [18].

3.2 Formal Gate Control Algorithm (Finite State Machine - FSM)

To ensure reliable decision-making and system behaviour, especially under challenging conditions like signal noise or simultaneous train detection, we implement a Finite State Machine (FSM) for managing the railway gate operation.

Figure 4. SERVO MOTOR

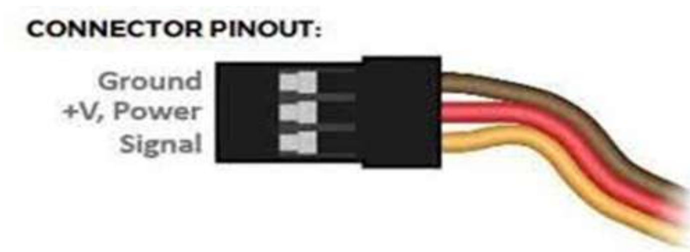

Figure 5. SERVO MOTOR PIN CONFIGURATION

Finite State Machine Overview[1]:
The FSM consists of the following states:

• State 1: Idle (Gate Open)

- No train detected by either vibration sensor.
- Gate remains open.
- LED remains OFF.
- Buzzer remains OFF.

• State 2: Train Approaching (First Sensor Triggered)

- First vibration sensor (Sensor A) detects vibration above the threshold.
- Send "Train Approaching" signal via NodeMCU to Firebase.
- LED turns ON.
- Buzzer sounds intermittently.
- Prepare for gate closure.

• State 3: Gate Closing

- The servo motor activates to close the gate.
- LED remains ON.
- Buzzer remains ON continuously during gate closure.

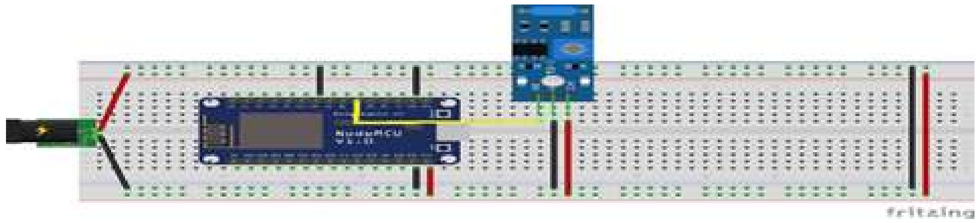

Figure 6. Tx CIRCUIT DIAGRAM

• State 4: Train Crossing (Gate Closed)

- Gate fully closed.
- Continuous monitoring of second vibration sensor (Sensor B) for train passage [30].

• State 5: Train Departure (Second Sensor Triggered)

- Second vibration sensor (Sensor B) detects train departure vibrations.
- Send "Train Passed" signal via NodeMCU to Firebase.
- Prepare for gate opening.

• State 6: Gate Opening

- Servo motor activates to open the gate.
- LED and buzzer turn OFF after successful gate opening.
- System resets to Idle.

The complete FSM workflow and transitions are summarized in Table 2.

Current State	Event	Next State	Action
Idle	Train detected by Sensor A	Train Approaching	Turn on LED, sound buzzer, prepare gate
Train Approaching	Gate close command sent	Gate Closing	Start servo motor to close gate
Gate Closing	Gate closed confirmed	Train Crossing	Maintain gate closed, monitor crossing
Train Crossing	Train detected by Sensor B	Train Departure	Prepare gate opening, turn off buzzer
Train Departure	Gate open command sent	Gate Opening	Start servo motor to open gate
Gate Opening	Gate opened confirmed	Idle	Reset system, turn off LED and buzzer

Table 2. State Transition Table for Gate Control System

3.3 CIRCUIT DIAGRAMS

3.3.1 TRANSMITTER CIRCUIT DIAGRAM

We used two transmitting nodes, one node placed two kilometres before the gate and another two kilometres after gate, as shown in Fig. 6 and Fig. 7.

3.3.2 RECEIVER CIRCUIT DIAGRAM

Only one node is used; this node is put on the gate, as shown in Fig. 8 and Fig. 9.

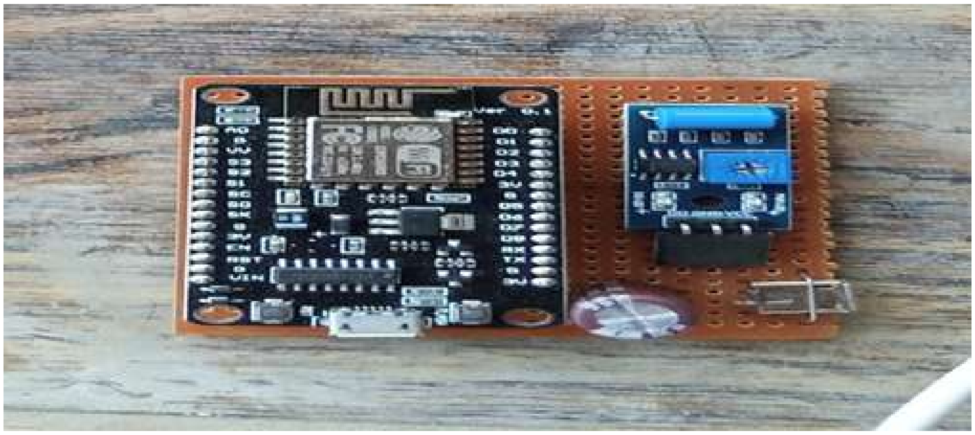

Figure 7. Circuit

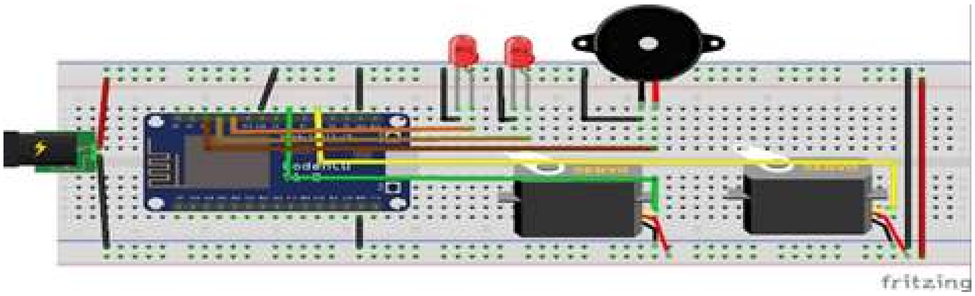

Figure 8. Rx circuit Block Diagram

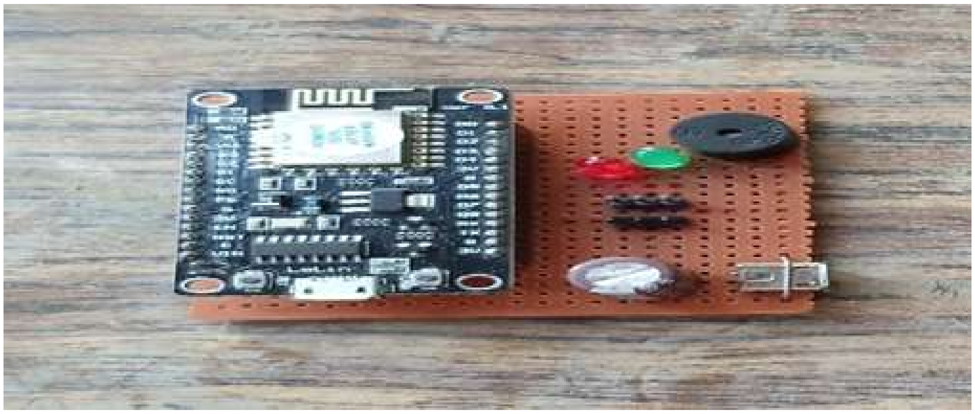

Figure 9. Rx Circuit

4 Resuls and Discussion

When we are implement the system, first off all we analyze the vibration pulses because we have to set the threshold/limit [19]. So, these simulation results shows the vibration pulses of train. We calculate the average of pulses, and set the threshold according to calculations. This part is necessary for our project. We analyze the vibration pulses with the help of Arduino IDE Software [26]. The programming output is shown in Fig. 10.

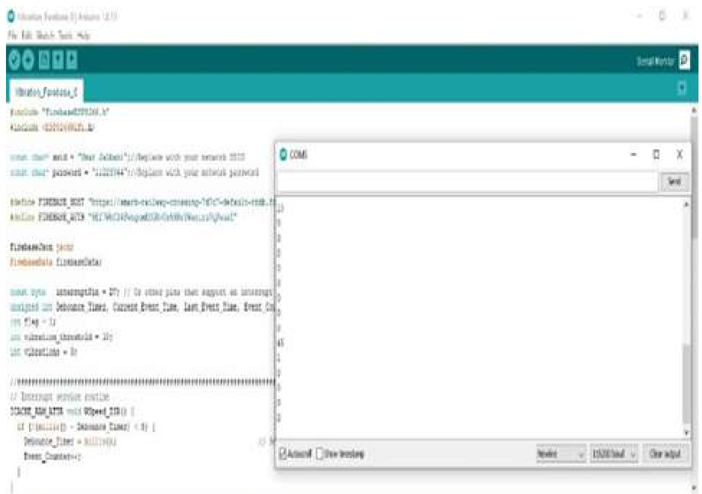

Figure 10. Programming screenshots

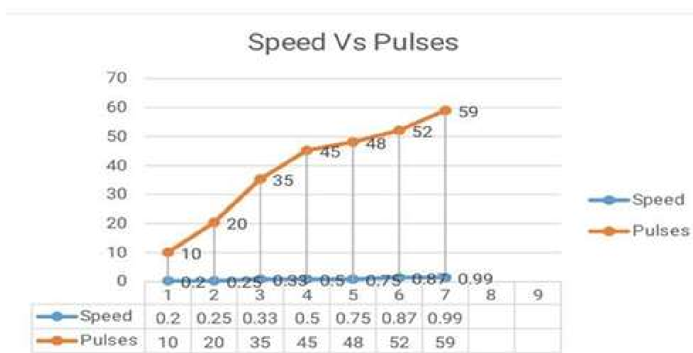

Figure 11. Speed VS Pulses

When weight of train increases, the vibration pulses also increases as shown in Fig. 12, 13

When train speed increases, the vibration pulses increases as shown in Fig. 13:

Fig. 14 shows the relation between weight, speed and pulses. It shows that the pulses increases with the increase in weight and speed.

5 Conclusion

The major goal of this initiative is to minimize the number of accidents caused by manual level crossings across Pakistan. To decrease loss, we employ the vibration sensor technology, which is both effective and inexpensive. We create a basic technique model that may be applied in real time to demonstrate our project concept. With the increase in population need for transportation systems had been increased. And the train is one of the safest and cheapest modes of transportation, not only do people use this mode of transportation, but it is also used

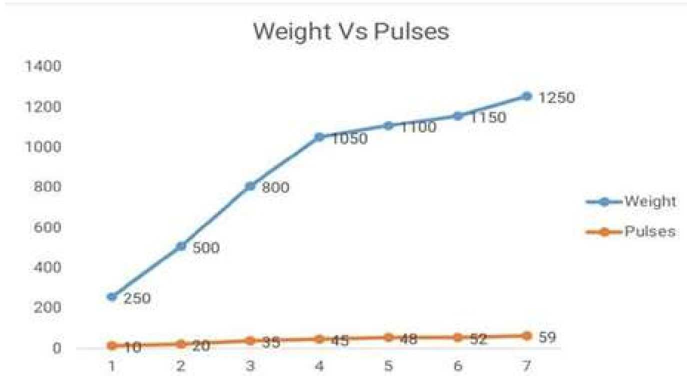

Figure 12. Weight VS Pulses

Figure 13. Weight VS Pulses

Figure 14. Speed VS Weight VS Pulses

for transporting any kind of the thing and heavy machines or any kind of goods and in train system portability of accidents get reduced compared any other mood of transportation, but unfortunately, train system has still some probability crossing gates are manual or unmanned crossing can cause the accident and occur loss of human life, so we are making our railway crossing automatic, by which accidents reduce and human life is safe.

We are making the system automatic with the help of vibration sensor. The vibration sensor senses the arrival and departure of the train and opens or closes the level crossing gate automatically with the help of Node mcu. Node mcu connects the whole system with the firebase, and firebase make communication between nodes. Our motive is to solve the problem by using the most effective and cheapest mode. The vibration detects the train's approach and departure and automatically opens or shuts the level crossing gate. Our main goal is to address the problem in the most efficient and cost-effective way possible.

Author Contributions

Asfand Ali: Conceptualization, dataset construction, experimental design, implementation of deep learning models, and result analysis. **Asim Irfan:** Supervision, methodology development, writing – original draft preparation, and correspondence. **Khushbu Magsi:** Data annotation, preprocessing, and evaluation of traditional machine learning models. **Zartasha Baloch:** Literature review, performance evaluation, editing.

Compliance with Ethical Standards

It is declare that all authors don't have any conflict of interest. It is also declare that this article does not contain any studies with human participants or animals performed by any of the authors. Furthermore, informed consent was obtained from all individual participants included in the study.

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