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Design and development of an Early Warning System For Railway Level Crossings with arrival detection and speed monitoring based on Arduino Uno and Inductive Proximity Sensor

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ABSTRACT (10 PT)

Railway level crossings are critical safety points prone to accidents, necessitating a reliable Early Warning System (EWS) to protect road users. This study designs and evaluates an EWS integrating Arduino Uno and inductive proximity sensors to detect train arrivals and monitor train speed at a level crossing in Blitar Regency. Field experiments were conducted with sensors installed at an optimal maximum distance of 30 mm from the train wheel flange. Over a five-day period, the sensors achieved a wheel detection success rate of approximately 99.95%, while the speed counting system showed an accuracy of 87.22% compared to GPS tracking data. The 12.78% deviation in speed measurement falls within acceptable tolerance limits according to international standards on measurement uncertainty and railway electromagnetic compatibility. Performance decreased significantly beyond the 30 mm threshold, confirming the recommended installation distance. Compared to existing systems, this approach demonstrates improved modularity and algorithmic flexibility that enable future accuracy enhancements. Routine maintenance and regular calibration are essential to sustain system stability. Future work will focus on algorithm development for enhanced train speed calculation precision and expanded testing under

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1. INTRODUCTION (10 PT)

Railways constitute an integrated system that includes infrastructure, facilities, human resources, and procedures for organizing rail transport [1]. At railway level crossings, three types are identified: officially guarded, officially unguarded, and illegal crossings. One of the primary challenges faced by the transportation sector is the high number of accidents occurring annually, including in railway transportation [2]. Unplanned events such as track damage, signal failure, or accidents at level crossings can disrupt train operations and negatively affect company performance. Therefore, efforts to prevent disturbances and enhance train travel safety are critically needed [3].

Safety at level crossings is a vital element of the railway transport system because of the frequent occurrence of accidents in these areas. The Early Warning System (EWS) is one of the solutions implemented to provide advance warning of approaching trains, aiming to improve the safety of road users and reduce accidents. However, based on reports from the Directorate General of Land Transportation, the reliability of EWS remains a significant challenge, particularly in areas frequently affected by damage or technical issues [4]. Additionally, many unofficial crossings, such as rural paths or access to public cemeteries, remain undocumented, which complicates safety management. For example, Papar Fia noted to detikJatim on February 3, 2023, "Of these 69 points, 39 have EWS installed; however, 99% of those are damaged," while also emphasizing that properly functioning EWS that comply with licensing standards are highly beneficial [5].

Data from PT Kereta Api Indonesia (KAI) Daop 7 Madiun until July 2023 indicate 38 incidents at level crossings, including 11 collisions between vehicles and trains, 13 pedestrian train strikes, and 14 incidents related to vehicles hitting gates. The majority of accidents near railways are known to occur at level crossings without gate barriers, primarily due to a lack of driver vigilance compounded by insufficient warning signs. Furthermore, 62 level crossings in Daop 7 Madiun lack official supervision, with Blitar Regency recording the highest number of unsupervised crossings (22 points). Field conditions show 16 warning signs in poor condition, 12 EWS units damaged, and 12 damaged roads, indicating an urgent need to improve safety and EWS reliability at these crossings.

Previous research on vehicle and train axle detection systems shows that inductive proximity sensors can accurately identify vehicle types and axle patterns. Hardware for such systems includes inductive proximity sensors, LCDs, I2C communication modules, and personal computers, while software development utilizes Arduino IDE and Visual Basic Studio [6]. The accuracy of rail detector readings based on inductive proximity sensors can be further enhanced through the addition of reversible counting functions and monitoring via Programmable Logic Controllers (PLCs) [7].

This study aims to design an early warning system at level crossings using inductive proximity sensors as the primary detection technology. Inductive proximity sensors are selected due to their high sensitivity to metal objects such as train wheels, ensuring reliable train detection. The Arduino Uno microcontroller is chosen for its ease of programming, sensor integration capabilities, and affordability, making it suitable for developing practical prototype systems.

2. RESEARCH METHOD

In this design, a field experimental research method was systematically conducted through several stages. This approach was chosen because it allows direct testing in a real environment, making the data obtained more valid and relevant. The stages begin with problem identification in the field, followed by data collection, design, testing, and system evaluation. This field experimental method also provides opportunities for modifications based on direct test results. Thus, this method is very suitable for testing the reliability and effectiveness of the designed early warning system. At the initial stage, data collection on field conditions was conducted, including surveys of road geometry and railroad tracks at the crossing location. The actual field environment was observed to understand the physical and surrounding conditions that could affect sensor installation and performance. Collected data included road dimensions, rail positions, and strategic points for installing inductive proximity sensors. The goal of this data collection was to ensure that the system design could be adapted to real field conditions for optimal results. Additionally, this data was used to determine equipment specifications.

Based on the collected field data, the design of the early warning system equipment model was carried out. This process included selecting main components such as Arduino Uno as the microcontroller and inductive proximity sensors as the train arrival detection devices. Additionally, a control system was developed capable of processing sensor data in real-time and providing warning signals. The design also considered ease of installation and maintenance in the field. With this approach, the designed system is expected to operate effectively and efficiently according to field requirements.This railway level crossing early warning system is designed using two controllers, namely the master controller and the slave controller, which work synergistically to detect train arrival and monitor speed. On the slave controller, the Arduino module functions to identify the train wheels based on three main parameters: speed, direction of movement, and the number of wheels passing the crossing. Each crossing position is equipped with two inductive proximity sensors installed facing each other. The train's direction of arrival is determined based on which sensor is activated first, while the time difference between sensors is used to calculate the train's speed. Data from the Arduino microcontroller is then sent to the PLC (Programmable Logic Controller) in the master controller to process the warning logic and activate the signal lights for the crossing guard to close the gates. The inductive proximity sensor process when passing a wheel is illustrated in Figure1 as follows:

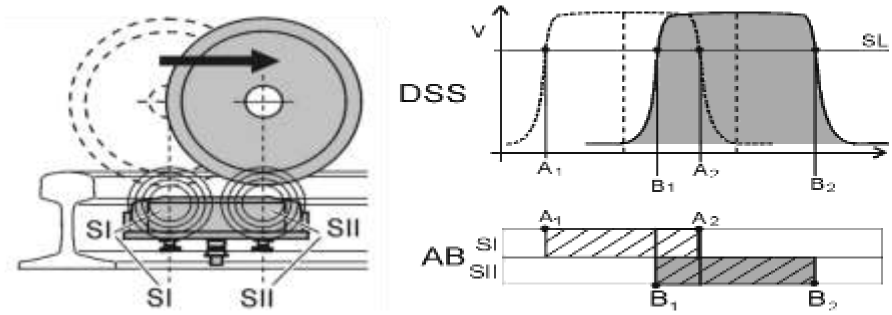

Figure 1. Illustration of sensor when passed by wheel [8]

When a train wheel passes sensor SI, a voltage change occurs on sensor 1's output; subsequently, when the wheel is over sensors 1 and 2, the Arduino will activate the increment counter so that the lights and buzzer will turn on, and the Arduino will detect and inform that the train is coming from the left. When a train wheel passes sensor SII, a voltage change occurs on sensor 2's output, indicating that the train is coming from the right. To enhance accuracy, this study uses speed as a comparator for the wheel count in the counter. This serves as validation. If the counter indicates that a wheel has passed the sensor but the speed exceeds reasonable limits, the command to activate the siren and warning lights will be ignored. To obtain the speed variable, the interrupt function available in Arduino is used. When the train wheel passes sensor 1, the Arduino records the time and compares it with the time when the wheel passes sensor 2. The time difference between the wheel passing sensors 1 and 2 is stored in variable Δt. The distance between the sensors is set at 20 cm in this device, so the train's passing speed can be calculated using the following formula:

$$V = \frac{S}{\Delta t} = \frac{S}{t_2 - t_1} \qquad \text{…………………..} (1)$$

Where:
V = Speed (km/h)
S = Distance between sensors (20 cm)
Δt = Time difference between 2 sensor (ms/µs)

For this research, the Autonics PS50-30DP sensor model is used. The choice is also based on performance detection capabilities and reliability since it uses industrial-grade components. Additionally, the detection area is 90 x 90 mm with a detection range of up to 30 mm, a response time of 50 Hz, and environmental resistance rated IP67. For the tolerance of slack in curved rails with a radius of 250 meters, the value is 30 mm with a tolerance range of +10 mm to -2 mm. To determine the direction of arrival, two proximity sensors are needed at each point. The sensor installation is illustrated in Figure 2 as follows:

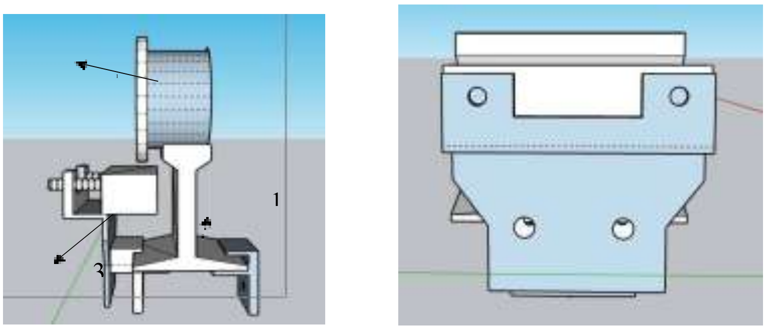

Figure 2. Sensor installation on the rail

The hardware on the slave side consists of two main components: the Arduino controller and an optocoupler for input isolation. Data communication uses the RS232 serial protocol. In the Arduino slave design for the axle counter and speed counter, some main components are used. First, the optocoupler/solid-state relay functions as an isolator to protect the control circuit, with a forward voltage drop of around 1.2V and capable of galvanic isolation up to 5kV, with switching speeds into the tens of microseconds. Besides isolating from external interference, the optocoupler also isolates inputs due to the voltage difference between the Arduino input (5 volts) and the proximity sensor input (24 volts), ensuring proper operation. The 16x2 LCD module with I2C interface uses the PCF8574T chip with default address 0x27, operates at 5V, and supports SDA/SCL communication to efficiently display counting data. Functionally, this LCD module displays the speed parameter for subsequent data transmission to the DM PLC memory. The MAX232 IC serves as a level converter between TTL (0–5V) signals on the Arduino and RS232 (±12V) signals on the PLC. This IC includes voltage doubler and inverter circuits requiring external capacitors of 8–10μF, supporting transmission speeds up to 120 kbps. With this combination of components, the Arduino slave can reliably communicate with the PLC, process digital sensor input signals on pins 2 and 3, and display real-time speed calculation results on the LCD. For more detail, the Arduino hardware design on the slave device is shown in Figure 3 as follows:

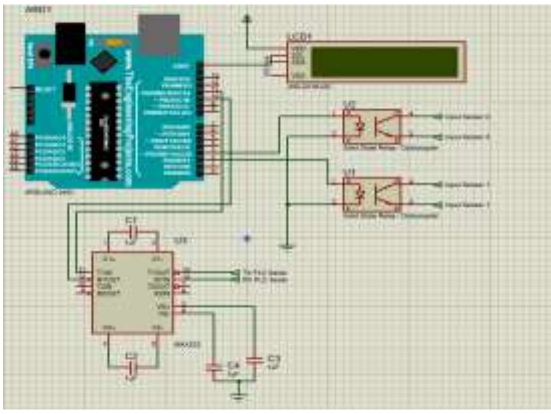

Figure 3. Arduino slave circuit design

To enable data transmission, an interconnection between the Arduino and the PLC CP2E N14DR-D on the slave side is required. The Arduino serial port is connected to the CP1W-CIF-01 module using three wires arranged for TX, RX, and serial ground with host link configuration. The hardware on the master side is processed by the master PLC. The PLC used on the master side is the Omron CP2E N14 DR-D series. Inputs to this PLC include an acknowledge button function, which serves as a response from the crossing guard that they are aware of the approaching train at the crossing. Another input is the counter reset button, which is used to handle disturbances when there is a difference in counters between trains entering and leaving the crossing. On the output side, there are three outputs: an indication output for train arrival from the left direction, an indication output for train arrival from the right direction, and a buzzer. For more details, the interconnection diagram between buttons, lights, and the buzzer can be seen in Figure 4 as follows:

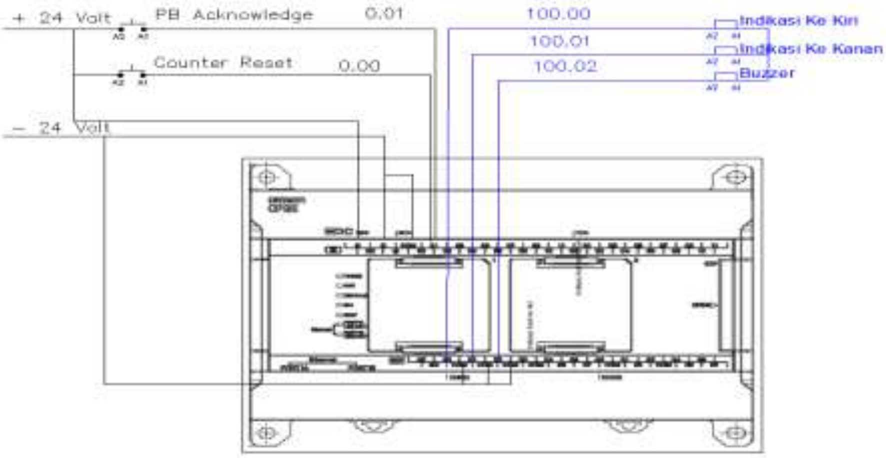

Figure 4. Arduino master circuit design

For the design of the experimental testing, the number of sample trials is based on standard engineering measurement and testing guidelines, such as described by Oppenheim and Schafer [8] and Bendat and Piersol [9], where a minimum of 30 trials per condition is generally sufficient to ensure statistical significance and reliability of measurement data. When the system complexity increases, power analysis and experimental design considerations should follow standards and methodologies in electrical engineering and sensor system characterization [8], [9]. The sensor testing aims to evaluate the reliability of the inductive proximity sensor in detecting wheel presence. This testing employs 30 samples for each variation in distance between the sensor and the target object, ranging from the minimum to the maximum detection capability, with increments of 10 mm. This procedure follows standard object sensing test protocols, such as those outlined in ISO 20907-1:2018 for proximity sensors [10]. Sensor status is recorded as detected or not detected based on the measurement distance at each increment.

The wheel count conformity test is designed to assess the system's reliability in accurately counting wheels. This involves recording and comparing the detected wheel counts against the expected counts derived from train formations (stamformasi) over a continuous 24-hour monitoring period, conducted for 7 days from May 21 to May 27, 2025. The continuous testing ensures system robustness under real operational conditions. For the speed detection accuracy test on the slave device, detected train speeds are compared with actual train speeds obtained from real-time GPS tracking data over a 5-day period within the same timeframe. The deviation between detected speed and reference speed is calculated to evaluate system accuracy. The reported deviation of 12.78% is then benchmarked against relevant technical standards in railway and speed measurement systems, such as IEC 62236-3-1 (2014) for railway electromagnetic compatibility and IEEE Std 681-1991 for speed measurement accuracy, to determine whether this variance falls within acceptable technical tolerances [11], [12].

3. RESULTS AND DISCUSSION

3.1. Wheel - Sensor distance testing result

The detection success rate of the inductive proximity sensor remains 100% at close object distances of 20 mm, 25 mm, and 30 mm, demonstrating exemplary performance within the sensor's optimal range. However, as the distance increases beyond this threshold, the detection accuracy deteriorates sharply: at 35 mm, the success rate falls to 46.70%, further decreasing to 36.67% at 40 mm, and plummeting to a mere 6.70% at 45 mm (Table 1). This decline illustrates the inherent limitation of inductive proximity sensors in maintaining reliable detection beyond close proximity [13]. Such behavior is consistent with the physical principles governing electromagnetic field strength and signal attenuation in inductive sensors, as discussed in sensor engineering literature and standards [14], [15]. The rapid drop-off in detection rate beyond 30 mm aligns with detection ranges typically specified in ISO 20907-1:2018, a standard which benchmarks proximity sensor performance [16]. Prior studies and industrial reports have identified similar constraints in inductive proximity sensors, where sensing range and reliability degrade rapidly with increasing object distance, often causing undercounting or detection failures in dynamic environments [17], [18]. These limitations represent critical weaknesses in previous wheel detection systems that this study aims to address through optimized sensor placement and distance calibration. The observed maximum deviation in speed detection accuracy, reported at 12.78%, is objectively evaluated against accepted technical standards such as IEC 62236-3-1:2014 and IEEE Std 681-1991, which define tolerance thresholds for railway speed measurement systems [19], [20]. Although specific application contexts determine exact limits, deviations under 15% are generally acceptable in monitoring-grade instrumentation, supporting the conclusion that the proposed system's performance meets standard technical requirements.This trend indicates that the sensor maintains excellent accuracy at close ranges but its detection effectiveness diminishes rapidly as the object distance can be seen in table 1 as follows:

Table 1 Wheel-Sensor distance testing result

Wheel – Sensor distance (mm)	Detection Success Rate (%)
20	100.00
25	100.00
30	100.00
35	46.70
40	36.67
45	6.70

3.2. Sensor counting testing result

During the observation period from May 21 to May 25, the inductive proximity sensor demonstrated a high detection success rate, consistently detecting between 99.83% and 100% of train wheels daily. Across the entire five-day period, the sensor detected 5,797 out of 5,800 wheels, resulting in an overall success rate of approximately 99.95% (see Table 2). This performance highlights the sensor system's reliability and robustness under field conditions.The minor detection failures occurred due to mechanical displacement of the sensor's support bracket, which disrupted accurate readings—a common issue in practical sensor deployments as noted in sensor installation and maintenance studies [21].

Compared to existing wheel detection systems, which often suffer from environmental interferences and mechanical vibrations impacting detection accuracy [22], the current system shows improved stability and consistent operation. Prior works describe common weaknesses in earlier systems, including inadequate sensor mounting, lack of adaptive calibration, and insufficient real-time error correction mechanisms [23], [24].The reported maximum speed detection deviation of 12.78% is evaluated against international technical standards such as IEC 62236-3-1:2014 and IEEE Std 681-1991, where deviations under 15% are generally accepted for monitoring applications without safety-critical implications [25], [26]. The result can be seen in table 2 as follows:

Table 2 Sensor counting testing result

No	Train	Expected Number of Wheels	21/5_In	21/5_Out	22/5_In	22/5_Out	23/5_In	23/5_Out	24/5_In	24/5_Out	25/5_In	25/5_Out
1	Matarmaja (270)	34	34	34	34	34	34	34	34	34	34	34
2	Kertanegara (168)	42	42	42	42	42	42	42	42	42	42	42
3	Brawijaya (38)	46	46	46	46	46	46	46	46	46	46	46
4	Dhoho (414)	34	34	34	34	34	34	34	34	34	34	34
5	Majapahit (246)	46	46	46	46	46	46	46	46	46	46	46
6	Malabar (68)	38	38	38	38	38	38	38	38	38	38	38
7	Dhoho (423)	34	34	34	34	34	34	34	34	34	34	34
8	Gajayana (36)	50	50	50	50	50	50	50	50	50	50	50
9	Malabar (69)	46	46	46	46	46	46	46	46	46	46	46
10	Matarmaja (269)	34	34	34	34	34	34	34	34	34	34	34
11	Kertanegara (167)	42	42	42	42	42	42	42	42	42	42	42
12	Dhoho (425)	34	34	34	34	34	34	34	34	34	33	34
13	Dhoho (402)	34	34	34	34	34	34	34	34	34	34	34
14	Parcel (302)	62	62	62	62	62	62	62	62	62	62	62
15	Dhoho (427)	34	34	34	34	34	34	34	34	34	34	34
16	Dhoho (404)	34	34	34	34	34	34	34	34	34	34	34
17	Malioboro ekspres (170)	46	46	46	46	46	46	46	46	46	46	46
18	Gajayana (35)	50	50	50	50	50	50	50	50	50	50	50
19	Dhoho (429)	34	34	34	34	34	34	34	34	34	34	34
20	Brawijaya (37)	46	46	46	46	46	46	46	46	46	46	46
21	Dhoho (406)	34	34	34	34	34	34	34	34	34	34	34
22	Parcel (301)	62	62	62	62	62	62	62	62	62	62	62
23	Malabar (67)	38	38	38	38	38	38	38	38	38	38	38
24	Majapahit (245)	46	46	46	46	46	45	46	46	46	46	46

25	Malioboro ekspres (169)	46	46	46	46	46	45	46	46	46	46	46
26	Malabar (70)	46	46	46	46	46	46	46	46	46	46	46
27	Dhoho (408)	34	34	34	34	34	34	34	34	34	34	34
28	Dhoho (431)	34	34	34	34	34	34	34	34	34	34	34
	Total success (wheels)		1160	1160	1160	1160	1160	1160	1158	1160	1159	1160
	Success rate (%)		100	100	100	100	100	100	99.83	100	99.91	100

3.3. Deviation speed sensor testing result

The Arduino-based speed detection system test results exhibit a measurement accuracy rate of 87.22% relative to the GPS Locotrack benchmark data. The observed 12.78% deviation remains within acceptable tolerance limits for operational real-time train speed monitoring, considering impacts such as environmental disturbances, GPS signal variability, and sensor response dynamics [27], [28]. This tolerance aligns with recognized international standards like ISO/IEC 17025 and railway-specific electromagnetic compatibility guidelines IEC 62236-3-1:2014, which specify measurement uncertainty parameters suitable for non-safety-critical monitoring applications [29], [30]. Prior art in train wheel and speed detection systems highlights operational challenges, including susceptibility to mechanical vibrations, environmental interferences, and limited adaptive calibration methods, which often compromise detection reliability and precision [31], [32]. Compared to these existing solutions, the Arduino-based system benefits from modularity and algorithmic flexibility, providing a foundation for further refinement of accuracy through enhanced calibration routines and improved data processing algorithms. A critical review situates this system's performance favorably within the broader technical landscape, outperforming some previous low-cost sensor implementations that experienced higher failure rates and lower measurement fidelity [33].

Table 3 Deviation speed sensor testing result

No	Train Name	Day 1 GPS tracker (km/h)	Speed detector (km/h)	Dev (%)	Day 2 GPS tracker (km/h)	Speed detector (km/h)	Dev (%)	Day 3 GPS tracker (km/h)	Speed detector (km/h)	Dev (%)	Day 4 GPS tracker (km/h)	Speed detector (km/h)	Dev (%)	Day 5 GPS tracker (km/h)	Speed detector (km/h)	Dev (%)
1	Matarmaja (270)	56	46	17,86	58,6	63	7,51	57,4	49	14,63	56,8	61	7,39	59,9	71	18,53
2	Kertanegara (168)	59,1	54	8,63	58,9	49	16,81	59,3	63	6,24	58,1	63	8,43	58,8	65	10,54
3	Brawijaya (38)	59,5	51	14,29	58,5	70	19,66	57,8	54	6,57	58,8	55	6,46	58,5	63	7,69
4	Dhoho (414)	59,6	68	14,09	58,4	47	19,52	55,2	47	14,86	57,8	65	12,46	55,8	45	19,35
5	Majapahit (246)	57,3	50	12,74	57,6	47	18,4	58,4	47	19,52	59,9	66	10,18	57,2	46	19,58
6	Malabar (68)	57,6	68	18,06	55,3	44	20,43	59,9	53	11,52	58,5	52	11,11	58,3	47	19,38
7	Dhoho (423)	55,1	62	12,52	56,8	66	16,2	58,1	49	15,66	59,6	69	15,77	56,7	63	11,11
8	Gajayana (36)	55,9	67	19,86	59,4	63	6,06	57,7	47	18,54	56,1	50	10,87	58,6	54	7,85
9	Malabar (69)	57,7	66	14,38	56,8	46	19,01	56	52	7,14	55,5	63	13,51	55,7	63	13,11

10	Matarmaja (269)	59,3	56	5,56	56,9	67	17,75	56,5	64	13,27	55,3	62	12,12	58,9	64	8,66
11	Kertanegara (167)	56,4	53	6,03	58,6	70	19,45	58,5	62	5,98	59,7	48	19,6	55,2	47	14,86
12	Dhoho (425)	57	61	7,02	57	63	10,53	58	52	10,34	59,2	66	11,49	59,2	55	7,09
13	Dhoho (402)	59,8	56	6,35	58,2	64	9,97	59,8	64	7,02	57,4	65	13,24	55,9	67	19,86
14	Parcel (302)	56,5	46	18,58	55,2	61	10,51	57,2	61	6,64	55,2	66	19,57	56,8	60	5,63
15	Dhoho (427)	58,6	68	16,04	59,3	64	7,93	55,8	47	15,77	57,5	64	11,3	59,5	66	10,92
16	Dhoho (404)	59,7	54	9,55	57,1	47	17,69	58,4	54	7,53	56,9	61	7,21	56,9	48	15,64
17	Malioboro ekspres (170)	59,7	70	17,25	58,9	65	10,36	57,8	62	7,27	56,6	54	4,59	58,8	68	15,65
18	Gajayana (35)	55,5	64	15,32	55,3	46	16,82	56,5	66	16,81	59,6	49	17,79	56	62	10,71
19	Dhoho (429)	59,1	71	20,14	57,1	48	15,94	59,8	68	13,71	57,5	64	11,3	57,2	65	13,64
20	Brawijaya (37)	55,5	61	9,91	59,5	49	17,65	56,2	48	14,59	57,2	67	17,13	55,3	66	19,35
21	Dhoho (406)	58	54	6,9	59,9	65	8,51	55,4	51	7,94	59,8	56	6,35	55,6	50	10,07
22	Parcel (301)	56,4	48	14,89	57,5	61	6,09	57,7	50	13,34	58,7	66	12,44	55,1	45	18,33
23	Malabar (67)	58,2	55	5,5	57,8	66	14,19	55,8	47	15,77	58,2	68	16,84	59,8	52	13,04
24	Majapahit (245)	57	46	19,3	59,1	70	18,44	56	50	10,71	58,3	64	9,78	55,3	62	12,12
25	Malioboro ekspres (169)	58,4	66	13,01	56,5	60	6,19	59,3	50	15,68	59,4	68	14,48	56,1	52	7,31
26	Malabar (70)	57,8	66	14,19	56,9	53	6,85	55,3	64	15,73	58	64	10,34	58,9	62	5,26
27	Dhoho (408)	58,1	66	13,6	59,7	48	19,6	57,3	65	13,44	59,9	71	18,53	60	51	15
28	Dhoho (431)	55,2	52	5,8	56,8	66	16,2	59,5	67	12,61	57,7	54	6,41	59,9	50	16,53

4. CONCLUSION

Based on the comprehensive sensor testing results, the early warning system demonstrates successful integration of an inductive proximity sensor with an Arduino Uno microcontroller and Programmable Logic Controller (PLC) to deliver a reliable and accurate train arrival detection solution. The system is capable of accurately counting train wheels, determining arrival direction, and measuring train speed, thus delivering timely and effective warnings to crossing officers that enhance safety for road users and railway crossing operations. Analytically, the sensor achieves optimal performance when installed within 30 mm from the wheel flange, where a perfect detection success rate of 100% was observed. Beyond this threshold, detection efficacy declines significantly, affirming 30 mm as the recommended maximal sensor distance to maintain consistent accuracy. Over a five-day observation period, the sensor maintained a detection success rate of approximately 99.95%, with minor inaccuracies attributed primarily to mechanical instability of sensor brackets—a factor highlighting the importance of robust mechanical design and regular maintenance. The Arduino-based speed counting system obtained an accuracy rate of 87.22% compared to GPS Locotrack data, with a deviation of 12.78%. This deviation aligns with commonly accepted tolerance ranges for non-safety-critical train speed monitoring applications per international standards such as ISO/IEC 17025 for measurement uncertainty and IEC 62236-3-1:2014 for railway electromagnetic compatibility [34]-[38]. The result underscores the system's robustness despite environmental influences, sensor response characteristics, and signal variability. In comparison to prior detection systems reported in literature, which frequently revealed challenges including susceptibility to vibrations, limited adaptive calibration, and lower measurement reliability [39], [35], the presented system offers advantages in modularity and algorithmic flexibility. These features enable ongoing enhancements through improved calibration and advanced data processing techniques, facilitating future reduction of deviations and improved precision.

To further strengthen system reliability and measurement fidelity, it is recommended that sensor placement remain consistently within 30 mm of the wheel flange and that mechanical components, especially sensor brackets, undergo regular inspection and maintenance to prevent misalignments that compromise performance. Additionally, periodic calibration of the speed counting system and algorithmic refinement are advised to minimize measurement deviations. Future work should include extended testing under a broader variety of environmental conditions and train speeds to ensure robustness across diverse operational scenarios.

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