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Performance Evaluation of a LiDAR-Integrated IoT System for Real-Time Vehicle Speed Enforcement

Raka Pratindy[1], Muhammad Azmi Wibowo[1], Dita Setyabudi[1,a)]

[1]*Automotive Engineering Technology, Polytechnic of Road Transportation Safety, Tegal, Indonesia*

E-mail: [a)] ditaesbud262@gmail.com

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Abstract: Traffic accidents in Indonesia are caused by several factors, including human, vehicle, and environmental factors. One of the primary causes of traffic accidents is human error resulting from driving at high speeds. This study presents the design and testing of an Internet of Things (IoT)-based vehicle speed detection system designed for use on toll roads. The developed system prototype integrates a TF-Mini LiDAR distance sensor, a GPS module, and a Raspberry Pi single-board computer. The system can measure vehicle speed in real time and capture images of vehicles that exceed the set speed limit. Test results indicate that the LiDAR sensor accurately measures vehicle distances up to 10 meters with an error rate of approximately 3%. Furthermore, the system reliably detects and reports vehicles traveling over the highway speed limit of 100 km/h. The IoT architecture enables remote monitoring via a web-based interface. The results of this study indicate that the developed system has the potential to serve as an affordable and integrated vehicle speed monitoring device. Future research will focus on a more in-depth calibration process, field implementation, and the development of automated warning features to notify authorities when speed limit violations occur.

Keywords: accident, high speed, highway, speed detection, TF-Mini LiDAR.

Abstrak: *Kecelakaan lalu lintas di Indonesia disebabkan oleh beberapa faktor, termasuk faktor manusia, faktor kendaraan, dan faktor lingkungan. Salah satu penyebab utama kecelakaan lalu lintas adalah kesalahan manusia yang disebabkan oleh berkendara dengan kecepatan tinggi. Penelitian ini memaparkan desain dan pengujian sistem pendeteksi kecepatan kendaraan berbasis Internet of Things (IoT) yang dirancang untuk digunakan di jalan tol. Prototipe sistem yang dikembangkan mengintegrasikan sensor jarak TF-Mini LiDAR, modul GPS, dan mikrokontroler Raspberry Pi. Sistem ini dapat mengukur kecepatan kendaraan secara real-time dan menangkap gambar kendaraan yang melebihi batas kecepatan yang ditetapkan. Hasil pengujian menunjukkan bahwa sensor LiDAR secara akurat mengukur jarak kendaraan hingga 10 meter dengan tingkat kesalahan sekitar 3%. Selain itu, sistem ini secara andal mendeteksi dan melaporkan kendaraan yang melaju melebihi batas kecepatan jalan tol sebesar 100 km/jam. Arsitektur IoT yang digunakan memungkinkan pemantauan jarak jauh melalui antarmuka berbasis web. Hasil penelitian ini menunjukkan bahwa sistem yang dikembangkan berpotensi berfungsi sebagai perangkat pemantauan kecepatan kendaraan yang terjangkau dan terintegrasi. Penelitian selanjutnya akan berfokus pada proses kalibrasi yang lebih mendalam, implementasi lapangan, serta pengembangan fitur peringatan otomatis untuk memberitahukan pihak berwenang ketika terjadi pelanggaran batas kecepatan.*

Kata kunci: *kecelakaan, kecepatan tinggi, jalan tol, deteksi kecepatan, TF-Mini LiDAR.*

INTRODUCTION

Road traffic accidents remain a major public health problem worldwide. According to data from the Indonesian National Police Traffic Corps (Korlantas Polri), the number of national traffic accidents in 2025 reached 141,608 incidents. Although this figure represents a 6.16 percent decrease compared to the previous year (which recorded 150,096 incidents), road safety remains a paramount concern. Among the various contributing factors, excessive vehicle speed is widely recognized as a critical variable affecting road safety, directly influencing both crash occurrence and injury severity [1]–[3].

Despite established speed limits, motor vehicle drivers frequently exceed designated speed thresholds. For instance, a notable traffic accident occurred on the Astra Toll Road Jombang–Mojokerto on November 4, 2021, at 12:30 PM WIB. Investigations revealed that the vehicle was traveling at a high speed of 130 km/h, significantly exceeding the maximum allowable speed limit of 100 km/h [4].

In Indonesia, Law Number 22 of 2009 on Traffic and Road Transportation (LLAJ) mandates that all two-wheeled and four-wheeled vehicle operators adhere to established minimum and maximum speed limits. Furthermore, Regulation of the Minister of Transportation (PM) No. 111 of 2015 specifies procedures for setting speed limits: a minimum speed of 60 km/h under free-flowing toll road conditions, and maximum speeds of 100 km/h for toll roads, 80 km/h for intercity roads, 50 km/h for urban areas, and 30 km/h for residential areas.

To support real-time vehicle speed monitoring and enhance enforcement, Internet of Things (IoT) technology has been increasingly adopted [5]–[7]. Through IoT architectures, speed data can be continuously collected and transmitted, enabling rapid detection of traffic violations [6], [8]. Previous studies, such as those by Khan et al., demonstrated that IoT-based approaches significantly improve speed monitoring efficiency [5]. Moreover, IoT-driven intelligent traffic management systems enhance road safety and traffic flow by integrating multi-source data from sensors, cameras, and GPS units [8], [9]. Implementing IoT within smart city frameworks has also been shown to optimize data processing, reduce congestion, and lower accident risks [8], [10].

Although IoT-based traffic monitoring has been thoroughly studied in the past, many current systems rely on microwave-based sensors, like the HB100, which frequently have issues with reliability at different detection angles and are susceptible to electromagnetic interference. By incorporating a TF-Mini LiDAR sensor based on the Time-of-Flight (ToF) principle into a thorough and integrated IoT architecture, our work fills these research gaps [11], [12]. This method is novel because it can provide real-time synchronization of speed data, GPS coordinates, and photographic evidence to a web-based dashboard for automated traffic enforcement, while maintaining better measurement consistency across various operational angles than traditional Doppler-based sensors. Therefore, for high-speed vehicle monitoring on toll roads, this integrated solution provides a more reliable, accurate, and cost-effective option [12].

This study focuses on designing and developing a vehicle speed detection system using Internet of Things (IoT) technology. A TF-Mini LiDAR sensor is utilized to improve the accuracy of speed measurement. To obtain more reliable results, several adjustments are made to the overall system design [13]. Furthermore, the display unit is improved to ensure that the information remains clear and readable under different lighting and weather conditions. In addition, a camera is integrated into the system to capture images that can be used as supporting evidence. Moreover, the web-based monitoring platform is further developed into a more integrated information system to support the implementation of IoT in vehicle speed monitoring more effectively [14]. Ultimately, in order to increase measurement accuracy and consistency under a range of operating situations, this research attempts to create and assess the performance of an Internet of Things-based vehicle speed monitoring system employing LiDAR sensors.

METHODS

This study adopts a Research and Development (R&D) approach, specifically utilizing the Sugiyono development model, to design, develop, and evaluate an Internet of Things (IoT)-based vehicle speed monitoring system. The methodical process encompasses identifying potential problems, data collection, product design, expert validation, design revision, and operational testing. Through this framework, the prototype is systematically engineered to overcome the accuracy and reliability limitations of earlier speed detection methods [6], [11].

Hardware Design

The central processing unit of the system is a Raspberry Pi 3 Model B+. The prototype incorporates a TF-Mini LiDAR sensor, which operates based on the Time-of-Flight (ToF) principle to determine distance by measuring the phase difference of infrared light pulses, resulting in high measurement accuracy. This sensor was selected due to its superior stability and accuracy compared to microwave-based sensors commonly used in traditional traffic monitoring [11], [15].

Additional components include a Logitech C270 webcam for evidentiary image capture, an OLED 128×64 display for local data visualization, a GPS Neo-8M module for spatial coordinate tracking, and an active buzzer for immediate audio notifications. The physical hardware arrangement and component layout of the developed prototype are shown in Figure 1.

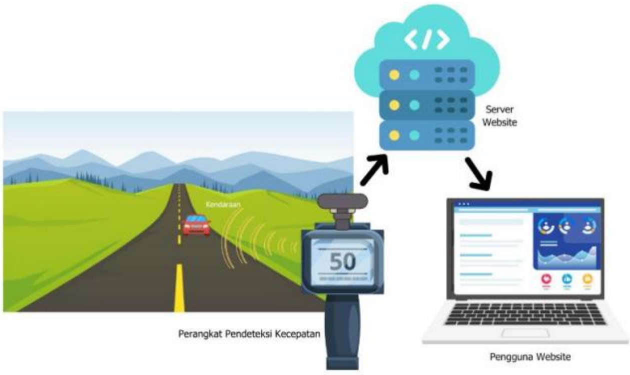

Figure 1. Placement of equipment

Figure 1 illustrates the spatial placement and physical arrangement of each hardware component within the enclosure. Meanwhile, the overall system architecture and functional integration among all modules are depicted in Figure 2.

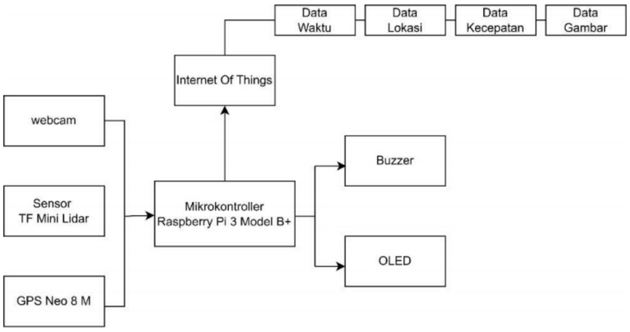

Figure 2. Block diagram

As shown in Figure 2, all hardware modules are interconnected to form a complete vehicle speed monitoring system. The TF-Mini LiDAR sensor functions as the primary measurement input, the Raspberry Pi executes real-time data processing and speed calculation algorithms, and the peripheral output devices manage display visualization, GPS tagging, and audio notifications.

Software Integration and Monitoring Platform

Python 3.12 was used to develop the core system logic for sensor data acquisition and signal processing. Circuit design and connectivity were simulated and documented using Fritzing software. An Internet of Things (IoT) architecture was implemented to enable remote monitoring and real-time data synchronization between the edge hardware and a web-based dashboard via an Application Programming Interface (API) [5], [16]. The system transmits real-time vehicle speed measurements, violation alerts, timestamps, GPS location data, and captured image files to the cloud server. The web-based monitoring interface is presented in Figure 3.

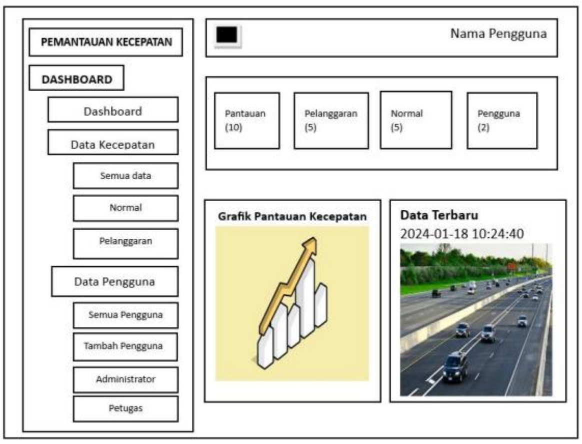

Figure 3. Diagram page display

As shown in Figure 3, the dashboard provides a clear visualization interface, allowing traffic operators to monitor vehicle speeds and log speed violations effectively.

Speed Measurement Algorithm

Vehicle velocity (V) is determined by calculating the spatial displacement between two consecutive distance readings (S_1 and S_2) over a fixed sampling interval (t) of 10 milliseconds (0.01 s). The system processes these inputs using the following formula:

$$V = \frac{S_1 - S_2}{0.01} \tag{1}$$

where V represents the vehicle speed in meters per second (m/s), S_1 and S_2 denote the initial and second distance measurements in meters (m), respectively, and 0.01 signifies the fixed sampling interval in seconds (s).

The calculated speed in m/s is subsequently converted to kilometers per hour (km/h). If the detected speed exceeds the statutory speed limit of 100 km/h for Indonesian toll roads [4], the system immediately triggers the webcam to capture a JPEG snapshot, activates the warning buzzer, and transmits the violation record to the server.

Testing and Calibration Procedures

Field testing was conducted at the Polytechnic of Road Transportation Safety campus to evaluate system performance across diverse operational scenarios [17]. The evaluation framework comprises three main stages, including distance accuracy testing, comparative angle analysis, and environmental stability testing. The distance accuracy test evaluates the LiDAR sensor's measurement precision across target distances up to 13 meters. Furthermore, comparative analysis assesses speed detection consistency at various installation angles ($15°$, $30°$, and $45°$) in comparison with conventional radar speed guns and previous HB100 sensor-based implementations. Finally, environmental testing examines sensor performance and operational stability under varying ambient light conditions, specifically morning, afternoon, and nighttime scenarios.

RESULTS AND DISCUSSION

The evaluation and findings of the developed IoT-based vehicle speed detection system are presented in this section. The prototype, which combines a TF-Mini LiDAR sensor, a GPS module, and a Raspberry Pi, was evaluated for performance through distance accuracy testing, comparative analysis with other sensors, and environmental stability testing under various lighting conditions [6], [18]. The distance measurement test results are presented in Table 1.

Table 1. Distance measurement test results

Target Distance (m)	Measured Distance (m)	Error Rate	Accuracy (%)
1	1.00	0.00000	100.0%
2	2.00	0.00000	100.0%
3	3.00	0.00000	100.0%
4	4.00	0.00000	100.0%
5	5.01	0.00200	99.8%
6	5.99	0.00167	99.8%
7	7.02	0.00286	99.7%
8	8.03	0.00375	99.6%
9	9.03	0.00333	99.7%
10	10.01	0.00100	99.9%
11	11.02	0.00182	99.8%
12	11.98	0.00167	99.8%
13	12.98	0.00154	99.8%
14	655.20	45.80000	54.2%

The TF-Mini LiDAR sensor's exceptional accuracy in measuring distances between 1 and 13 meters is demonstrated in Table 1. The test results show that the sensor maintains a high degree of precision with low error rates, featuring accuracy values that reflect very minor variations, such as 99.8% at 5 meters and 99.8% at 13 meters. These figures demonstrate measurements that are extremely close to the reference distance under controlled testing conditions. High accuracy values near 100% are attributed to minimal variance in significant figures and appropriate environmental calibration.

Technically, the sensor maintains a slight overall systematic error margin (around 3% in general operation) influenced by factors such as surface reflectivity. The effective operational limit of the sensor is clearly defined at a distance of 14 meters, where it produces an invalid reading of 655.2 meters. Although the calculated nominal accuracy for this point appears as 54.2%, this extreme divergence indicates that the ToF processing unit cannot produce a valid output beyond 13 meters due to signal saturation or data overflow.

Comparison of Device Testing

Comparative testing was conducted among three devices: a commercial radar speed gun, the earlier system utilizing an HB100 sensor, and the proposed system featuring the TF-Mini LiDAR sensor. The purpose of this experiment was to evaluate measurement accuracy across different operational angles. At an average vehicle speed of 40 km/h, testing was performed from three detection angles: 15°, 30°, and 45°. The comparative results are summarized in Table 2.

Table 2. Angle test results

Angle	Speedgun Accuracy (%)	HB100 Accuracy (%)	LiDAR Accuracy (%)
15°	92.1%	87.1%	91.1%
30°	91.0%	82.5%	89.5%
45°	88.8%	80.5%	86.8%

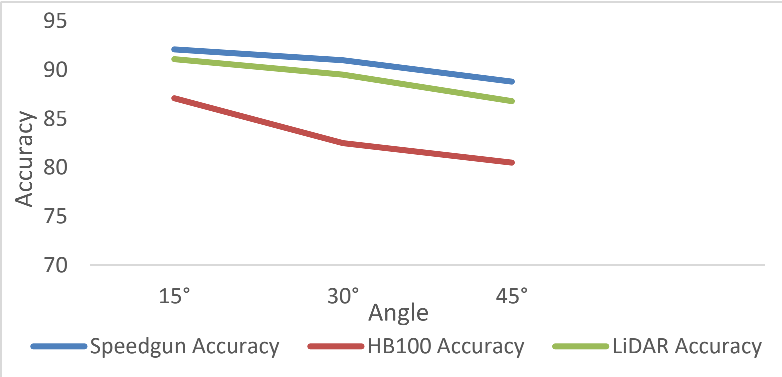

Figure 4. Sensor accuracy vs. detection angle

As the detection angle increases from 15° to 45°, Table 2 indicates that measurement accuracy decreases across all devices. This phenomenon is directly linked to measurement geometry, where an increased angle introduces a larger cosine error relative to the vehicle's true motion vector. Additionally, as the detection angle widens, the effective reflective area of the vehicle surface varies, which may attenuate the intensity of infrared pulses returned to the sensor. Line-of-sight distortion further affects the accuracy of the Time-of-Flight calculation, where signals may experience multi-path reflections or time-smearing. Nevertheless, because its focused laser beam is less vulnerable to complex Doppler shift variations, which commonly afflict microwave-based systems at non-perpendicular angles, the LiDAR sensor maintains superior stability compared to the HB100 sensor at higher angles [19].

Equipment Testing Under Environmental Conditions

Equipment testing was performed to evaluate the operational performance and functionality of each hardware component, including the TF-Mini LiDAR sensor, OLED display, webcam, GPS module, and buzzer. Specifically, trials were conducted under three distinct ambient lighting conditions, namely morning, afternoon, and night, to evaluate environmental stability. The test results are presented in Table 3.

Table 3. Test results across morning, afternoon, and night conditions

Condition	Average Device Speed (km/h)	Accuracy (%)	Error (%)
Morning	34.4	86.1%	13.9%
Afternoon	35.8	89.5%	10.5%
Night	36.8	92.0%	8.0%

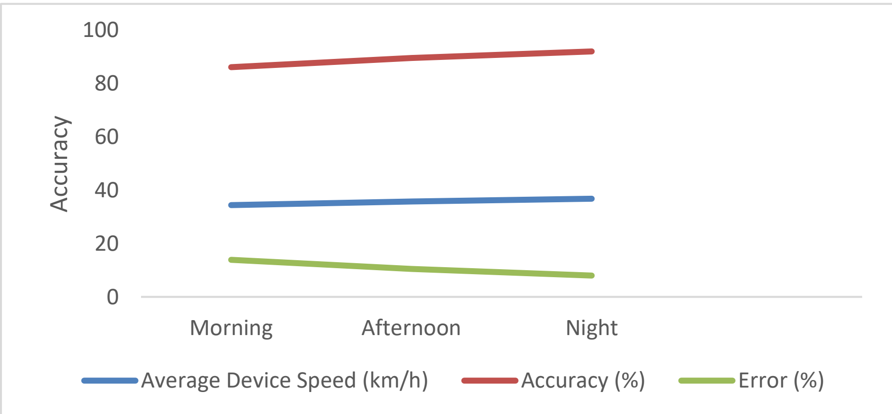

Figure 5. Average sensor test accuracy

As shown in Table 3 and Figure 5, external illumination conditions noticeably influence system performance. The morning measurements yielded the lowest average accuracy (86.1%), which is primarily attributed to strong direct sunlight interfering with the LiDAR sensor's optical signal reflection and reception process.

Performance improved in the afternoon, reaching an average accuracy of 89.5%. This enhancement is likely due to more balanced lighting conditions, which reduce optical noise and improve measurement consistency.

Nighttime testing produced the highest accuracy at 92.0%, as minimal ambient light interference allows the LiDAR optical receiver to function under optimal signal-to-noise ratios. Overall, these findings highlight the impact of environmental lighting on optical LiDAR systems, indicating that while the proposed system operates reliably across diverse lighting conditions, its performance is optimal in low ambient light.

CONCLUSIONS

As an integrated traffic enforcement tool for toll roads, the creation of an IoT-based vehicle speed detection system using a Raspberry Pi 3 Model B+ and TF-Mini LiDAR sensor has shown considerable promise. A GPS module for location tracking, a webcam for photographic evidence, and an OLED display for real-time visualization are integrated into the physical hardware. This design enables effective remote traffic management by facilitating the smooth transfer of data from sensor input to a web-based monitoring interface.

The system provides highly accurate distance measurement within the 1 to 13 meter range, which represents the optimal operational boundary for the prototype based on experimental results. Additionally, a comparative analysis reveals that the TF-Mini LiDAR sensor outperforms the microwave-based HB100 sensor utilized in earlier research in terms of stability and accuracy at different detection angles (15°, 30°, and 45°). The Time-of-Flight (ToF) principle, which is less vulnerable to electromagnetic interference and angular movement than Doppler-based microwave systems, is credited for this advancement.

Environmental testing demonstrated that the reliability of the system is significantly influenced by external lighting conditions. Because ambient light caused fewer interferences with the infrared signal reflection process at night, the prototype achieved its peak accuracy of 92.0%. Conversely, morning testing yielded the lowest accuracy (86.1%), as intense sunlight and high illumination levels hampered the sensor's detection capabilities. These findings indicate that the system performs best under low ambient light conditions.

Vehicles violating the 100 km/h toll road speed restriction are reliably detected through the integration of the core system logic. When a violation is identified, the system automatically sounds an audible alert, captures a JPEG image of the vehicle, and transmits real-time data to the server, including the recorded speed, timestamp, and GPS coordinates. Ultimately, this research offers a reliable and cost-effective IoT solution for automated traffic monitoring, providing law enforcement agencies with more accurate and comprehensive data compared to previous prototypes.

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