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An Adaptive Automatic Braking System for Enhanced Road Safety

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Abstract – *In the pursuit of enhancing vehicle safety and mitigating accidents caused by human factors, this study aims to develop an automatic braking system for electric vehicles that determines braking deceleration based on vehicle speed and distance, and is further integrated with a drowsiness detection system. This fuzzy logic-based system was designed to improve driving safety by reducing reliance on driver attention. It integrates a LiDAR sensor for distance, a magnetic speed sensor for speed, and an ESP32 microcontroller as the main control. The system's primary advantage lies in its ability to adaptively and quickly process various parameters using fuzzy logic rules to manage deceleration. Communication between modules is efficiently facilitated by the CANBUS protocol, ensuring fast and accurate data exchange. Experimental validation demonstrates the high accuracy of the LiDAR sensor, exhibiting an average error of less than 1%. The speed sensor shows a consistent relationship between inverter frequency and car speed, with the overall deceleration system performing well despite an average error of 7.1%. Furthermore, the implemented fuzzy system successfully replicates MATLAB output with minimal errors and achieves a more stable Duty Cycle setting compared to non-fuzzy control. These results collectively confirm the system's reliable, adaptive, and responsive performance across a wide range of operational conditions, significantly contributing to mitigating traffic accidents caused by human error.*

Keywords – *Automatic Braking; Fuzzy Logic; Adaptive Deceleration; LiDAR Sensor; Magnetic Speed Sensor.*

I. Introduction

BRAKING is a critical aspect of vehicle safety systems, especially in emergency situations or when the driver loses concentration. Conventional braking systems rely entirely on human response, which is often unreliable in very short periods of time, for example when the driver is drowsy or a sudden object occurs in front of the vehicle. One solution that continues to be developed to improve vehicle safety is a fuzzy logic-based automatic braking system [1].

In recent years, vehicle braking systems have seen rapid advancements, including electronic ABS [2], brake-by-wire technology [3], and pneumatic systems for heavy vehicles [4]. Despite these innovations and the development of proximity sensor-based automatic braking systems aimed at reducing accidents [5], a critical research gap remains: the widespread implementation and optimization of automatic braking systems that specifically leverage LiDAR sensor technology to significantly reduce reliance on human attention [6]. Recent advancements in vehicle braking systems have focused on integrating LiDAR technology to enhance safety and autonomy. LiDAR-based systems have demonstrated high accuracy in obstacle detection and distance measurement [7], enabling effective collision avoidance [8]. These systems can control brake fluid pressure, reducing vehicle jerking and improving stopping distances [9]. Combining LiDAR with other technologies like ABS and pneumatic bumpers further enhances vehicle safety [10]. Automatic braking systems utilizing sensors and actuators have shown promise in preventing accidents [?, 11, 12]. However, challenges remain, including high costs and performance in adverse weather conditions [13]. The integration of LiDAR in autonomous vehicles contributes to advanced functionalities such as emergency braking and adaptive cruise control [13, 14].

This research aims to bridge this gap by developing an automatic braking system for electric vehicles that determines braking deceleration based on vehicle speed and distance, and is further integrated with a drowsiness detection system. This integrated approach enhances driving safety by minimizing the impact of human factors like delayed reaction, inattention, and fatigue, which are major contributors to traffic accidents

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amidst increasing vehicle ownership and global traffic congestion. Recent research has focused on developing automatic braking systems for electric vehicles to enhance safety and reduce accidents. These systems integrate drowsiness detection [15–17] with obstacle detection using sensors like ultrasonic and cameras [18, 19]. Advanced algorithms, including neural networks and fuzzy logic, process sensor data to determine appropriate braking actions [15, 20]. Some systems incorporate dynamic braking based on Time to Collision calculations [21] and contactless brake blending for improved performance and environmental benefits [22]. These integrated approaches aim to minimize human factors like delayed reactions and fatigue, which are major contributors to traffic accidents. Prototype testing and simulations have shown promising results in enhancing vehicle safety and reducing collision risks [15, 20].

Automatic braking systems with a fuzzy logic approach have the advantage of being able to process data from various parameters such as vehicle speed and distance to objects with adaptive and fast decisions. This system utilizes fuzzy logic rules to determine the deceleration speed based on the real conditions of the vehicle. Several studies have shown the success of this method in avoiding collisions and providing smooth and appropriate deceleration on the road [23]. In previous research, an automatic braking system has been successfully designed using fuzzy control to detect distance and speed, with results showing that the system is able to stop within a safe distance even at high speeds [24].

The use of the CAN bus communication protocol in these systems is essential to ensure fast, stable, and accurate data exchange between devices in the vehicle. CAN bus is an industrial communication standard widely used in automotive systems due to its reliability in organizing data transmission in environments full of electromagnetic interference. Various studies have adopted the CAN bus standard, for example for temperature and humidity monitoring systems using a network of multiple sensors communicating with each other via the CAN protocol [25].

However, most of the research still focuses on software simulation or simple prototype scale. There is still a need to develop a more integrated system between speed sensors, distance sensors, and system communication to detect driver conditions such as drowsiness or loss of control.

Therefore, this research aims to develop a comprehensive fuzzy logic-based automatic braking system that not only precisely controls vehicle deceleration based on real-time speed and distance data but also communicates seamlessly with other modules through the CANBUS protocol. The system is designed using an ESP32 as the main microcontroller and integrates a TF Mini LiDAR sensor for distance measurement and a magnetic speed sensor for speed. Through this approach, the system is expected to provide an adaptive, safe, and efficient braking solution for modern vehicles, thereby enhancing overall driving safety and reducing accident risks by minimizing human error. The system also provides advantages in terms of user convenience by informing vehicle conditions in real-time through a digital data interface. By combining fuzzy logic, advanced sensors, CAN bus-based inter-module communication, and precise AC motor speed regulation, this system represents a significant step towards smarter vehicles that are responsive to road emergencies.

II. Research Methods

This section details the methodology employed to develop the adaptive automatic braking system. The research approach was systematically divided into three primary phases: electronic system design, control and communication system design, and finally, system implementation and comprehensive testing on a converted vehicle. This section elaborates on the specific tools and materials utilized, along with the step-by-step procedures followed in each phase of the research.

i. Electronic System Design

The design of the electronic system begins with selecting the components necessary to support its control performance:

1. **ESP32** serves as the main controller, chosen for its 32-bit dual-core processor operating at a maximum frequency of 240 MHz [26]. Additionally, the ESP32 supports CANBUS communication and boasts 520 KiB of RAM along with up to 16 MiB of flash memory, making it superior to comparable microcontrollers in its price range [27].
2. **TF Mini-S LiDAR sensor** is employed due to its effective detection range of 0.1–12 meters [28].
3. **Magnetic speed sensor** is utilized to determine wheel rotation speed, with its data processed manually [29].
4. **SN65HVD230D** module is integrated to enable CANBUS communication with external systems such as the drowsiness detection module.
5. **Electric gas throttle** sends an analog signal to the controller, which is then translated into motor movement [30].
6. **ATV12HU15M2 inverter** drives the 3-phase motor and is selected for its capability to control motors up to 1.5 kW (2 hp) with a 200–240V single-phase supply [31].

7. **LC-LM358-PWM2V converter** is used to transform PWM signals from the microcontroller into the required voltage for the inverter.

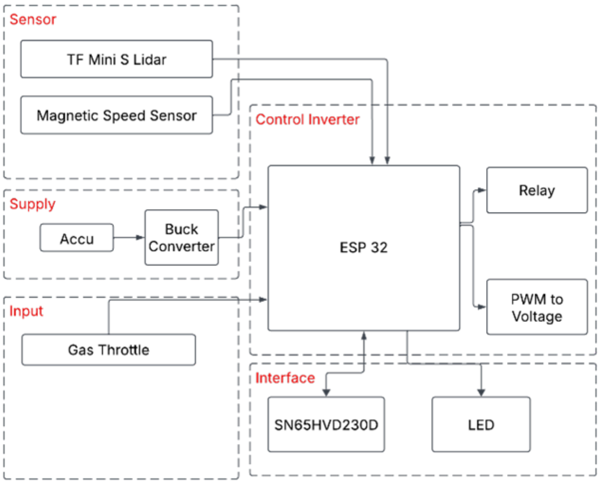


Figure 1: Electronic Schematic Planning

The schematic in Figure 1 shows the overall circuit designed for the Automatic Braking System prototype. Key components include the relay (for starting/stopping the inverter), IO connectors (for sensor and actuator connections), and a CAN bus interface. Power is supplied via a 12V DC jack, stepped down to 5V using a buck converter to power the system and IO.

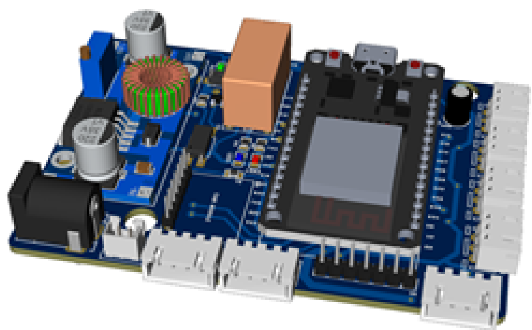


Figure 2: PCB Creation

As shown in Figure 2, the double-layer PCB measures 87.5 mm $\times$ 62 mm, with 1.5 mm path width for power lines and 0.8 mm for data lines. Vias (1.7 mm outer, 0.8 mm hole) connect top and bottom layers. The I/O connectors use JST XH 2.45 right-angle types for neat cable routing.

ii. Designing a Control System

The control system integrates several stages, beginning with sensor data acquisition and ending with actuator control:

1. The 3-phase motor is driven through an inverter, controlled by input frequency (0–50 Hz).
2. The gas pedal signal is captured via the ADC pin of the microcontroller [32], filtered using an Exponential Moving Average (EMA) filter [33], and converted via a PWM-to-voltage module.
3. Start/stop operations are handled via a relay in a 2-wire configuration.
4. Fuzzy Logic-based braking control uses input from the LiDAR, magnetic speed sensor, and drowsiness detection system to manage deceleration (up to 2 Hz).
5. The system sends data (speed, pedal position, RPM) over CANBUS, which can be shown on the odometer.

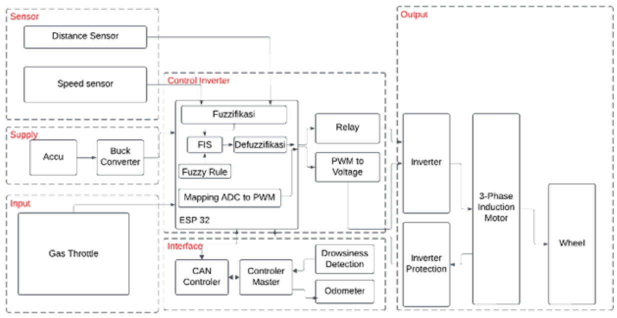


Figure 3: System Block Diagram

Figure 3 illustrates the high-level system block diagram showing component interactions in the automatic braking mechanism.

In Figure 4, the flowchart presents the control flow: sensor data undergoes range classification, followed by a braking decision (either by the driver or system). The fuzzy logic module then generates a PWM signal that is converted to voltage and sent to the inverter, driving the 3-phase motor.

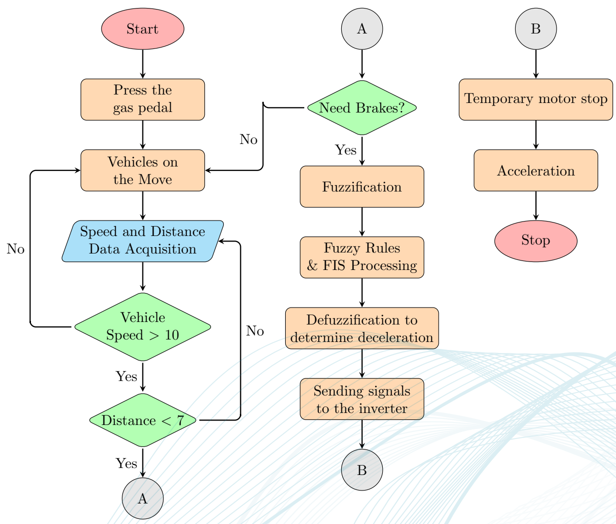


Figure 4: System Flowchart

iii. Fuzzy Logic Control System

In this research, the control system used is Mamdani fuzzy logic, where each input has its own membership function used as a comparison reference to determine the output. The output is then used to determine the deceleration rate. The membership function transforms crisp inputs into fuzzy membership degrees [34]. The system utilizes three variables:

1. **Distance**: Measures the distance between the vehicle and the object ahead, obtained using a TF Mini-S LiDAR sensor.
2. **Speed**: Measures vehicle speed, obtained from a magnetic speed sensor.
3. **Deceleration**: Represents the braking or deceleration value to stop the motor.

iv. Distance Membership Function

The *Distance* input variable has three trapezoidal membership functions: **Close**, **Medium**, and **Far**. The details are:

1. **Close**: Value is 1 from 0.2 to 1.5 meters, then linearly decreases to 0 at 2.5 meters.
2. **Medium**: Starts increasing from 1.5 meters, peaks at 2.5–4 meters, then decreases to 0 at 5.5 meters.
3. **Far**: Starts increasing from 4 meters, peaks at 5.5–7 meters, and remains 1 beyond 7 meters.

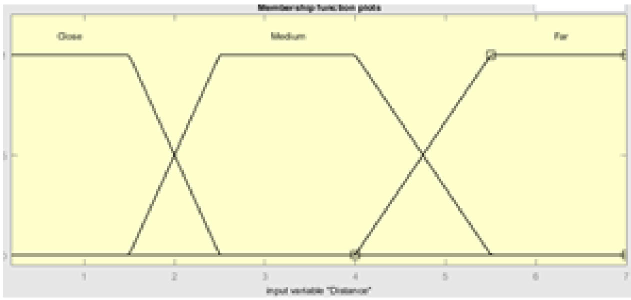


Figure 5: Distance Membership Function

v. Speed Membership Function

The *Speed* input also uses three trapezoidal membership functions: **Slow**, **Medium**, and **Fast**.

1. **Slow**: Value is 1 between 10 and 30 km/h, then linearly drops to 0 at 40 km/h.
2. **Medium**: Rises from 30 km/h, peaks at 40–50 km/h, then drops to 0 at 60 km/h.
3. **Fast**: Rises from 50 km/h, peaks at 60–70 km/h, and remains 1 beyond 70 km/h.

vi. Deceleration Membership Function

The *Deceleration* output variable also uses three trapezoidal membership functions: **Fast**, **Medium**, and **Slow**.

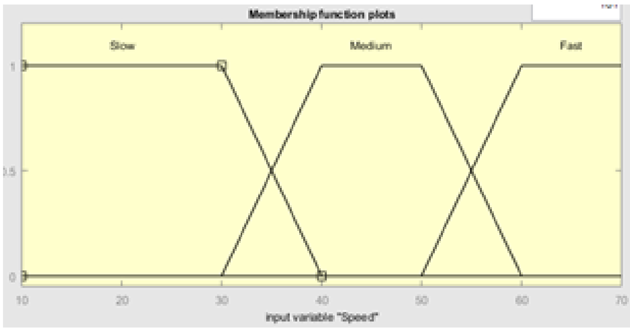


Figure 6: Speed Membership Function

1. **Fast**: Value is 1 from 10 to 30 ms, then decreases linearly to 0 at 50 ms.
2. **Medium**: Rises from 20 ms, peaks at 40–70 ms, then drops to 0 at 90 ms.
3. **Slow**: Rises from 70 ms, peaks at 85–100 ms, and remains 1 beyond 100 ms.

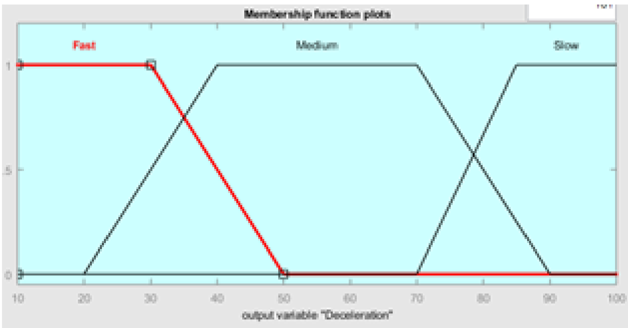


Figure 7: Deceleration Membership Function

vii. Fuzzy Rules

The fuzzy rules are applied to determine the fuzzy output value from the fuzzy input. These rules form the basis of inference in the system. The following rules were used in this study:

1. IF Distance is **Close** AND Speed is **Slow** THEN Deceleration is **Medium**
2. IF Distance is **Close** AND Speed is **Medium** THEN Deceleration is **Fast**
3. IF Distance is **Close** AND Speed is **Fast** THEN Deceleration is **Fast**
4. IF Distance is **Medium** AND Speed is **Slow** THEN Deceleration is **Slow**
5. IF Distance is **Medium** AND Speed is **Medium** THEN Deceleration is **Medium**
6. IF Distance is **Medium** AND Speed is **Fast** THEN Deceleration is **Fast**
7. IF Distance is **Far** AND Speed is **Slow** THEN Deceleration is **Slow**
8. IF Distance is **Far** AND Speed is **Medium** THEN Deceleration is **Slow**

9. IF Distance is **Far** AND Speed is **Fast** THEN Deceleration is **Medium**

These rules reflect the adaptive nature of the braking system. For instance, when the vehicle is too close to an obstacle and moving fast, the system aggressively applies fast deceleration. On the contrary, if the vehicle is far and moving slowly, only mild deceleration is required.

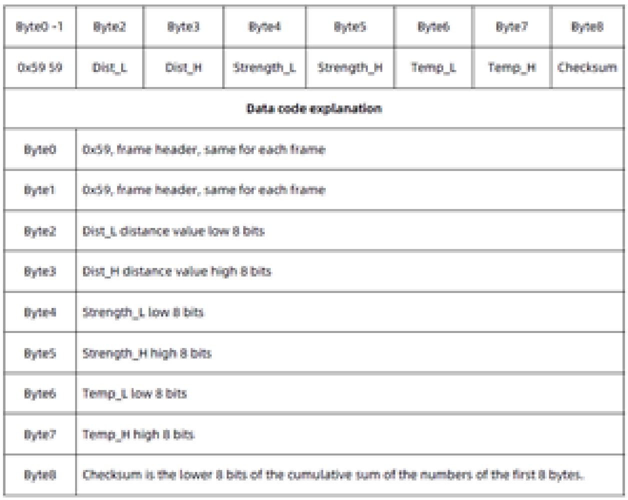
viii. Fuzzy Rule Table

Table 1: Fuzzy Rule Table

Distance	**Speed**	**Deceleration**
Close	Slow	Slow
Close	Medium	Medium
Close	Fast	Fast
Medium	Slow	Slow
Medium	Medium	Medium
Medium	Fast	Fast
Far	Slow	Slow
Far	Medium	Slow
Far	Fast	Medium

ix. Data Acquisition & Output Control Design

In LiDAR sensor reading, data parsing is required because the data sent through the serial includes distance, strength, and temperature packed as shown below:



Byte0 -1	Byte2	Byte3	Byte4	Byte5	Byte6	Byte7	Byte8
0x59 59	Dist_L	Dist_H	Strength_L	Strength_H	Temp_L	Temp_H	Checksum
Data code explanation							
Byte0	0x59, frame header, same for each frame						
Byte1	0x59, frame header, same for each frame						
Byte2	Dist_L distance value low 8 bits						
Byte3	Dist_H distance value high 8 bits						
Byte4	Strength_L low 8 bits						
Byte5	Strength_H high 8 bits						
Byte6	Temp_L low 8 bits						
Byte7	Temp_H high 8 bits						
Byte8	Checksum is the lower 8 bits of the cumulative sum of the numbers of the first 8 bytes.						

Figure 8: Format of LiDAR Sensor Output Data

Only the distance data is needed, so it is extracted from Byte 2 and Byte 3. Byte 2 represents the lower part, while Byte 3 represents the higher part. Since the distance is a 2-byte value, it is calculated as:

$$\text{Distance (cm)} = \text{Byte2} + \text{Byte3} \times 255 \tag{1}$$

$$\text{Distance (m)} = \frac{\text{Distance (cm)}}{100} \tag{2}$$

The magnetic speed sensor outputs HIGH logic when detecting magnets, and LOW otherwise. RPM is calculated by counting pulses within a specific time window (e.g., 100 ms) and converting to revolutions per minute:

$$\text{RPM} = \left(\frac{\text{Pulse Count} \times 60}{\text{Number of Magnets}} \right) \tag{3}$$

Then, the linear speed is calculated using:

$$\text{Speed} = \left(\frac{\text{RPM} \times \text{Wheel Diameter} \times \pi}{60.0} \right) \tag{4}$$

For output control, PWM signals are mapped to voltage using the following formula:

$$V_{out} = \left(\frac{\text{PWM}}{\text{PWM}_{\text{Max}}} \right) \times V_{\text{Max}} \tag{5}$$

The deceleration process begins by stopping the driver input. The duration of deceleration is based on the defuzzified fuzzy output, calculated in milliseconds. During this process, PWM is gradually reduced to a minimum value (e.g., 10), then the motor is electrically braked by briefly reversing its direction. Finally, PWM is set to 0 for 5 seconds before the system becomes responsive again.

x. System Implementation and Testing Method

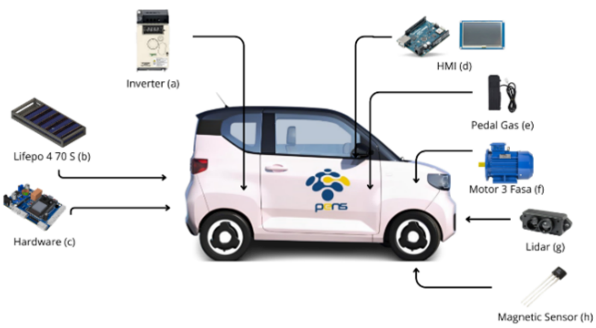


Figure 9: System Planning in Vehicle

This stage involved comprehensive planning and installation validation. The design was customized for autonomous braking based on sensor data. The system coordinates mechanical and electrical components to precisely regulate the 3-phase motor and throttle.

The testing methodology included several key stages:

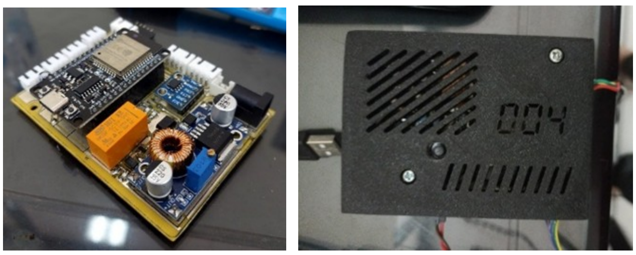
1. **Tool Design Verification:** Checked all PCB components for proper installation before testing sensors and outputs.

2. **Sensor Input Testing:**
   (a) *Distance Sensor Test:* TF Mini-S LiDAR tested against manual measurements using BW TFDS software.
   (b) *Speed Sensor Test:* Magnetic sensor tested by moving the vehicle using inverter and reading values from axle rotation.
3. **PWM to Voltage Conversion Test:** Verified PWM values from microcontroller against actual voltage to the inverter.
4. **Control System and Output Testing:**
   (a) *Fuzzy Control System Test:* Designed and simulated in MATLAB Fuzzy Logic Designer.
   (b) *Motor Deceleration Test:* Compared MATLAB defuzzified output with actual motor braking time calculated from inverter frequency changes.

III. Results and Discussion

i. Tool Design Result

In analyzing the performance of the automatic braking system, it is essential to test the physical design and integration of the tool to ensure that all sensors and components are functioning as expected. The first step involves verifying the installation of components on the PCB (Printed Circuit Board). This validation ensures correctness before proceeding to test sensor input and output signals.



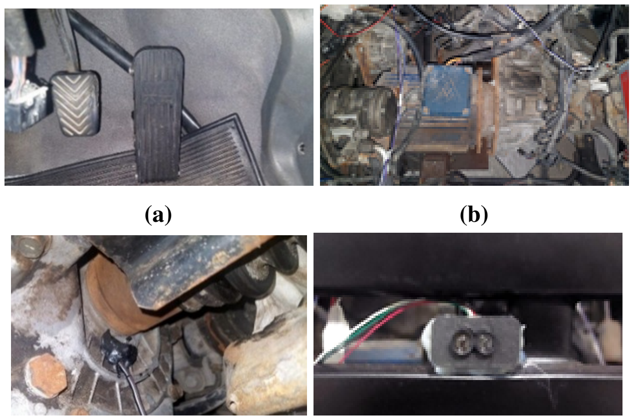
(a) (b)

Figure 10: PCB and system installation testing results (a) Assembled PCB with component layout (b) System integration testing in vehicle

In the vehicle, it is also necessary to validate the performance of the entire system, including sensors, actuators, and the inverter. The system test involves observing motor behavior and verifying sensor data when the vehicle is powered on.

ii. Testing Inputs and Sensors

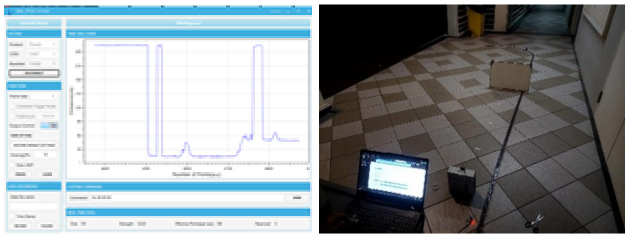
The first test conducted was the distance sensor test, where the sensor readings were compared against manual measurements. The measurements were carried out



(c) (d)

Figure 11: Application of the system in vehicle

using the BW_TFDS software, which is the dedicated interface for the TF Mini-S LiDAR sensor.



(a) (b)

Figure 12: Proximity sensor testing using BW_TFDS software

The results from the test show that the LiDAR sensor produces highly accurate readings, with an average error of less than 1%. This demonstrates its suitability for applications requiring high precision. The detailed results are provided in Table 3.

Table 2: Distance Sensor Test Results

Sensor (cm)	Measurement (cm)	Error (%)
147	150	2.0
299	300	0.3
550	550	0.0
907	900	0.8
1387	1400	0.9
147	150	2.0

Table 3: Distance Sensor Test Results

iii. Speed Sensor Testing

After testing the distance sensor, the speed sensor was tested directly on the vehicle. The test was performed by moving the vehicle using an inverter while observing sensor readings placed on the wheel axle. These readings were monitored through a serial monitor interface. To assess the impact of gear changes, the test was conducted in each gear mode.

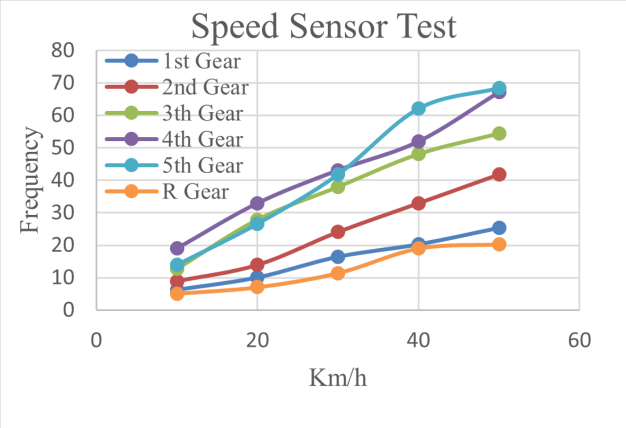


Figure 13: Speed Sensor Testing Graph

The results show a consistent correlation between inverter frequency and vehicle speed. As the inverter frequency increased from 10 Hz to 50 Hz, the vehicle speed also increased across all gears. This confirms that the inverter frequency is directly proportional to the motor and vehicle speed.

Notably, each gear produced a different speed range: Gear 1 provides lower speeds with higher torque, Gear 5 provides the highest speed for cruising, and Reverse Gear (R) yields the lowest backward speed. The observed speed ranged from 5.07 km/h to 68.4 km/h, matching the expected behavior of a vehicle transmission system. These results validate that the magnetic speed sensor functions reliably and aligns well with the mechanical characteristics of the drivetrain.

iv. PWM to Voltage Testing

Following the speed and distance tests, the system was evaluated for how PWM values from the microcontroller are converted into voltage to control the inverter.

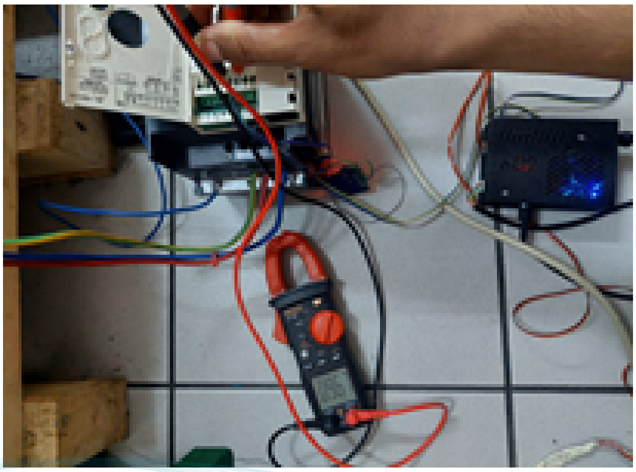


Figure 14: Testing PWM to Voltage Conversion

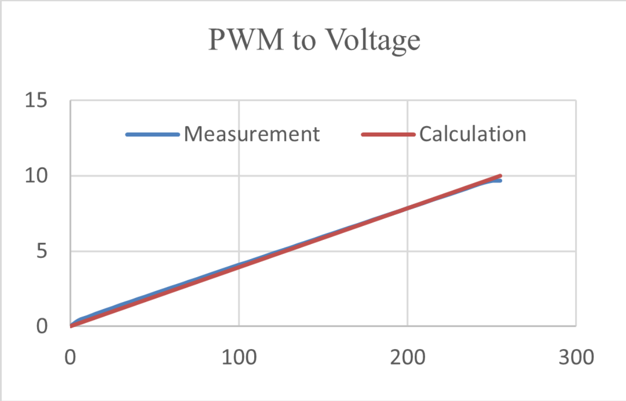


Figure 15: PWM to Voltage Value Testing Graph

Overall, the test results indicate good consistency between PWM input and measured output voltage. While there are minor deviations at lower PWM levels, the accuracy improves significantly at higher PWM, which is crucial for reliable inverter control in real-time applications.

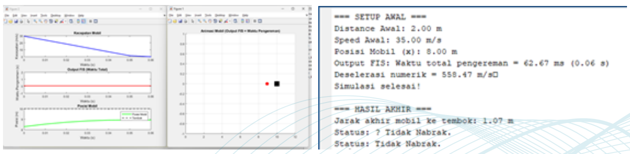
Table 4: PWM to Voltage Test Results

PWM	Voltage (Measured)	Voltage (Calculated)	Error (%)
50	2.18	1.96	11.2
100	4.08	3.92	4.0
150	5.96	5.88	1.3
200	7.84	7.84	0.0
250	9.66	9.80	1.5
255	9.67	10.00	3.3

v. Control System and Output System Testing

After completing the sensor and input tests, the next stage involves evaluating the overall control system and output response. This stage includes two main procedures: testing the fuzzy control system in a simulation environment and testing the real-world deceleration response of the motor.

The fuzzy control system test was conducted by first identifying the optimal fuzzy set using MATLAB's Fuzzy Logic Designer. The resulting set was then tested in simulation to evaluate the vehicle's braking capability under various input conditions [35].



(a) **(b)**

Figure 16: Fuzzy Logic Testing in MATLAB

Simulation results show that the system is capable of braking effectively before hitting an obstacle across several parameter variations. Table 5 summarizes the test outcomes.

Table 5: Fuzzy Logic Simulation Results

Distance (m)	Speed (km/h)	Deceleration (ms)	Car-Stop Dist. (m)	Hit?
7	70	55.00	5.40	No
5	50	68.08	3.50	No
3	50	55.00	1.86	No
1	60	25.32	0.51	No
1	70	25.32	0.43	No
7	10	88.56	6.61	No
2	30	62.67	1.21	No

After validating the fuzzy logic in simulation, the next test involved implementing the fuzzy control system on the actual microcontroller. The output from MATLAB (defuzzification results) was compared with the motor deceleration time derived from frequency change measurements.

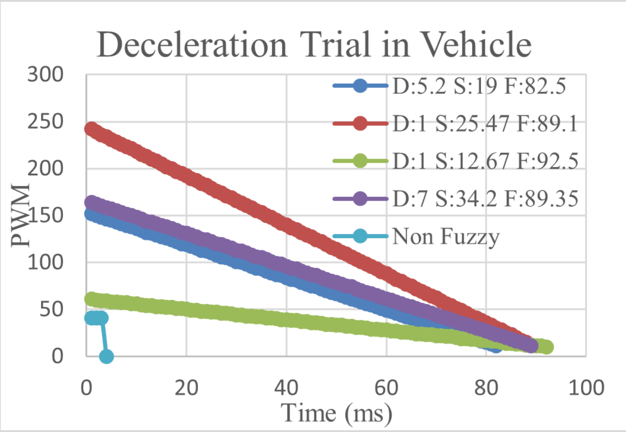


Figure 17: Graph of Motor Deceleration Test Results

Table 6: Fuzzy Logic Implementation Result on Motor

MATLAB Output (ms)	Microcontroller Output (ms)	Error (%)
68.00	82.80	17.87
88.56	89.10	0.60
88.56	95.50	7.27
87.00	89.35	2.63
Non Fuzzy	Non Fuzzy	–

Test results indicate that the vehicle's deceleration system performs reliably, with an average error of 7.1%. Notably, the fuzzy logic control regulates the Duty Cycle more stably and consistently compared to the "Non-Fuzzy" scenario.

This confirms that fuzzy logic not only compensates for microcontroller data uncertainties but also adjusts the vehicle's deceleration behavior in real time. Even with microcontroller response limitations, the consistent fuzzy inference calculations enable adaptive and accurate deceleration. Therefore, the system proves to be both responsive and robust under dynamic driving conditions.

IV. Conclusion

Based on the tests conducted, the automatic braking system demonstrates promising performance. The TFMini-S LiDAR sensor exhibits high accuracy with an average error of less than 1%. The magnetic speed sensor shows a consistent relationship between inverter frequency and car speed across different gear levels, despite minor errors in tachometer readings. The PWM-to-voltage conversion indicates good consistency with minimal error at higher PWM values, although further calibration is required to enhance accuracy at lower ranges.

The fuzzy system implementation on the microcontroller successfully replicates MATLAB outputs with relatively small errors and even achieves zero error in some scenarios. This confirms its effectiveness in adaptively and responsively managing vehicle deceleration. Although an average error of 7.1% was observed during motor deceleration tests—primarily due to microcontroller processing delays—the fuzzy logic-based calculations remain accurate and efficient, making the system reliable across a broad range of operational conditions.

This system offers a practical and robust solution for improving real-time vehicle safety. By reducing dependence on human attention and reacting intelligently to dynamic driving environments, the system contributes significantly to reducing traffic accidents due to human error. Adaptive braking behavior based on vehicle speed, proximity distance, and potential driver drowsiness further underlines its role in enhancing driving safety.

Despite the encouraging results, several limitations were encountered that warrant attention in future work:

1. **Sensor Range and Environmental Limitations:** The TFMini-S LiDAR sensor is limited in range and is susceptible to interference from ambient UV light. Future research should consider integrating more advanced multi-directional sensors or alternative optical solutions with better noise immunity.
2. **Speed Sensor Interference:** Noise interference between the magnetic speed sensor and the inverter occasionally disrupted data accuracy. Shielded cabling, filtering techniques, or sensor placement optimization are potential mitigation strategies to explore.
3. **Mechanical Braking Integration:** The current implementation controls motor deceleration but lacks direct mechanical brake actuation. Future development should integrate the fuzzy braking logic with a physical braking mechanism to improve realism and address inertial dynamics in actual driving conditions.

Acknowledgment

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