# A Fuzzy Logic-Based Regenerative Braking Framework Incorporating Driver Drowsiness Indicators

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***Abstract:*** *Electric vehicles increasingly rely on regenerative braking systems to improve energy efficiency while maintaining driving safety and passenger comfort. However, conventional braking strategies typically respond only to vehicle dynamics and environmental conditions, without accounting for the driver's physiological state, which may lead to delayed or insufficient intervention during fatigue-related situations. To address this limitation, this study presents a fuzzy logic–based adaptive braking framework that integrates driver drowsiness indicators into the decision-making process for regenerative braking. The proposed system employs a Sugeno-type fuzzy logic controller developed and validated in MATLAB/Simulink, followed by real-time implementation on a prototype electric vehicle platform using a Raspberry Pi Pico microcontroller. Inputs to the controller include vehicle speed, obstacle distance, and driver state parameters such as eyelid closure, head tilt, yawning, and shoulder movement. An experimental evaluation was conducted under three representative scenarios: obstacle presence, slight drowsiness, and severe drowsiness. Results demonstrate that the controller produces appropriate braking responses across all cases, with prototype braking forces closely aligned with simulation outcomes, exhibiting error margins ranging from 3.56% to 10.83%. Further analysis of deceleration, braking time, stopping distance, and jerk confirms that the proposed system maintains a balance between safety and passenger comfort, while introducing a conservative safety bias under drowsy driving conditions. These findings suggest that fuzzy logic provides a reliable and practical approach for integrating driver state awareness into regenerative braking systems, thereby supporting safer and more adaptive electric vehicle operation.*

***Keywords:*** **Fuzzy Logic Control, Regenerative Braking, Electric Vehicles, Driver Drowsiness, Adaptive Braking**

## 1. INTRODUCTION

The rapid adoption of electric vehicles (EVs) has increased the demand for braking systems that are not only energy-efficient but also capable of ensuring high levels of driving safety and passenger comfort. Regenerative braking systems play a central role in this context by recovering kinetic energy during deceleration and converting it into electrical energy, thereby extending driving range and improving overall vehicle efficiency [1], [2]. Despite these advantages, the effectiveness of regenerative braking is strongly influenced by nonlinear vehicle dynamics, variable driving conditions, and the interaction between control strategies and human driving behaviour, which can lead to delayed braking responses or excessive jerk if not properly managed [3], [4].

To address these challenges, fuzzy logic control has been widely adopted in regenerative braking applications due to its ability to handle uncertainty, imprecise inputs, and nonlinear system behaviour without relying on an accurate mathematical model. By emulating human reasoning, fuzzy logic controllers enable flexible and adaptive braking decisions based on multiple input variables such as vehicle speed and obstacle distance. Previous studies have demonstrated that fuzzy-based regenerative braking strategies can improve energy recovery while maintaining smoother deceleration profiles and reduced jerk compared to conventional rule-based approaches [5], [6], [7], [8], [9]. These characteristics make fuzzy logic a practical solution for real-time braking control in electric vehicles.

In addition to vehicle dynamics, driver condition plays a critical role in braking safety. Driver drowsiness is widely recognised as a major contributor to road accidents, as fatigue impairs reaction time, situational awareness, and decision-making ability [10]. Recent advances in sensing and vision-based technologies have enabled the detection of fatigue-related behaviours such as eyelid closure, head tilt, yawning, and abnormal posture [11], [12], [13], [14]. While these systems demonstrate promising accuracy in identifying driver state, their functionality is typically limited to warning or alert mechanisms, and direct integration with vehicle control systems remains limited.

The separation between driver monitoring systems and regenerative braking control represents an important gap in existing research. Most regenerative braking studies focus on energy optimisation and braking performance, primarily based on vehicle dynamics and environmental parameters [1], [2], [3], [4]. Whereas drowsiness detection research concentrates on recognition accuracy without closing the control loop [10], [11], [12], [13], [14]. Integrating driver state information directly into braking control decisions offers the potential to enhance safety by enabling earlier and more appropriate intervention during fatigue-related driving scenarios, while still maintaining passenger comfort constraints such as acceptable jerk levels [15], [16], [17], [18].

Motivated by this gap, this study proposes a fuzzy logic–based regenerative braking framework that explicitly incorporates driver drowsiness indicators into braking control. The proposed controller integrates vehicle dynamics, obstacle distance, and driver state parameters within a unified fuzzy inference system. The framework is developed and evaluated through MATLAB/Simulink simulation and real-time prototype implementation to assess braking response, consistency, and practical feasibility under representative driving scenarios.

## 2. RELATED WORK

Regenerative braking systems are widely recognised as an effective approach for improving the energy efficiency of electric vehicles by recovering kinetic energy during deceleration and converting it into electrical energy. Conventional regenerative braking strategies typically allocate braking force based on vehicle speed, braking demand, and battery state of charge. While these approaches are effective under controlled conditions, their performance can degrade under nonlinear vehicle dynamics and varying driving environments, resulting in reduced energy recovery or less stable braking behaviour [1], [3], [4].

To overcome these limitations, fuzzy logic control has been extensively applied in regenerative braking systems due to its ability to manage uncertainty and imprecise inputs without relying on an accurate mathematical model. By emulating human reasoning, fuzzy logic controllers enable adaptive braking decisions under varying speed and distance conditions. Previous studies have reported that fuzzy-based regenerative braking strategies can enhance energy recovery while reducing abrupt deceleration and excessive jerk compared to conventional rule-based methods [5], [6], [7], [8].

Several researchers have further enhanced fuzzy logic–based braking systems by integrating optimisation techniques such as genetic algorithms and swarm-based methods, resulting in improved braking smoothness and energy recovery under diverse driving cycles [6], [7]. Hybrid approaches that combine fuzzy logic with neural or game-theoretic methods have also been explored to enhance braking performance under complex operating conditions [3].

In parallel with advances in braking control, driver safety has received increasing attention, particularly in relation to fatigue and drowsiness. Driver drowsiness is recognised as a major contributor to road accidents, as reduced alertness negatively affects reaction time and situational awareness [10]. Recent developments in sensing and vision-based technologies have enabled the detection of fatigue-related behaviours such as eyelid closure, head tilt, yawning, and abnormal posture [11], [12], [13],[14].

Passenger comfort is another important consideration in braking system design, as excessive jerk and abrupt deceleration can reduce ride quality and driver acceptance. Experimental studies have shown that maintaining jerk within acceptable thresholds is essential for achieving smooth and comfortable braking responses [15], [16]. Consequently, recent research emphasises braking strategies that balance safety, comfort, and energy efficiency [17], [18].

Despite extensive research in regenerative braking and driver monitoring, these two domains are often treated independently. There remains limited work on integrating driver state information directly into regenerative braking control decisions. This gap motivates the present study.

**Table 1. Summary of Identified Research Gaps and Proposed Contributions**

| Research Gap in Existing Studies | Proposed Contribution of This Study |
|---|---|
| Regenerative braking systems are primarily designed based on vehicle dynamics and energy recovery considerations, without explicitly accounting for driver condition [1], [2], [3],[4] | Integration of driver drowsiness indicators into regenerative braking control using a fuzzy logic–based framework |
| Fuzzy logic–based regenerative braking approaches mainly emphasise energy efficiency and braking smoothness, with limited consideration of human-state variability *Regenerative braking of electric vehicles based on fuzzy control strategyRegenerative braking of electric vehicles based on fuzzy control strategy* [5],[6],[7],[8],[9] | Adaptive braking decisions that jointly consider vehicle dynamics and driver drowsiness to enhance safety and comfort |
| Driver drowsiness detection systems commonly operate as standalone warning or alert mechanisms rather than active control components [10],[11],[12],[13],[14] | Closed-loop incorporation of driver state information directly into braking control decisions |
| Limited real-time experimental validation of drowsiness-aware braking strategies on embedded vehicle platforms [15], [16], [17], [18] | Prototype implementation and experimental validation of the proposed framework on an embedded electric vehicle platform |

In response to these gaps, the present study focuses on developing a fuzzy logic–based regenerative braking framework that incorporates driver drowsiness indicators into braking control decisions for electric vehicles. By addressing key limitations identified in existing studies, particularly the separation between driver monitoring systems and braking control strategies, this work aims to improve braking safety and passenger comfort under fatigue-related driving conditions. The proposed system emphasises practical feasibility through simulation and real-time prototype implementation, contributing to more adaptive and safety-oriented regenerative braking solutions for electric vehicle applications.

# 3. METHODOLOGY

This study proposes a fuzzy logic–based regenerative braking framework that integrates driver drowsiness indicators into braking control decisions for electric vehicles. The overall fuzzy reasoning process adopted in this work is illustrated in Figure 1, which presents the sequence of fuzzification, rule evaluation (inference), aggregation of rule outputs, and validation of the braking decision prior to actuation. This structure ensures that braking commands are generated only when the inferred output satisfies predefined safety and relevance criteria.

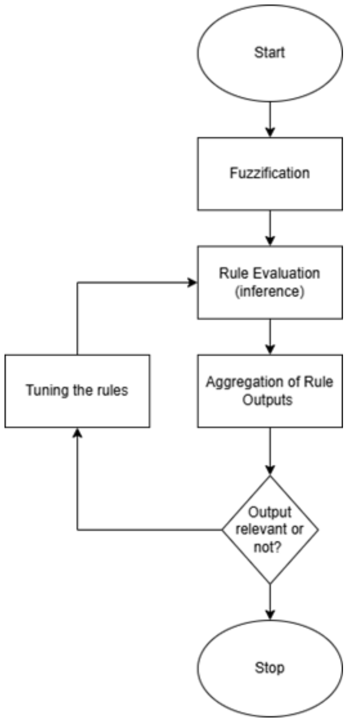



**Figure 1. FLC Simulation Flowchart**

The laboratory-scale prototype used for real-time validation is shown in Figure 2. A Raspberry Pi Pico microcontroller serves as the electronic control unit, interfacing with ultrasonic sensors for front and rear obstacle detection and rotary encoders for estimating vehicle speed. The braking command generated by the fuzzy logic controller is applied to the motor through pulse-width modulation using an L298N motor driver, enabling proportional and adaptive braking control.

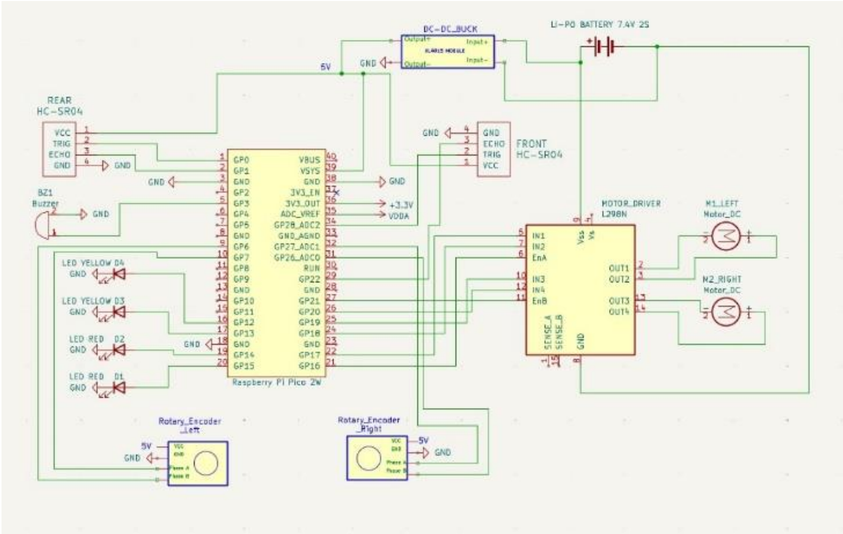


**Figure 2. Schematic Diagram of Car Prototype**

The embedded software execution flow implemented on the microcontroller is illustrated in Figure 3. At system initialisation, Gaussian and triangular membership functions are defined, followed by declaration of fuzzy rules. Real-time inputs from vehicle sensors and driver state indicators are continuously acquired. The braking force is computed using weighted sum inference based on the activated rules, and the resulting output is issued as the braking command.

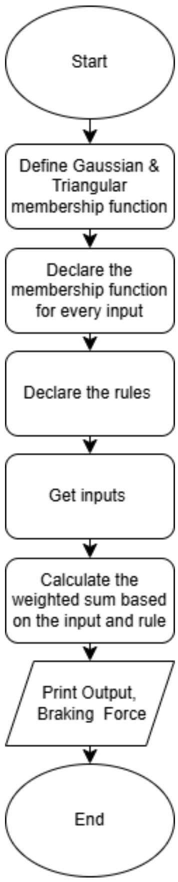



**Figure 3. Flowchart for FLC Program**

Prior to hardware experimentation, the braking logic was verified in a MATLAB/Simulink environment to ensure correct functional behaviour under controlled conditions. The simulation model used for this evaluation is presented in Figure 4, which integrates the fuzzy logic controller with braking response blocks for computing deceleration, braking time, stopping distance, and jerk. The simulation results were subsequently compared with experimental measurements obtained from the prototype to validate the consistency and reliability of the proposed braking framework.

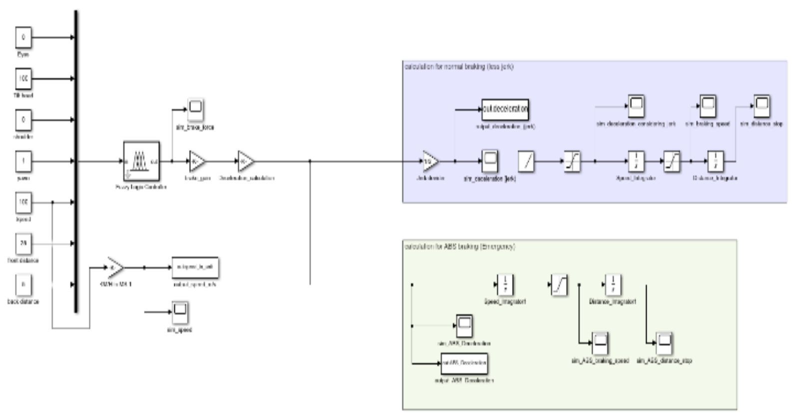


**Figure 4. Simulation In Simulink**

## 4. RESULT AND DISCUSSION

The performance of the proposed fuzzy logic controller was first evaluated in the MATLAB/Simulink environment under three representative driving scenarios to verify its braking decision behaviour. The braking force output recorded through the Scope block, as illustrated in Figure 5, shows stable and consistent braking activation, confirming that the fuzzy rules were triggered correctly. Braking force values varied according to both environmental conditions and driver state, ranging between 0 and 100 N. The numerical simulation results are summarised in Table 2.

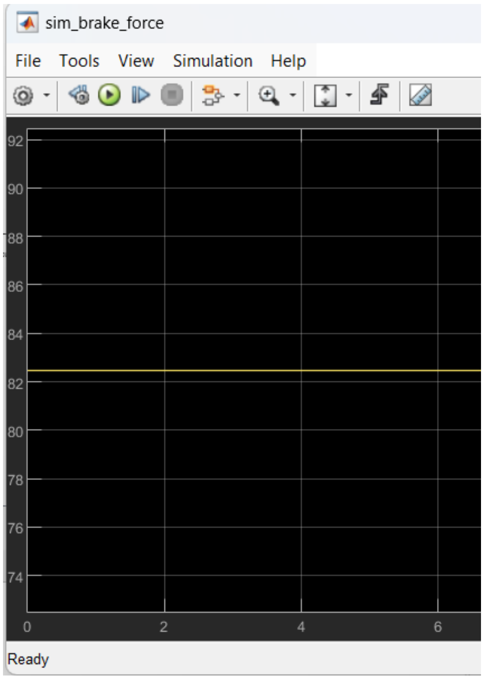



**Figure 5. Braking Force Values in MATLAB Simulation**

**Table 2. Braking Force Results (Simulation)**

| Scenario | Braking Force (N) |
|---|---|
| **Obstacle Ahead** | **100.00** |
| **Slightly Drowsy** | **50.00** |
| **Fully Drowsy** | **90.22** |

In the obstacle-ahead scenario, the controller applied a maximum braking force of 100 N, indicating a decisive emergency response under collision-risk conditions. For the slightly drowsy scenario, a moderate braking force of 50 N was applied, striking a balance between safety requirements and driving comfort. In the fully drowsy condition, the controller produced a high braking force of 90.22 N, demonstrating its ability to escalate braking intensity in response to severe fatigue cues. These results confirm that the fuzzy logic controller adapts the braking force based on both the driver's condition and the surrounding environment.

To assess real-time feasibility, the laboratory-scale prototype was tested under the same input conditions as the simulation. Braking force values were displayed via a graphical user interface running on the embedded platform, as shown in Figure 6, with updates at 0.1-second intervals. The prototype braking force results, averaged across three trials for each scenario, are presented in Table 3. In the obstacle-ahead scenario, the prototype produced a high average braking force of 96.44 N, closely matching the simulation result and demonstrating effective emergency braking. Minor variations between trials were attributed to sensor latency and actuator response.

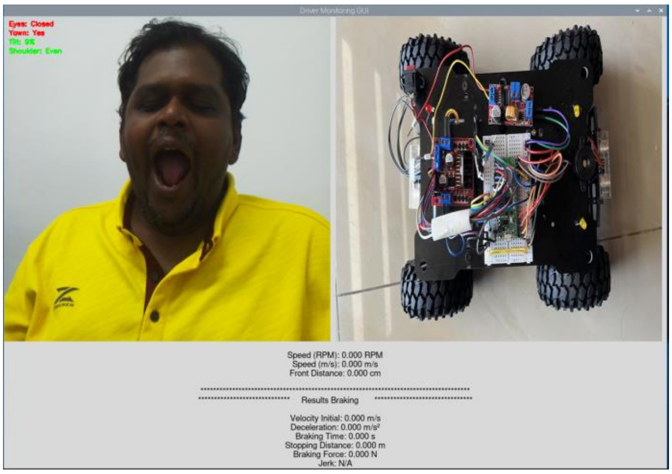


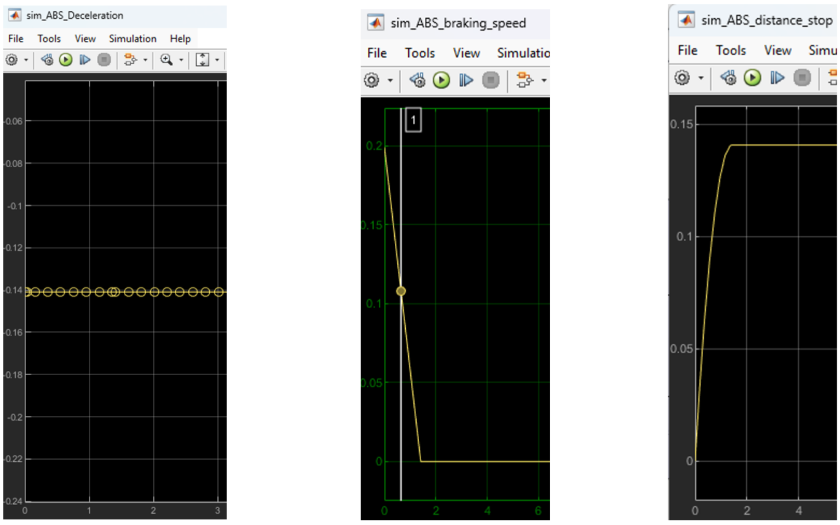

**Figure 6. GUI for Prototype Result**

**Table 3. Braking Force Results (Prototype)**

| Scenario | Braking Force (N) | | | Average (N) |
|---|---|---|---|---|
| | Trial | | | |
| | | 2 | 3 | |
| **1: Obstacle Ahead** | 100.00 | 89.47 | 99.84 | 96.44 |
| **2: Slightly Drowsy** | 46.44 | 49.97 | 45.95 | 47.45 |
| **3: Fully Drowsy** | 99.98 | 99.99 | 100.00 | 99.99 |

For the slightly drowsy scenario, the prototype generated an average braking force of 47.45 N, aligning well with the simulated value of 50 N and reflecting moderate intervention during early fatigue. In the fully drowsy scenario, the prototype consistently applied near-maximum braking force, with an average value of 99.99 N. These results indicate strong agreement between the simulation and experimental behaviors, confirming the controller's reliability in responding to severe drowsiness conditions.

Further analysis of braking response parameters, including deceleration, braking time, stopping distance, and jerk, was conducted to evaluate both safety and comfort characteristics. The response profiles obtained from the MATLAB simulation are illustrated in Figure 7, with numerical values summarised in Table 4. In the obstacle-ahead scenario, the simulation produced a high deceleration of 0.156 m/s², a short braking time of 0.647 s, a minimal stopping distance of 0.032 m, and a moderate jerk of 0.241 m/s³, reflecting decisive emergency braking. In contrast, the fully drowsy scenario resulted in a lower deceleration of 0.035 m/s², a longer braking time of 3.404 s, and an increased stopping distance of 0.445 m, accompanied by a very low jerk of 0.010 m/s³, indicating a smooth and comfort-oriented response.




(a) (b) (c)

**Figure 7. Braking Response Parameters: (a) Deceleration, (b) Braking Time, (c) Stopping Distance**

**Table 4. Braking Response Results (Simulation)**

| Scenario | Braking Response Parameters | | | |
|---|---|---|---|---|
| | Braking Deceleration ($m/s^2$) | Braking Time (s) | Stopping Distance (m) | Jerk ($m/s^3$) |
| **Obstacle Ahead** | 0.156 | 0.647 | 0.032 | 0.241 |
| **Fully Drowsy** | 0.035 | 3.404 | 0.445 | 0.010 |

Prototype braking response parameters, presented in Table 5, followed similar trends. In the obstacle-ahead scenario, deceleration values ranged between 0.116 and 0.156 m/s², with braking times of 0.628–0.843 s and stopping distances of 0.031–0.041 m. Jerk values remained within 0.200–0.248 m/s³, indicating firm yet controlled braking. For the fully drowsy condition, lower deceleration values of 0.049–0.050 m/s², longer braking times of 3.753–4.335 s, and increased stopping distances of 0.353–0.396 m were observed, while jerk values remained minimal, ranging from 0.011 to 0.013 m/s³, confirming stable and smooth braking behavior.

**Table 5. Braking Response Results (Prototype)**

| Scenario | Trial | Braking Response Parameters | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Braking Deceleration (m/s2) | | Braking Time (s) | | Stopping Distance (m) | | Jerk (m/s3) | |
| 1: Obstacle Ahead | 1 | 0.156 | 0.139 | 0.628 | 0.717 | 0.031 | 0.035 | 0.248 | 0.200 |
| | 2 | 0.116 | | 0.843 | | 0.041 | | 0.138 | |
| | 3 | 0.1441 | | 0.679 | | 0.033 | | 0.212 | |
| 2: Fully Drowsy | 1 | 0.049 | 0.050 | 3.885 | 3.991 | 0.373 | 0.374 | 0.012 | 0.012 |
| | 2 | 0.050 | | 4.335 | | 0.396 | | 0.011 | |
| | 3 | 0.050 | | 3.753 | | 0.353 | | 0.013 | |

A direct comparison of braking force between the simulation and prototype is provided in Table 6, where the errors ranged from 3.56% to 10.83%, remaining within acceptable limits for a hardware-based implementation. Notably, the prototype applied slightly stronger braking in the fully drowsy scenario, suggesting a conservative safety bias. A detailed comparison of braking response parameters is presented in Table 7. In the obstacle-ahead scenario, simulation and prototype results were closely aligned, with errors of approximately 10% for deceleration, braking time, and stopping distance. In contrast, jerk values were lower in the prototype, indicating smoother deceleration.

**Table 6. Comparison of Braking Force Between Simulation and Prototype**

| Scenario | Simulation (N) | Prototype (N) | Error (%) |
|---|---|---|---|
| **Obstacle Ahead** | 100.00 | 96.44 | 3.56 |
| **Slightly Drowsy** | 50.00 | 47.45 | 5.10 |
| **Fully Drowsy** | 90.22 | 99.99 | 10.83 |

**Table 7. Comparison of Braking Response Parameters**

| Scenario | Simulation/Prototype | Braking Response Parameters | | | |
|---|---|---|---|---|---|
| | | Braking Deceleration ($m/s^2$) | Braking Time (s) | Stopping Distance (m) | Jerk ($m/s^3$) |
| **Obstacle Ahead** | Simulation | 0.156 | 0.647 | 0.032 | 0.241 |
| | Prototype | 0.139 | 0.717 | 0.035 | 0.200 |
| | Error (%) | **10.9%** | **10.81%** | **9.375%** | **17.01 %** |
| **Fully Drowsy** | Simulation | 0.035 | 3.404 | 0.445 | 0.010 |
| | Prototype | 0.050 | 3.991 | 0.374 | 0.012 |
| | Error (%) | **42.86%** | **17.24%** | **15.96%** | **20.00 %** |

In the fully drowsy scenario, larger discrepancies were observed, particularly in deceleration and jerk. These differences can be attributed to inherent variations between the idealised simulation environment and the physical prototype. Hardware constraints, sensor noise, processing delays, road friction, wheel slip, and minor mechanical variations contribute to amplified braking responses under real-world conditions. Additionally, rapid fluctuations in drowsiness and distance inputs may cause the fuzzy controller to react more strongly in the prototype, resulting in occasional overshoot.

Despite these deviations, the overall performance of the fuzzy logic controller remained consistent and reliable across both simulation and prototype platforms. Importantly, the integration of driver drowsiness indicators introduced a deliberate safety-oriented bias in the prototype, ensuring robust braking performance under uncertain driver conditions while maintaining jerk values within acceptable comfort thresholds. This balance between safety and comfort highlights the suitability of the proposed framework for intelligent regenerative braking applications in electric vehicles.

# 5. CONCLUSION

This study demonstrated that the proposed fuzzy logic–based regenerative braking framework effectively integrates driver drowsiness indicators into braking control decisions for electric vehicles. By combining vehicle dynamics with driver state information, the system adapts braking intensity appropriately under obstacle, slight drowsiness, and severe drowsiness conditions. Simulation and prototype results showed consistent braking behaviour, with close agreement between MATLAB/Simulink and real-time implementation. The observed conservative braking response under severe drowsiness highlights the system's safety-oriented design while maintaining acceptable comfort levels. Overall, the findings confirm the practical feasibility and reliability of fuzzy logic as an effective approach for enhancing braking safety in intelligent electric vehicle applications.

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