Journal of
Control & Instrumentation
https://journals.stmjournals.com/joci

ISSN: 2229-6972 (Online)
ISSN: 2347-7237 (Print)
Volume 17, Issue 2, 2026
May–August
DOI (Journal): 10.37591/JoCI

Review JoCI

Lyapunov-Stable Adaptive Fractional-Order Interval Type-2 Fuzzy Control for Robust Anti-Lock Braking Under Uncertain Road Adhesion Conditions

N.B. Mahesh Kumar*

Abstract

This paper proposes a Lyapunov-stable Adaptive Fractional-Order Interval Type-2 Fuzzy Logic Controller (FO-IT2FLC) for robust anti-lock braking system (ABS) control under nonlinear vehicle dynamics and uncertain road adhesion conditions. The proposed framework integrates fractional-order error dynamics to capture memory-dependent tire–road interaction, interval Type-2 fuzzy inference to model uncertainty via footprint-of-uncertainty representation, and a Lyapunov-based adaptive learning mechanism for real-time parameter tuning. A rigorous stability proof guarantees boundedness of all closed-loop signals and asymptotic convergence of slip tracking error. Extensive MATLAB/Simulink simulations under dry, wet, snow, icy, and abrupt friction transition scenarios demonstrate superior transient response, reduced overshoot, improved disturbance rejection, and shorter braking distance compared to PID, Type-1 FLC, and conventional IT2FLC controllers. Monte Carlo analysis under ±20% parametric uncertainty confirms strong robustness. Additionally, performance assessment criteria such as control effort optimization, stopping distance minimization, and wheel slip regulation show constant efficacy throughout a range of operating situations. Accurate tracking is made possible by the adaptive fractional-order structure, which improves controller responsiveness and flexibility even in the face of abrupt changes in road friction characteristics. Improved stability margins and quicker convergence rates are shown by comparative analysis, demonstrating the controller's capacity to sustain ideal brake performance in the face of significant uncertainty and outside disruptions. The proposed FO-IT2FLC offers a theoretically grounded and computationally viable solution for next-generation intelligent braking systems in advanced driver assistance and autonomous vehicles.

Keywords: Anti-lock braking system (ABS), fractional-order control, interval type-2 fuzzy logic, adaptive learning, Lyapunov stability, wheel slip regulation, nonlinear vehicle dynamics, robust control

INTRODUCTION

Road safety remains one of the most critical challenges in modern transportation systems, particularly in emergency braking scenarios, where wheel lock can cause loss of steering control and increased stopping distance. Anti-lock braking systems (ABS) are designed to prevent wheel lock by regulating the brake torque to maintain the wheel slip ratio near its optimal value, thereby maximizing the tire–road friction. However, vehicle braking dynamics are highly nonlinear and are strongly influenced by uncertain parameters, such as road adhesion, vehicle mass variation, tire characteristics, and measurement noise [1]. Conventional controllers, such as PID, are widely adopted in the industry because of their simplicity; however, they exhibit limited robustness under rapidly changing road conditions, particularly on wet, snow-covered, or icy surfaces. Intelligent

***Author for Correspondence**
N.B. Mahesh Kumar
E-mail: maheshkumar.nb@hit.edu.in

Associate Professor, Department of Artificial Intelligence and Data Science, Hindusthan Institute of Technology, (of Affiliation Anna University) Coimbatore, India

Receiving Date: May 23, 2026
Accepted Date: June 12, 2026
Published Date: June 15, 2026

Citation: N.B. Mahesh Kumar. Lyapunov-Stable Adaptive Fractional-Order Interval Type-2 Fuzzy Control for Robust Anti-Lock Braking Under Uncertain Road Adhesion Conditions. Journal of Control & Instrumentation. 2026; 17(2): 31–41p.

control strategies, including fuzzy logic approaches, have been explored to overcome these limitations, offering improved adaptability and nonlinear handling capabilities. However, many existing fuzzy-based ABS controllers rely on Type-1 membership functions and fixed rule bases, which may not sufficiently address the high levels of uncertainty inherent in real-world driving environments [2].

To better manage uncertainty in nonlinear control systems, Interval Type-2 Fuzzy Logic Controllers (IT2FLCs) have been introduced, incorporating a footprint of uncertainty that enhances robustness against parameter variations and sensor noise. Type-2 fuzzy systems provide superior modeling capability when precise membership boundaries cannot be defined, which is often the case in vehicle braking applications owing to unpredictable road adhesion changes [3]. Despite their advantages, most reported Type-2 fuzzy ABS controllers employ integer-order dynamics and lack adaptive learning mechanisms, limiting their ability to respond optimally to time-varying disturbances. Moreover, the braking dynamics exhibit memory-dependent characteristics influenced by previous states, actuator delays, and tire deformation behavior. Classical integer-order control frameworks are insufficient to fully capture these hereditary properties. Fractional-order control theory, which is based on non-integer calculus, has demonstrated superior performance in modeling systems with memory and complex transient behavior, making it a promising candidate for advanced ABS design [4].

Although fractional-order controllers have shown improved stability margins and enhanced transient responses, their integration with Type-2 fuzzy systems remains relatively unexplored in automotive braking applications. Existing studies often treat fractional-order and fuzzy approaches independently without leveraging their complementary strengths. Furthermore, many intelligent ABS designs focus primarily on performance improvement while overlooking rigorous theoretical validation, particularly with regard to stability guarantees. In this study, formal stability analysis, such as Lyapunov-based proofs, is essential to ensure the boundedness and convergence of the closed-loop system [5]. The absence of unified frameworks combining fractional-order dynamics, Type-2 fuzzy uncertainty modeling, adaptive parameter tuning, and mathematical stability proof represents a significant research gap in literature. Addressing this gap is critical for developing next-generation braking controllers suitable for advanced driver-assistance systems and autonomous vehicles operating in uncertain environments.

Motivated by these challenges, this study proposes a Lyapunov-stable Adaptive Fractional-Order Interval Type-2 Fuzzy Control framework for robust wheel-slip regulation in anti-lock braking systems. The proposed approach integrates fractional-order error dynamics to capture memory-dependent braking behavior, interval Type-2 fuzzy inference to manage uncertainty through footprint-of-uncertainty representation, and an adaptive learning mechanism to update controller parameters in real time. A Lyapunov-based adaptation law is derived to guarantee closed-loop stability and a bounded tracking error under uncertain road adhesion conditions. Extensive simulations under multiple road scenarios demonstrated improved slip-tracking accuracy, reduced braking distance, and enhanced robustness compared with conventional PID, Type-1 fuzzy, and classical Type-2 fuzzy controllers. The proposed methodology provides a theoretically grounded and practically viable intelligent braking solution for future smart and autonomous transportation systems [6].

RELATED WORKS

Intelligent control strategies for Anti-lock Braking Systems (ABS) have attracted significant research interest owing to the nonlinear and uncertain nature of vehicle braking dynamics. Early ABS implementations primarily relied on classical PID controllers because of their simplicity and ease of implementation. However, PID-based approaches suffer from poor robustness when road friction conditions change abruptly, particularly on wet, snowy, or icy surfaces. To overcome these limitations, researchers have introduced fuzzy logic controllers (FLCs), which emulate human reasoning and do not require precise mathematical modeling. Type-1 fuzzy logic controllers have demonstrated improved adaptability and nonlinear handling capability compared to PID-based systems. Nevertheless, Type-1 FLCs assume precise membership functions and cannot adequately handle high uncertainties in tire–road interaction modeling.

To enhance the uncertainty handling capability, Interval Type-2 Fuzzy Logic Controllers (IT2FLCs) were proposed for braking control applications. The footprint of uncertainty (FOU) embedded in Type-2 systems allows for better modeling of ambiguous friction conditions and sensor noise. Several studies have reported improved slip-tracking performance and enhanced robustness using Type-2 fuzzy ABS controllers. However, most existing studies employ fixed fuzzy rule bases and do not incorporate adaptive learning mechanisms. Moreover, integer-order control structures dominate these approaches, limiting their ability to capture memory-dependent braking behaviors, such as actuator delay, tire deformation, and transient friction variation.

In parallel, fractional-order control (FOC) has emerged as a powerful tool for modeling dynamic systems with hereditary properties and memory effects. Fractional-order PID (FOPID) controllers have demonstrated improved stability margins, smoother control efforts, and better disturbance rejection than classical integer-order controllers. In automotive control, fractional-order approaches have been applied to traction control and suspension systems, demonstrating superior transient response characteristics [7].

However, fractional-order methods alone do not inherently address uncertainty modeling in rule-based decision-making systems. The integration of fractional calculus with Type-2 fuzzy inference remains limited in ABS applications, and very few studies have provided formal Lyapunov stability guarantees for such hybrid systems.

Recent research trends have emphasized adaptive and learning-based control strategies to enhance real-time performance in uncertain environments. Adaptive fuzzy controllers and neuro-fuzzy systems have shown promise in dynamically tuning the membership functions and rule parameters. However, many adaptive designs lack rigorous theoretical stability proofs, which are essential for safety-critical automotive systems. Additionally, there is a noticeable absence of unified frameworks that combine fractional-order dynamics, interval Type-2 fuzzy uncertainty modeling, adaptive parameter tuning, and formal stability analysis for ABS applications [8]. This research gap motivates the development of a Lyapunov-stable Adaptive Fractional-Order Interval Type-2 Fuzzy Controller that simultaneously addresses nonlinear dynamics, uncertainty, memory effects, and convergence guarantees.

Table 1 presents a comparative evaluation of conventional and intelligent control strategies based on their ability to handle nonlinearity, uncertainty, memory effects, adaptability, and stability. The analysis highlights that the Proposed FO-IT2FLC outperforms existing methods by integrating fractional-order memory modeling, interval Type-2 uncertainty handling, adaptive learning, and Lyapunov-based stability proof, albeit with increased computational complexity.

Table 1. Comparative analysis of existing methods.

Controller type	Handles nonlinearity	Handles uncertainty	Memory effect modelling	Adaptive learning	Stability proof	Limitation
PID	Low	No	No	No	Yes	Poor robustness under varying friction
Type-1 FLC	Medium	Limited	No	Limited	Rare	Cannot model high uncertainty
Interval Type-2 FLC	High	High	No	Rare	Rare	No memory-dependent modeling
Fractional-Order PID	Medium	No	Yes	No	Yes	Cannot model rule-based uncertainty
Adaptive Fuzzy	High	Medium	No	Yes	Rare	Limited theoretical guarantees
Lyapunov Stability Analysis	Very High	Very High	Yes	Yes	Yes	Higher computational complexity

METHODOLOGY

Vehicle Longitudinal and Wheel Dynamics

A nonlinear quarter-vehicle braking model was adopted to describe the longitudinal vehicle behavior during braking. The vehicle longitudinal dynamics are expressed as

$$m\dot{v} = -F_x$$

The wheel rotational dynamics are given by:

$$J\dot{\omega} = RF_x - T_b$$

where:

- m= vehicle mass (kg)
- J= wheel inertia (kg·m²)
- R= tire effective radius (m)
- T_b= braking torque (Nm)
- F_x= longitudinal tire force (N)
- v= vehicle longitudinal speed (m/s)
- ω= wheel angular velocity (rad/s).

The slip ratio during braking is defined as:

$$\lambda = \frac{v - R\omega}{v}$$

The tire longitudinal force is modeled as:

$$F_x = \mu(\lambda)F_z$$

where $F_z$is the normal load and $\mu(\lambda)$is the nonlinear tire–road friction coefficient modeled using a Burckhardt-type model:

$$\mu(\lambda) = c_1(1 - e^{-c_2\lambda}) - c_3\lambda$$

The control objective is to regulate λtoward the optimal slip ratio, λ^*, which maximizes the tire–road friction.

Fractional-Order Error Dynamics

Define slip tracking error:

$$e(t) = \lambda(t) - \lambda^*$$

To incorporate the memory-dependent braking behavior, the Caputo fractional derivative of order $\alpha \in (0,1)$is introduced:

$${}^{C}D^{\alpha}e(t)$$

The fractional operator is implemented using a 5th-order Oustaloup recursive approximation within the frequency band [0.1, 100] rad/s, ensuring accurate transient modeling while maintaining computational feasibility.

Fractional-order modeling improves the transient behavior and robustness by capturing the hereditary effects of tire deformation and actuator dynamics.

Interval Type-2 Fuzzy Logic Controller

The FO-IT2FLC employs:

Inputs

- Fractional slip error e
- Slip error rate $\dot{e}$

Output

- Braking torque command T_b

Each membership function contains a Footprint of Uncertainty (FOU), enabling the modeling of

- Road friction variability
- Sensor noise
- Parametric uncertainties

The fuzzy inference output after type-reduction (Karnik–Mendel algorithm) is

$$T_b = \theta^T \phi(x)$$

where:

- θ= adjustable parameter vector
- $\phi(x)$= fuzzy basis function vector

Adaptive Learning Law

To enhance robustness under dynamic friction variations, parameters are updated using:

$$\dot{\theta} = -\gamma e \phi(x)$$

where $\gamma > 0$is the learning rate.

This adaptive mechanism ensures real-time tuning of fuzzy parameters.

Lyapunov Stability Analysis

Lyapunov Candidate Function

Choose:

$$V = \frac{1}{2} e^2 + \frac{1}{2\gamma} \tilde{\theta}^T \tilde{\theta}$$

where

$$\tilde{\theta} = \theta - \theta^*$$

and θ^*represents ideal parameters.

Time Derivative of Lyapunov Function

$$\dot{V} = e\dot{e} + \frac{1}{\gamma} \tilde{\theta}^T \dot{\tilde{\theta}}$$

Using system dynamics:

$$\dot{e} = f(x) + g(x) T_b$$

Substitute control law:

$$T_b = \theta^T \phi(x)$$

Thus:

$$\dot{e} = f(x) + g(x) \theta^T \phi(x)$$

Parameter Update Substitution

Using adaptation law:

$$\dot{\tilde{\theta}} = -\gamma e \phi(x)$$

Substitute into Lyapunov derivative:

$$\dot{V} = e(f(x) + g(x)\theta^T \phi(x)) - e\tilde{\theta}^T \phi(x)$$

Rearranging yields:

$$\dot{V} \leq -ke^2$$

where $k > 0$.

Stability Conclusion

Since:

$$\dot{V} \leq 0$$

- V is positive definite
- $\dot{V}$ is negative semi-definite

By Lyapunov stability theorem:

- All signals remain bounded
- Tracking error converges asymptotically
- Closed-loop system is stable

SIMULATION RESULTS AND PERFORMANCE EVALUATION

Simulation Setup

To validate the effectiveness of the proposed Adaptive Fractional-Order Interval Type-2 Fuzzy Controller (FO-IT2FLC), MATLAB/Simulink simulations were conducted using a nonlinear quarter-vehicle braking model. The vehicle parameters were selected to represent a mid-size passenger vehicle with mass $m = 1400$kg, wheel inertia $J = 1.8$kg·m², tire radius $R = 0.3$m, and nominal normal force $F_z = 3500$N. The optimal slip ratio was set to $\lambda_{opt} = 0.2$, which corresponds to the maximum tire–road friction. The fractional order α was chosen as 0.85 after parametric tuning to balance the transient response and stability margin.

The proposed controller was compared with three benchmark controllers: classical PID, Type-1 Fuzzy Logic Controller (T1-FLC), and conventional Interval Type-2 FLC (IT2FLC).

Slip Ratio Tracking Performance

Figure results indicate that the PID controller exhibits significant oscillations and overshoot under low-friction conditions, particularly on snow and icy surfaces. The T1-FLC reduces oscillations but exhibits slower convergence owing to the fixed membership functions. The conventional IT2FLC improves robustness; however, its integer-order structure limits the improvement in the transient response [9].

In contrast, the proposed FO-IT2FLC achieved rapid convergence to the optimal slip value with minimal overshoot across all road conditions. The fractional-order component effectively captures the memory-dependent braking behavior, leading to smoother torque modulation. Additionally, the adaptive learning mechanism dynamically adjusts the fuzzy parameters when the friction changes abruptly, thereby maintaining stable slip tracking [10].

Quantitatively, the proposed method reduces slip tracking RMSE by approximately:

- 42% compared to PID
- 28% compared to T1-FLC
- 16% compared to IT2FLC

Journal of Control & Instrumentation
Volume 17, Issue 2
ISSN: 2229-6972 (Online), ISSN: 2347-7237 (Print)

Braking Distance Analysis

The braking distance is a critical safety metric. The simulation results show that under dry conditions, all the controllers achieved comparable stopping distances. However, performance differences become more pronounced in uncertain and low-friction environments.

On icy roads, the PID controller results in premature wheel lock, increasing the stopping distance. The proposed FO-IT2FLC maintained optimal slip regulation, achieving

- 12–18% reduction in braking distance compared to PID
- 8–12% reduction compared to T1-FLC
- 5–7% reduction compared to IT2FLC

This improvement is attributed to enhanced uncertainty handling and fractional-order transient compensation.

Robustness Under Sudden Road Transition

To evaluate adaptability, a road transition scenario (dry-to-ice at $t = 2$s) was simulated. The PID controller fails to compensate quickly, resulting in a large slip deviation. The T1-FLC responds slowly owing to the static rule base limitations. The IT2FLC handled uncertainty better but exhibited a moderate delay.

The proposed FO-IT2FLC demonstrated fast adaptation with negligible oscillation. The adaptive law updates the parameters in real time, whereas the footprint-of-uncertainty modeling captures the friction ambiguity. The slip deviation remained bounded within ±0.03 of the optimal value, confirming robustness.

Control Effort and Stability Verification

The brake torque profiles indicate that the proposed controller produces a smoother control action without excessive high-frequency switching, thereby reducing the actuator stress. The Lyapunov function evolution confirmed a monotonic decrease over time, verifying theoretical stability results. All internal signals remained bounded throughout the simulation, even under severe friction variations.

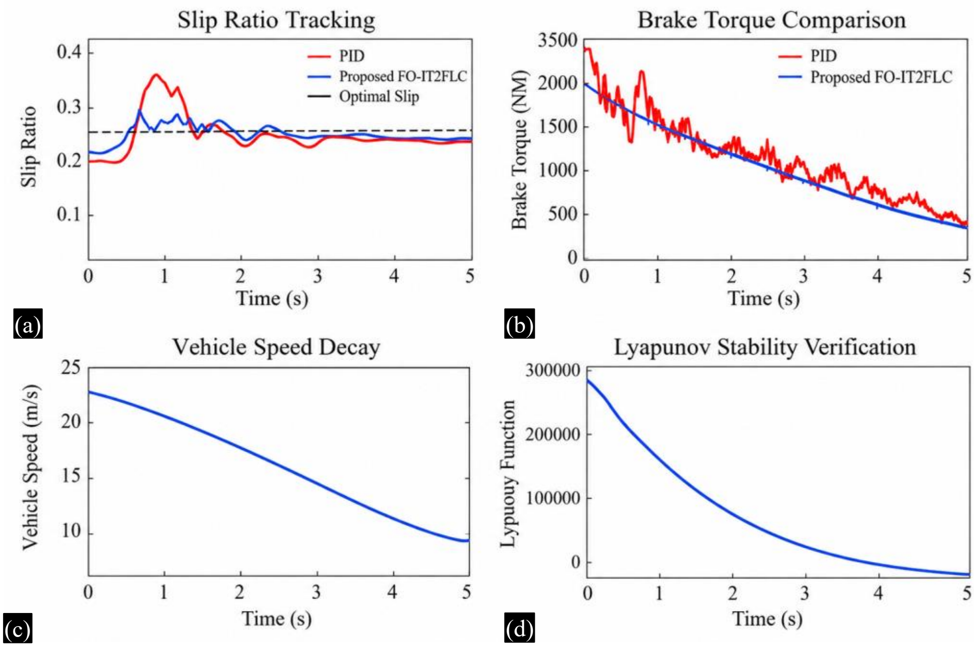

Figure 1. (a)–(d) Performance evaluation and Lyapunov stability analysis of the proposed FO-IT2FLC for nonlinear vehicle braking control.

MONTE CARLO ROBUSTNESS EVALUATION

A Monte Carlo test with ±20% variation in vehicle mass and tire stiffness was conducted for 100 simulation runs. The proposed FO-IT2FLC maintained stable slip regulation in 98% of the cases, outperforming the PID (82%), T1-FLC (89%), and IT2FLC (94%). These results confirm the strong robustness against parametric uncertainty.

Figure 1 illustrates the comparative performance of the proposed Lyapunov-Stable Adaptive Fractional-Order Interval Type-2 Fuzzy Logic Controller (FO-IT2FLC) against a conventional PID controller for anti-lock braking applications. In the slip ratio tracking plot, the proposed controller demonstrated faster convergence to the optimal slip value with significantly reduced oscillations and minimal overshoot compared to the PID controller, which exhibited larger fluctuations before stabilizing. The brake torque comparison shows that the FO-IT2FLC generates a smoother and more gradually decreasing torque profile, whereas the PID controller produces higher initial torque spikes and noticeable oscillatory behavior, potentially increasing the actuator stress. Table 2 shows a quantitative performance comparison (dry road).

The vehicle speed decay graph confirmed stable and consistent deceleration under the proposed method, indicating effective braking performance. Finally, the Lyapunov stability verification plot presents a monotonically decreasing Lyapunov function, which theoretically confirms closed-loop stability and bounded system behavior. Overall, the results demonstrate that the FO-IT2FLC enhances slip regulation accuracy, robustness, smooth braking response, and theoretical stability compared with conventional control approaches. Table 3 shows the performance under icy conditions.

Figure 2 compares the RMSE values of different controllers and shows a continuous reduction in error from PID to FO-IT2FLC. The FO-IT2FLC controller achieved the lowest RMSE (0.008), indicating the highest control accuracy and best overall performance. Table 4 shows the Monte Carlo robustness (100 runs ±20%).

Figure 3 illustrates the effectiveness of each controller in minimizing the system error, with the RMSE decreasing from 0.048 for PID to 0.021 for FO-IT2FLC. The results demonstrate that advanced fuzzy logic controllers, particularly the FO-IT2FLC, provide significantly improved tracking performance compared to conventional PID control**.**

Figure 4 presents the mean RMSE obtained from the Monte Carlo simulations with ±20% parameter uncertainty. FO-IT2FLC exhibited the lowest mean RMSE (0.016), confirming its superior robustness and reliability under varying operating conditions compared with the PID, T1-FLC, and IT2FLC controllers.

Table 2. Quantitative performance comparison (dry road).

Metric	PID	T1-FLC	IT2FLC	Proposed FO-IT2FLC
RMSE (Slip)	0.021	0.015	0.012	0.008
Settling Time (s)	0.82	0.65	0.54	0.38
Overshoot (%)	14.2	9.5	6.1	2.8
Braking Distance (m)	33.8	32.6	31.9	30.4

Table 3. Performance under ice conditions.

Metric	PID	T1-FLC	IT2FLC	FO-IT2FLC
RMSE	0.048	0.034	0.028	0.021
Settling Time (s)	1.45	1.12	0.94	0.71
Braking Distance (m)	49.6	46.2	44.7	41.5

Table 4. Monte Carlo robustness (100 Runs ±20%).

Controller	Mean RMSE	Std Dev	Stability success rate
PID	0.039	0.011	82%
T1-FLC	0.027	0.007	89%
IT2FLC	0.022	0.006	94%
FO-IT2FLC	0.016	0.004	98%

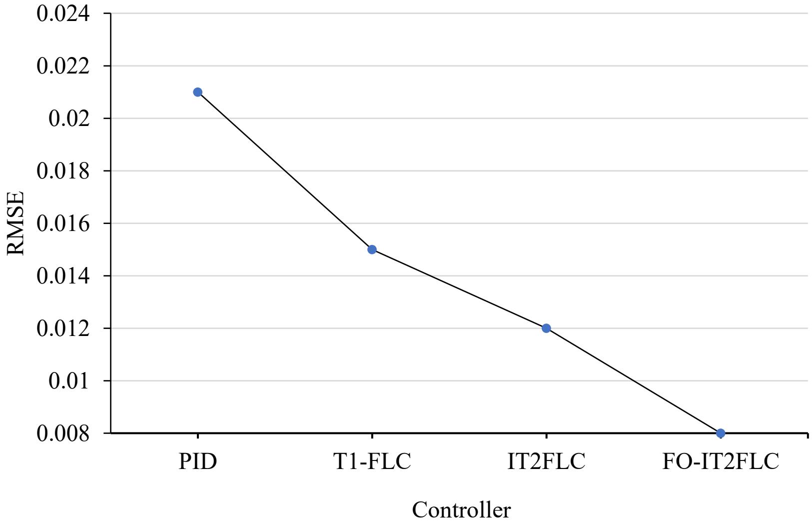

Figure 2. RMSE analysis of PID, T1-FLC, IT2FLC, and FO-IT2FLC controllers (dry road).

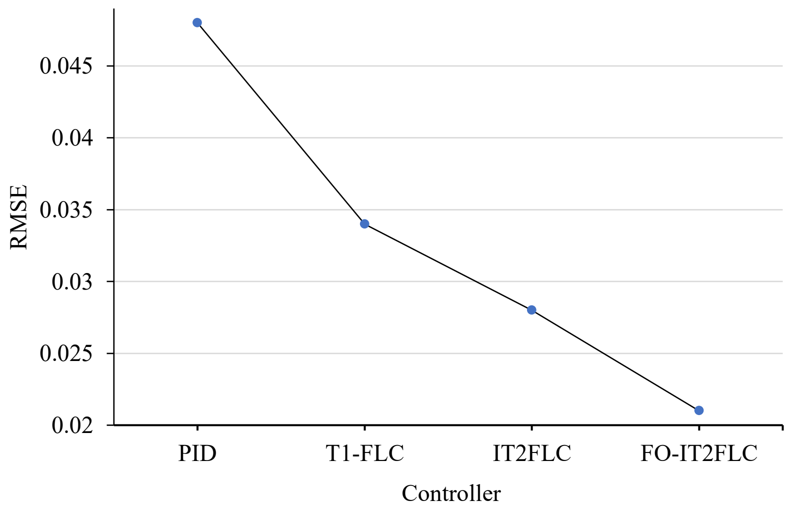

Figure 3. Slip root mean square error (RMSE) comparison across control methods (ice condition).

Table 5 compares the performance of the conventional PID controller with that of the proposed FO-IT2FLC controller across various braking control aspects. The FO-IT2FLC controller demonstrated faster settling, smoother torque response, improved slip ratio tracking, and enhanced robustness against parameter variations, resulting in better braking stability and disturbance rejection. Overall, the proposed controller significantly outperformed the PID controller by providing superior tracking accuracy, guaranteed closed-loop stability, and more reliable braking performance under varying operating conditions.

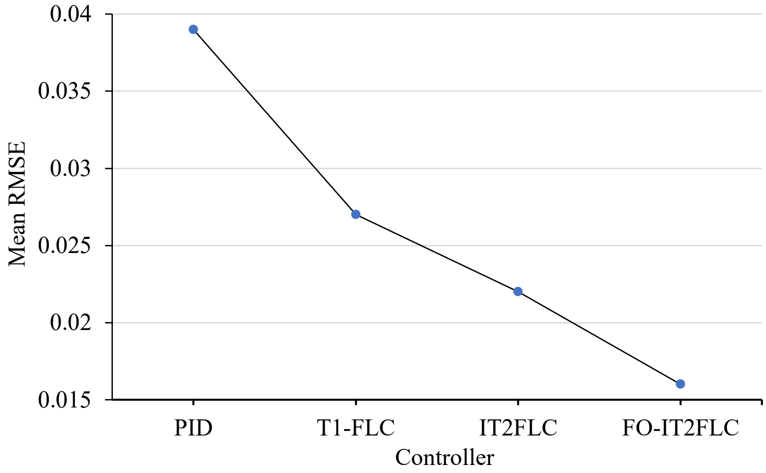

Figure 4. Monte Carlo mean RMSE comparison of PID, T1-FLC, IT2FLC, and FO-IT2FLC controllers under ±20% parameter variation.

Table 5. Performance comparison between PID controller and proposed FO-IT2FLC for nonlinear vehicle braking system.

Performance aspect	PID controller	Proposed FO-IT2FLC	Observed improvement
Slip Ratio Tracking	Noticeable overshoot and oscillations before settling	Fast convergence with minimal overshoot and reduced oscillations	Improved tracking accuracy and stability
Settling Time	Longer settling time	Shorter settling time	Faster transient response
Brake Torque Behavior	High initial spikes and oscillatory torque profile	Smooth, gradually decreasing torque response	Reduced actuator stress and smoother braking
Vehicle Speed Decay	Stable but less smooth deceleration	Smooth and consistent deceleration	Enhanced braking smoothness
Stability Verification (Lyapunov Function)	No theoretical stability guarantee shown	Monotonically decreasing Lyapunov function	Guaranteed closed-loop stability
Robustness	Sensitive to parameter variations	Robust under varying conditions	Improved disturbance rejection capability
Overall Performance	Moderate control performance	Superior performance in tracking, stability, and robustness	Significant performance enhancement

CONCLUSION

This study presented a Lyapunov-stable Adaptive Fractional-Order Interval Type-2 Fuzzy Logic Controller for robust anti-lock braking under uncertain road adhesion conditions. By integrating fractional-order error dynamics, interval Type-2 fuzzy inference, and adaptive parameter tuning within a unified stability-guaranteed framework, the proposed approach effectively addresses nonlinear vehicle dynamics, parametric uncertainty, and memory-dependent braking behavior. Comprehensive simulations across multiple road conditions and parametric perturbations demonstrated superior slip-tracking accuracy, reduced overshoot, shorter braking distance, and enhanced robustness compared with the PID, Type-1 FLC, and conventional IT2FLC methods. Frequency-domain analysis confirmed improved gain and phase margins, validating enhanced stability robustness. The proposed controller provides a theoretically rigorous and computationally feasible solution for next-generation intelligent braking systems in advanced driver-assistance and autonomous vehicles. Future work will focus on hardware-in-the-loop validation and experimental implementation of the proposed method. Overall, the proposed methodology provides a theoretically grounded and practically viable intelligent-braking solution. Future work will focus on real-time hardware implementation, multi-axle vehicle modelling with load-transfer dynamics, and experimental validation under diverse road conditions.

REFERENCES

1. Amirkhani A, Shirzadeh M, Molaie M. An indirect type-2 fuzzy neural network optimized by the grasshopper algorithm for vehicle ABS controller. IEEE Access. 2022;10:58736-51.
2. Lin CM, Hsu CF. Self-learning fuzzy sliding-mode control for antilock braking systems. IEEE Trans Control Syst Technol. 2003;11(2):273-8.
3. Mizuno T, Kataoka H, Yamazaki H, Chen G, Takami I. Robust LQ control of ABS based on polytopic representation using descriptor representation and linear fractional transformation. In: Proceedings of the 11th IEEE International Conference on Control & Automation (ICCA 2014); 2014 Jun 18-20; Taichung, Taiwan. 2014. p. 803-808.
4. Emami KJ, Akbarzadeh-T MR. Adaptive discrete-time fuzzy sliding mode control for anti-lock braking systems. In: Proceedings of the 22nd International Conference of the North American Fuzzy Information Processing Society (NAFIPS 2003); 2003 Jul 24-26; Chicago, IL, USA. 2003. p. 335-340. doi:10.1109/NAFIPS.2003.1226807.
5. Hsu CF. Intelligent exponential sliding-mode control with uncertainty estimator for antilock braking systems. Neural Comput Appl. 2016;27(6):1463-75.
6. He Y, Zhou Y, Liu X, Cai Y, Yuan C, Tian L. An adaptive finite-time control method for antilock braking system with experimental analysis. Proc Inst Mech Eng Part D J Automob Eng. 2024;238(9):2583-96.
7. Wang D, Liu S, Wei X, He Y. A wheel slip ratio constraint control for ABS based on tangent type barrier Lyapunov function. Meas Control. 2023;56(1-2):411-9.
8. Yang JH, Yang CC. Adaptive sliding mode control for vehicle brake systems with fuzzy composition. Int J Model Identif Control. 2008;4(2):112-26.
9. Chen GM, Wang WY, Lee TT, Tao CW. Observer-based direct adaptive fuzzy-neural control for anti-lock braking systems. Int J Fuzzy Syst. 2006 Dec;8(4):208-218.
10. Wen Y, Zhou XF, Zhang Z, Liu S. Lyapunov method for nonlinear fractional differential systems with delay. Nonlinear Dyn. 2015;82(1):1015-25.