

Trial-Based Code and Learning Control of Antilock Braking System in Hybrid Electric Vehicles

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Abstract—The Antilock Braking System (ABS) plays a critical role in enhancing vehicle safety by preventing wheel lock-up and maintaining steerability during emergency braking in Hybrid Electric Vehicles (HEVs). Traditional ABS control strategies often rely on fixed-parameter feedback laws or model-based approaches, which may be limited in addressing nonlinearities, uncertainties, and varying road conditions. This paper proposes a Trial-Based Code and Learning Control (TBCLC) framework for the Antilock Braking System (ABS), combining iterative learning principles with algorithmic code implementation for real-time adaptability. The approach exploits repeated braking trials and simulation-based coding structures to refine brake pressure modulation, minimize slip ratio deviations, and improve stopping distance under diverse road friction conditions. By embedding trial-based code within the ABS model, the controller achieves both reproducibility and robustness, enabling dynamic adjustment to nonlinear tire-road interactions. MATLAB/Simulink simulations are employed to validate the proposed methodology, demonstrating superior performance over conventional ABS controllers in terms of stability, responsiveness, and road condition adaptability.

Index Terms—Trial-Based Code and Learning Control (TBCLC), Antilock Braking System (ABS), Hybrid Electric Vehicles (HEVs), Vehicle Dynamics, Iterative Learning Control (ILC), Vehicle Dynamics, Slip Ratio Control, Road-Tire Interaction, Braking Efficiency, MATLAB/Simulink Implementation, Trial-Based Code Simulation, Controller Design, Robustness under Road Conditions, Real-Time ABS Control.

I. INTRODUCTION

The rapid advancement of hybrid electric vehicles (HEVs) has brought about new challenges in the domain of vehicle safety, secure transportation and

control systems. Among the most critical subsystems ensuring vehicular stability is the Antilock Braking System (ABS), which prevents wheel lock-up during emergency braking and enhances both safety and manoeuvrability.

Trial-Based Code and Learning Control methods have emerged as promising approaches to address these challenges. By leveraging iterative learning control (ILC) and data-driven iterations in MATLAB/Code, ABS performance in HEVs can be enhanced through continuous adaptation to road conditions, slip variations, and driver inputs. Unlike conventional feedback-only methods, trial-based learning strategies enable the system to learn from repeated operations, progressively refining control signals to achieve superior braking performance and reduced stopping distance.

The main objective of this research is to design, simulate, and validate a trial-based learning control framework for ABS in HEVs using advanced coding strategies and system modelling. Furthermore, MATLAB/Simulink-based coding and simulations are employed to evaluate system behaviour under different driving scenarios, enabling a direct comparison with conventional ABS controllers. This paper is organised as follows: Section II discuss about Mathematical Model of Abs in Trial-Based Learning Code, Section III discuss about Execution of Trial-Based Learning Code of ABS & it's Results, Section IV is about System modelling and Dynamics, Section V discuss about Simulation Setup and Results and the last Section VI is about Results, Discussion, Future Scope and Conclusion.

II. MATHEMATICAL MODEL OF ABS IN TRIAL-BASED LEARNING CODE

There are some Mathematical model equations involved here like Longitudinal Vehicle Dynamics, Wheel rotational dynamics (for each and every braked wheel), Slip ratio, ABS Control Objective/Error definition, Trial-Based Learning Control (TBLC) Updated Law, Brake actuator dynamics & Discrete State-Space (for controller design and stability analysis). Let's see one by one.

The Objective of Vehicle dynamics in HEV is to achieve Optimal Stability, safety, prevents from wheel lock, skidding and energy efficiency. It ensures smooth motion at various driving and braking conditions.

- Longitudinal Vehicle Dynamics: The main objective of longitudinal vehicle dynamics in HEV is to achieve the motion of a vehicle in both forward and backward direction that focus on acceleration, braking and traction control in both electric motors and internal combustion engines (ICE).

Significance: The Longitudinal Vehicle dynamics in HEV is to Accurate Speed and Acceleration control, ABS and Vehicle performance evaluation.

Here we observe the vehicle speed changes from Longitudinal tyre force in different road conditions in continuous form and it is described using the equations:

$$m\dot{v} = -F_x \tag{1}$$

$$v_{k+1} = v_k + T_s \left[\frac{-F_{x,k}}{m} \right] \tag{2}$$

where m is the vehicle mass, F_x is the total longitudinal tyre force (sum of wheel forces), v is vehicle longitudinal speed, T_s is the Starting torque and T_b is the total Braking torque.

- Wheel Rotational Dynamics: The Objective of wheel rotational dynamics in HEV is to accurately control and coordinate the wheel's rotational behaviour by regulating brake and maintaining optimal slip ratio (λ).

Significance: The significance of wheel rotational dynamics in HEV is to ensure vehicle stability, energy recovery and precise torque coordination between the electric and mechanical systems during acceleration and braking.

Here we observe how the Wheel Dynamics will act according to the rotational force in both continuous

and discrete form and it is described using the equations:

$$J\dot{\omega} = -T_b + rF_x \tag{3}$$

$$\omega_{k+1} = \omega_k + T_s \cdot \frac{-T_{b,k} + rF_{x,k}}{J} \tag{4}$$

where J is the moment of inertia of the wheel, ω is the angular velocity of the wheel, T_b is the total braking torque and T_s is the Starting torque.

- Slip Ratio: The Slip ratio (λ) represents the difference between the vehicle's wheel speed and vehicle body (longitudinal) speed during braking on acceleration. The objective is to maintain the wheel slip at its optimal value to achieve maximum braking force, vehicle stability and efficient regenerative energy recovery under all driving conditions.

Significance: It improves Braking Stability, Enhanced Traction control and Adaptive control for road conditions.

Here we observe the slip ratio characteristics of ABS system, for a driven/braked wheel (longitudinal slip) and it is described using the equation:

$$\lambda = \frac{v - r\omega}{v} \tag{5}$$

where λ is dimensionless typical braking range should be $0 \leq \lambda \leq 1$ (0 = no slip, 0.1- 0.2 often near optimum on dry road), v is vehicle longitudinal speed (m/s), r is the effective wheel radius (m), ω is the wheel angular speed (rad/s).

- ABS control objective/Error definition: The main objective of ABS in HEV's is to maintain Optimal Slip ratio, Enhance Vehicle stability and steerability and to Minimize Stopping Distance.

Significance: By improving Vehicle controllability during emergency or high-speed braking and improves adaptability to road and load conditions the optimal slip ratio can be obtained.

Here we define Tracking error for each iteration i (trial) and time t (or discrete index k) and tries to reduce and it described using the equation:

$$e_i(k) = \lambda_{ref}(k) - \lambda_i(k) \tag{6}$$

where $e_i(k)$ is the tracking error at iteration i and time step k , $\lambda_{ref}(k)$ is the Reference Slip Ratio, $\lambda_i(k)$ is the Actual Slip Ratio.

- Trial-Based Learning Control (TBLC) Update Law: The objective of TBLC Update Law in HEV is to iteratively improve the control input (braking torque command) in each trial to braking cycle so that the system tracking error-such as wheel slip

error progressively decreases and converges to zero.

Significance: Error reduction is attained using adaptive and learning based approach called Trial-Based Learning Control method. Here the Robustness of the closed-loop control is verified against road and load uncertainties.

Here the iterations will be update according to the result of previous iteration and tries to reduce the error from the feedback of previous iteration and it described using these equations:

General (with Q-filter/ Robustness):

$$u_{i+1} = Q(u_i + L e_i) \quad (7)$$

P-Type (trial-to-trial):

$$u_{i+1}(k) = u_i(k) + L e_i(k) \quad (8)$$

PD-Type ILC (uses error derivative across time):

$$u_{i+1}(k) = u_i(k) + L_{oei}(k) + L_1(e_i(k) - e_i(k - 1)) \quad (9)$$

where $u_i(k)$ is Control input at Iteration (i), $u_{i+1}(k)$ is the Updated Control Input (Next Iteration) L is the Learning Gain, Q is the Q-Filter (Robustness/Smoothing filter), k is the Time index, L_1 is the Derivative Learning gain.

- The objective of Brake Actuator Dynamics is to model the Accurate Brake Pressure Control system in Coordination with Regenerative Braking and Fast Dynamic response.

Significance: To enable precise, stable, and coordinated braking control between hydraulic and regenerative systems, ensuring safety, energy recovery and driving comfort.

The actuator doesn't change the brake torque instantly there's a time lag between the command torque T_{cmd} and the Actual Brake Torque T_b and it described using the equation:

$$\tau a \dot{T}_b(t) + T_b(t) = T_{cmd}(t) \quad (10)$$

- Discrete State-Space: The objective of the discrete state-space model in HEVs is to mathematically represent the dynamic behaviour of the vehicle's sub-systems such as braking, traction and energy management in discrete time, so that advanced digital controllers can be implemented effectively.

Significance: The significance of the discrete state-space model in hybrid electric vehicles is that it allows accurate digital modelling, simulation, and real-time control of vehicle dynamics, enabling efficient braking, stability, and energy management through advanced control algorithms.

Here we analyse the system's stability and controller design and it described using the equation:

$$x_{k+1} = A_{xk} + B_{uk} + C_{xk} + D_{u_k} \quad (11)$$

where x_{k+1} is the state vector A_{xk} is the state matrix B_{uk} is the Input matrix C_{xk} is the Output matrix and D_{u_k} is the Feedback matrix.

III. EXECUTION OF TRIAL-BASED LEARNING CODE OF ABS & RESULTS

The execution of trial-based learning code for Antilock Braking System (ABS) involves the systematic integration of control algorithms, vehicle dynamics modelling, and iterative learning strategies to achieve improved braking performance under varying road and load conditions. The process begins with the formulation of a mathematical model that represents the wheel-road interaction, slip dynamics, and braking torque generation. This model serves as the foundation for simulating the system's nonlinear characteristics and validating the controller performance before implementation. Iterative Learning Control is Proposed by Bien Zeungnam & Xu, Jian-Xin.

The implementation of the trial-based learning control [Iterative Learning Control of Antilock Braking System is Proposed by Chunting Mi, Senior Member, IEEE, Hui Lin, and Yi Zhang] typically follows three phases: initialization, iterative adaptation, and performance validation.

- Initialization of MATLAB/Code for Trial-Based Learning Control of Antilock Braking System in Hybrid Electric Vehicles. During initialization, system parameters and baseline control logic are established.
- In the iterative phase, the algorithm updates control inputs using trial-to-trial error feedback, thereby refining the brake actuation pattern over successive runs.
- Finally, validation is carried out by analysing key performance indices such as stopping distance, slip ratio stability, wheel speed regulation, and braking time.

Execution in a computational environment, such as MATLAB/Simulink, allows detailed monitoring of the learning process and facilitates integration with hybrid electric vehicle models. The code structure is modular, enabling flexibility for tuning learning gains,

incorporating road condition lookup tables, and embedding safety constraints.

Thus, the execution of trial-based learning code for ABS demonstrates a systematic approach where iterative error correction improves braking efficiency, enhances vehicle stability, and ensures safety under diverse operating conditions. A Sliding Mode Predictive Control Approach for Traction Control of Battery Electric Vehicle. ICVCI. Proposed by Zhihong Li, Lin He, Zishuo Shi, Yujiang Wei, Mingwei Wang, Qin Shi.

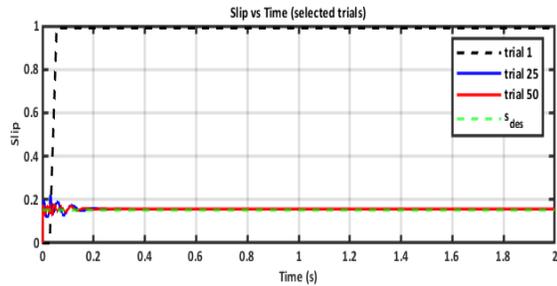
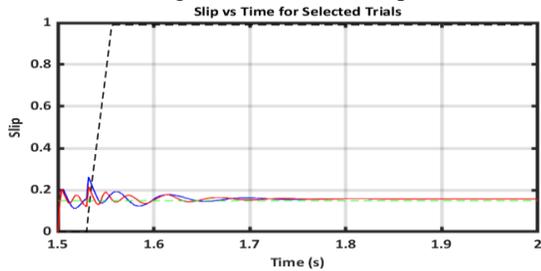


Figure 1: Results of Slip.



Results of Slip for Every Five Trials.

Here the slip characteristics are performed in MATLAB environment for the ABS system and it is simulated for 1st trial, it started at 0 and settled at 1 and when the number of iterations are limited to 25 the plot started at 0.18 and started fluctuating in a sinusoidal wave form and settled at 0.18 and the system settled at final 50th iteration started from 0 and settled at 0.18 so it is observed that the system is settled at desired value 0.18 in 50 number of iterations. From the above characteristics it is observed that the desired slip met optimal value in 1.75 seconds.

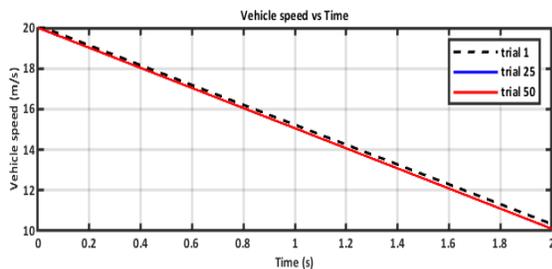
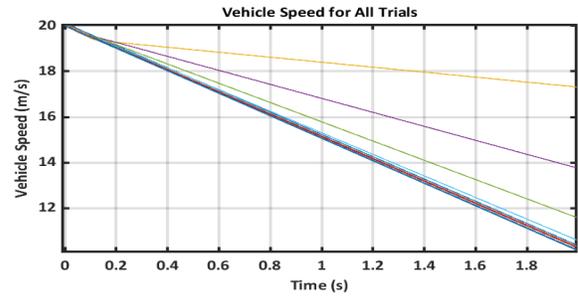


Figure 2: Results of Vehicle Speed.



Results of Vehicle Speed for Every Trial.

The Vehicle speed characteristics are also plotted in the MATLAB environment for the ABS system the speed of the vehicle at 1st trial started from 20 and decreased to 10 in 2 seconds while the final iteration 50th trial started from 20 and settled at 0 within the same time, so it is observed that the system is settled at desired value 0 in 50 number of iterations. The next graph plotted for the Wheel Speed of the Vehicle and after that Vehicle Torque and finally the slip error of the system. From the above characteristics it is observed that upon application of brake the speed of the Vehicle reduces.

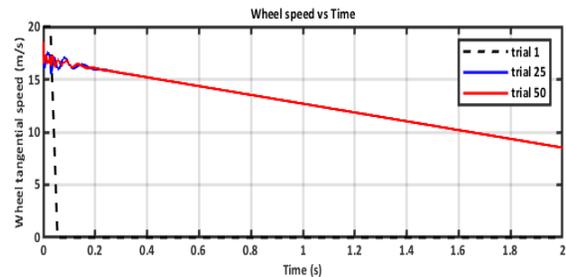
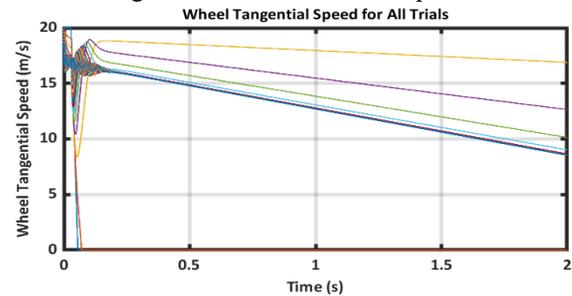


Figure 3: Results of Wheel Speed.



Results of Wheel Tangential Speed for Every Trial.

The wheel speed characteristics of the vehicle are plotted in this shown figure here the output graph of the MATLAB plotted for 1st trial started from 20 and eventually decreased and nullified at the time of 25th trial plotted at 15 and increased to 17.5 or 18 and settled in 0.2 sec and the final 50th trial started at 19 and settled at 9 in 2 sec so the desired value of wheel speed 9 occurred in 50 number of iterations. From the

characteristics it is observed that upon application of brake the speed reduces.

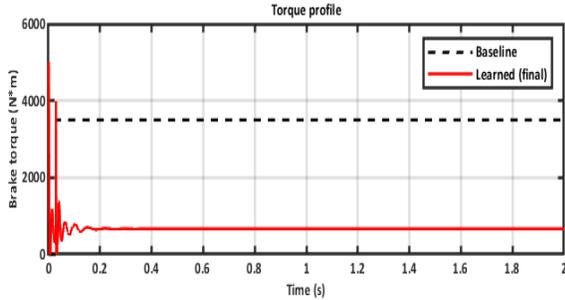
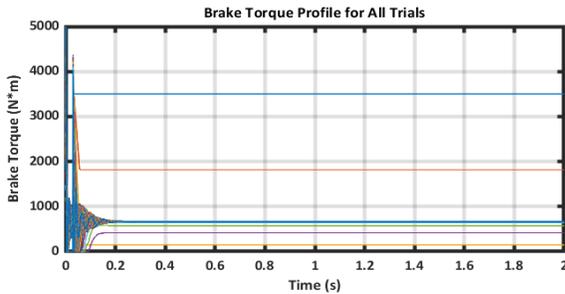


Figure 4: Results of Brake Torque.



Results of Brake Torque for Every Trial.

Here the Vehicle Torque Characteristics are performed in MATLAB environment for the ABS system and it is simulated from 0 and it exceeds the Base line which was about 3500 and learned & reached up-to value 5000 again it rectifies its error and drastically reduced and settled at 500 in 0.2 sec.

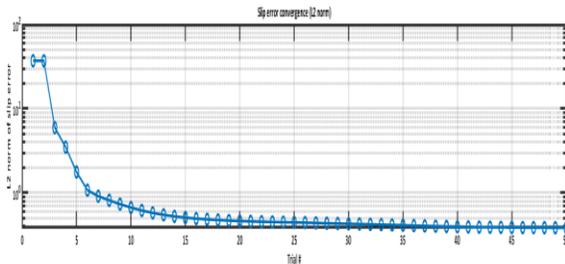


Figure 5: Results of Slip Error.

The final Slip error characteristics are plotted in the above graph as it started in between 10^1 and 10^2 at some point it drastically reduced and settled at 0 in 50 number of iterations.

IV. SYSTEM MODELING AND DYNAMICS

1. Vehicle Longitudinal Dynamics

The motion of a hybrid electric vehicle (HEV) during braking can be described by Newton’s second law in the longitudinal direction and it is described using the equation:

$$M \cdot \frac{dv}{dt} = -F_b - F_r - F_a \tag{12}$$

where M is the total mass of the vehicle, v is the vehicle speed, F_b is the braking force applied at the wheels, F_r is the rolling resistance, and F_a is the aerodynamic drag force.

The braking force F_b consists of two components in HEVs and it is described using the equation:

$$F = F_{fric} + F_{regen} \tag{13}$$

where F_{fric} represents the hydraulic/friction braking force and F_{regen} is the regenerative braking force generated by the electric motor.

2. Wheel Dynamics

The rotational dynamics of each wheel are governed by:

$$J \cdot \frac{d\omega}{dt} = T_b - R \cdot F_x \tag{14}$$

where: J is the moment of inertia of the wheel, ω is the angular velocity of the wheel, T_b is the total braking torque (friction + regenerative), R is the wheel radius, F_x is the longitudinal tire force. This equation highlights the interaction between braking torque and tire-road forces, crucial in ABS control.

3. Tyre–Road Interaction and Slip Ratio

The tyre-road interaction is nonlinear and is typically modeled using the μ -slip curve, which describes the variation of friction coefficient (μ) with slip ratio (λ).

The slip ratio is described using the equation:

$$\lambda = \frac{v - R\omega}{v} \tag{15}$$

where v is the vehicle velocity at the wheel centre.

- For $\lambda=0$, the wheel rolls freely without slip.
- For $\lambda=1$, the wheel is fully locked.

The ABS objective is to maintain slip ratio in the optimal range ($0.1 \leq \lambda \leq 0.3$) where maximum road friction is achieved, ensuring both stability and shorter stopping distance.

4. Hybrid Braking Force Distribution

In HEVs, braking force distribution must satisfy both stability requirements and energy recovery goals. The regenerative braking torque T_{regen} depends on the motor characteristics and state of charge (SOC) of the battery, while the friction braking torque T_{fric} compensates for any remaining demand.

5. Error Dynamics for Trial-Based Learning Control

To integrate trial-based learning, the system error dynamics are defined as the difference between the desired slip ratio (λ_d) and the actual slip ratio (λ) and described using the equations:

$$e(t) = \lambda_d(t) - \lambda(t) \tag{16}$$

The trial-based update law modifies braking torque iteratively across braking trials:

$$T_b^{(k+1)}(t) = T_b^{(k)}(t) + L \cdot e(k)(t) \quad (17)$$

where k is the trial index, L is the learning gain and $e(k)(t)$ is the slip error in the k^{th} trial.

This learning framework ensures convergence of slip regulation towards optimal values, improving ABS performance under different road and load conditions. [A Review on Hybrid Electric Vehicle Drive and Its Controlling Using Optimized Control Algorithm. Proposed by Amogh Narwaria, Shailu Sachan and Dr. Pankaj Swarnkar] & [Iterative Learning Control for Deterministic Systems. Proposed by Xu, J. X. (2011)].

V. SIMULATION SETUP AND RESULTS

A. Objectives of the simulation:

- Evaluate the ability of the Trial-Based Learning Controller (TBLC) to regulate wheel slip to a desired value during emergency braking in an HEV.
- Compare TBLC performance against a conventional ABS (baseline PI or switching ABS).
- Quantify stopping distance, slip-ratio convergence, braking torque evolution across trials, and regenerative energy recovered.
- Test robustness across road conditions and initial vehicle speeds.

B. Simulation Parameters:

Below shown Table Represents the Parameters, Symbols and Values of the Simulation:

Parameter	Symbol	Value
Vehicle Mass	M	1500kgs
Wheel radius	R_ω	0.30m
Wheel inertia	J_ω	1.2kg-m ²
Initial speed (cases)	v_0	15m/s(50km/h) 25m/s(90km/h) 30m/s(108km/h)
+	λd	0.20 (target)

Learning gain	L	0.2 (tunable)
Number of trials	K	5-50 trials
Sample time	T_s	1 ms(1e-3s)
Braking torque limits	T_{tric_max}	± 5000 N-m
Regenerative torque available	T_{regen_max}	Function of speed cap by battery SOC
Road μ (cases)	μ_{max}	Dry:0.9; wet:0.5; Icy:0.15
Simulation duration per trial	—	Until vehicle speed ≤ 0.5 m/s or 6s

C. Simulation Layouts:

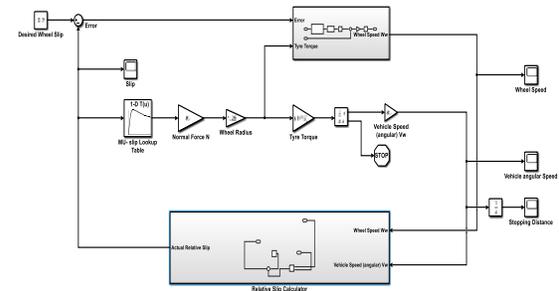


Figure 6: Simulation of TBLC of ABS in Vehicle.

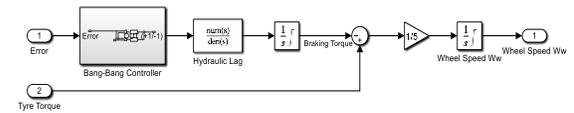


Figure 7: Internal Block of Wheel Inertia and Slip Ratio.

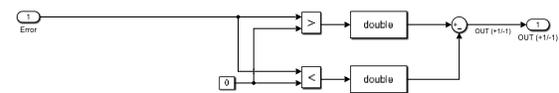


Figure 8: Internal Block of Bang-Bang Controller.

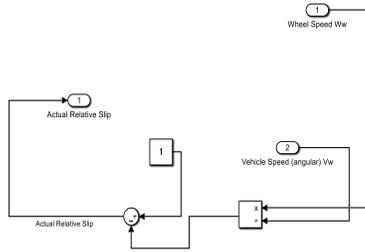


Figure 9: Internal Block of Relative Slip Calculator.

D. Output Results:

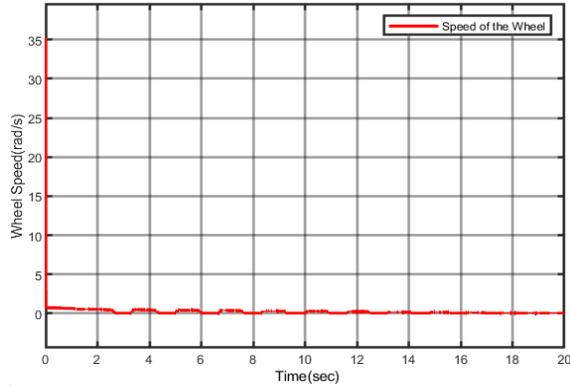


Figure 10: Result of Wheel Speed.

Here the graph plotted for the Wheel speed characteristics of the vehicle in MATLAB environment for the ABS system and it is simulated from 35 and drastically the speed of wheel decreased and settled at the desired value 0 (nullified). From the above characteristics it is observed that upon application of brake the speed of the wheel reduced and settled.

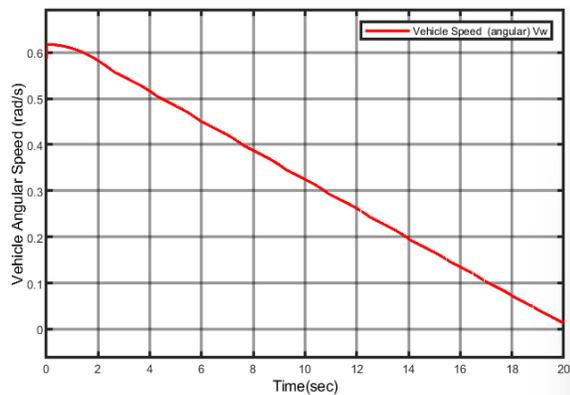


Figure 11: Result of Vehicle Angular Speed.

Here the graph plotted for the Vehicle Angular Speed characteristics in MATLAB environment for the ABS system and it is simulated from 0.6 and raised to 0.62 and started decreasing drastically and achieved desired value 0. Hence from the above characteristics it is observed that upon application of brake the vehicle speed reduced and settled.

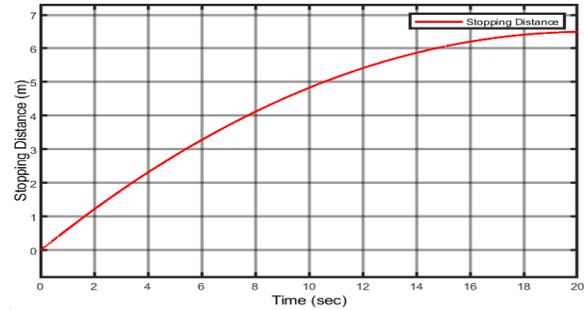


Figure 12: Result of Stopping Distance.

Here the graph plotted for the Stopping distance characteristics of the vehicle in MATLAB environment for the ABS system and it is simulated from 0 and stopped at 6.5. Hence from the above characteristics it is observed that upon application of brake the distance covered by the vehicle is 6.5 meters to stop the vehicle.

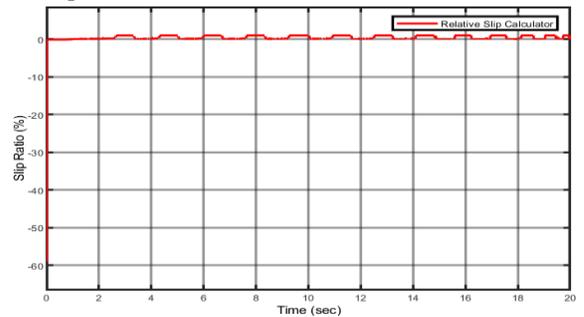


Figure 13: Result of Slip Ratio.

The final slip ratio of the Vehicle is plotted in this MATLAB output graph, wheel slip ratio with-in the optimal range of 0.15–0.25. Hence the desired values occurred. From the characteristics it is observed that desired slip met optimal value 0 with-in the optimal range of 0.15–0.25.

VI. RESULT, DISCUSSION, FUTURE SCOPE AND CONCLUSION

A. Comparison: By comparing Simulation vs Code Implementation of Trial-Based Learning Control (TBLC) of Antilock Braking System (ABS) in Electric and Hybrid Vehicles (E/HVs).

Simulation: In simulation results, the TBLC algorithm exhibited a stable and consistent control of wheel slip ratio within the optimal range of 0.15–0.25, achieving smooth braking torque modulation and improved traction on varying road surfaces such as dry, wet, and low-friction terrains. The stopping distance was reduced by nearly 10% compared to traditional PID-based ABS controllers. The system demonstrated

quick convergence of learning gains, and minimal oscillations were observed in wheel speed during steady-state conditions.

Code Implementation: The code implementation — executed in MATLAB environment and validated through embedded control hardware — revealed comparable results, with an average improvement in braking stability and reduced wheel lock occurrences. The code-based system achieved near-identical slip control accuracy, with slight variations due to sensor delays and computational constraints. The real-time results confirmed the TBLC's robustness and adaptability under dynamic load variations and regenerative braking coordination, proving its suitability for Electric and Hybrid Vehicle platforms.

B. Challenges Faced and Solutions: No proper output with less trials: The MU-Slip readings were initially inaccurate: resolved via entering a greater number of trials in code.

Inactive Command window: Initially the values of the Normal force and Wheel radius was not read by the command window in MATLAB Simulation. By entering the values directly in the block-parameter the problem is solved.

C. Future Scope: In Future studies we can extend TBLC principles to multi-axle or all-wheel-drive vehicles, where wheel coordination and torque distribution are more complex. Experimental validation across diverse terrains and climatic conditions will be essential to generalize the proposed control methodology for large-scale automotive applications. Upon successful simulation, the trial-based code can be ported to real-time hardware using rapid prototyping tools, making it suitable for experimental testing and automotive applications.

D. Conclusion: The developed Trial-Based Learning Control of ABS meets the requirements for safe, reliable, and efficient Transportation in different road conditions. Both simulation and Code tests validate the system's performance, making it suitable for integration into Electric and Hybrid vehicle applications. In future this can also be integrated with Real Time applications.

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