**1. Introduction**

The effectiveness of Anti-lock Braking Systems (ABS) in maintaining vehicular control and minimizing stopping distances is well-documented under ideal or moderately slippery conditions such as wet or icy roads. However, real-world driving often involves rough and irregular terrains such as gravel, potholes, and unpaved roads. These environments introduce challenges that significantly affect ABS performance, yet are underrepresented in existing research. This study seeks to bridge that gap by systematically investigating the behavior of ABS on rough road surfaces through advanced modeling and control strategies.

**2. Methodology**

This study employs a multi-faceted simulation and control framework to analyze ABS behavior under rough terrain conditions. The methodology is composed of the following key components:

**2.1 Terrain-Specific Simulation Setup**

Using MATLAB Simulink, we construct a detailed vehicle model incorporating:

* Tire dynamics based on the **Burckhardt tire model** and **discrete tire modeling** for granular terrain feedback.
* Road profiles representing **rough terrains**, such as gravel roads and pothole-filled surfaces, by varying friction coefficients and introducing surface irregularities.

**2.2 Wheel Speed Fluctuation Analysis**

On rough roads, **wheel speed sensors** are prone to false readings due to vertical wheel oscillations from uneven surfaces. These fluctuations are analyzed to:

* Differentiate between **actual wheel lock** and **false slip signals**.
* Enhance the accuracy of ABS response through improved signal filtering and processing.

**2.3 Advanced Control Strategy Integration**

Three control strategies are explored and benchmarked:

* **Fuzzy Sliding Mode Control (FSMC):** Combines robustness of sliding mode with fuzzy logic to adapt brake pressure modulation in real-time.
* **Barrier Function-Based Integral Sliding Mode Control (BF-ISMC):** Imposes constraints on slip ratio to maintain safety and stability boundaries under disturbances.
* **Exploration-Exploitation Control (DCEE using Regularized Particle Filter):** A dual learning approach that continuously estimates road friction and vehicle states, enabling adaptive brake force application.

**2.4 Performance Metrics and Evaluation**

The effectiveness of ABS under rough road conditions is evaluated using the following metrics:

* **Braking Distance:** Measures the stopping efficiency across terrain types.
* **Slip Ratio Control Accuracy:** Assesses how well traction is maintained.
* **Wheel Speed Fluctuation Management:** Identifies false-positive lock detections and correction efficiency.
* **Brake Pressure Modulation:** Evaluates responsiveness and appropriateness of brake force adjustments.
* **Vehicle Stability:** Measured through yaw rate and lateral acceleration during braking maneuvers.

**3. Novelty of the Study**

This study introduces several innovative elements that distinguish it from conventional ABS research:

**3.1 Focus on Rough and Uneven Terrains**

Most existing studies center around ABS performance on wet, dry, or icy roads. This study uniquely targets **rough and unpredictable terrains**, exploring the impact of terrain-induced dynamic disturbances on wheel-road interaction and ABS performance.

**3.2 Integration of Real-Time Estimation with Control**

By incorporating the **Regularized Particle Filter (RPF)** with dual exploration-exploitation control, the system can:

* Adaptively learn and respond to unknown road conditions.
* Enhance braking performance in real-time, particularly where terrain characteristics fluctuate unpredictably.

**3.3 Multi-Model Control Comparison**

This research uniquely benchmarks and compares the performance of:

* **Fuzzy-based**,
* **Barrier function-constrained**, and
* **Dual control estimation-based** ABS approaches.

This comparative insight provides a deeper understanding of how different control mechanisms handle **nonlinearities**, **uncertainties**, and **terrain-induced disruptions**.

**3.4 Advanced Tire Modeling for Terrain Representation**

A **discrete tire modeling** approach is utilized to capture complex tire-road interactions with higher accuracy, unlike simplified linear models used in earlier studies. This adds realism to simulation outcomes and improves the predictability of ABS algorithms under rugged driving conditions.

**4. Conclusion**

This study offers a novel perspective on Anti-lock Braking System (ABS) performance by shifting the focus from ideal test environments to **realistic, rugged road conditions**. The combination of advanced modeling, adaptive control strategies, and performance evaluation metrics ensures that the developed insights are both **scientifically rigorous** and **practically applicable**. The findings aim to contribute significantly to the development of next-generation ABS technologies tailored for diverse and challenging real-world terrains.