

Regenerative Braking Systems in Electric Two- Wheelers: A Comprehensive Survey

¹Bhagya, ²Basavarajappa Y H

[#]Department of Electric Vehicle Technology, Visvesvaraya Technological University
—Jnana Sangamall, Belagavi – 590018, Karnataka, India

¹bhagyasm789@gmail.com

²yhbphd@gmail.com

Abstract—Regenerative braking is a pivotal technology for extending the range and improving the energy efficiency of electric two-wheelers (E2Ws). This survey systematically reviews over 45 research contributions spanning 2005–2025, covering the fundamental physics of regenerative braking, motor drive topologies, energy storage interfaces, control strategies (rule-based, fuzzy logic, sliding mode, model-predictive, and deep reinforcement learning), two-wheeler-specific stability constraints, and standardised evaluation methodologies. Taxonomy tables classify each reviewed work by control approach, vehicle type, and key performance metric. Open research challenges—including real-time terrain adaptation, thermal management of regenerative duty, and integration with vehicular communication networks—are identified and promising future directions outlined. This survey is intended to serve as a foundational reference for researchers and engineers working on smart energy management in electric two-wheelers.

Keywords—Regenerative braking, electric two-wheeler, fuzzy logic, energy management, BLDC motor, review.

I. INTRODUCTION

Electric two-wheelers (E2Ws) have emerged as a sustainable urban mobility solution, driven by rising fuel costs, tightening emission norms, and advances in lithium-ion battery technology. Globally, E2W sales crossed 50 million units in 2024, with India and China collectively accounting for over 80% of the market. Despite continued improvements in battery energy density, range anxiety remains a key barrier to mass adoption.

Regenerative braking (RB)—the process by which kinetic energy during deceleration is converted back to electrical energy and stored in the battery—offers a practical pathway to extending range without increasing battery size or weight. In urban duty cycles characterised by frequent stop-and-go events, regenerative braking can recover 10–30% of total traction energy, depending on the quality of the control strategy.

While regenerative braking in electric cars has been studied extensively and is commercially mature, its counterpart in two-wheelers poses unique engineering challenges: narrower tyre contact patches, significant pitch dynamics under braking, single-chain drivetrain configurations, lower vehicle mass (increased sensitivity to torque disturbances), and cost constraints that limit sensor integration. This survey reviews the state of the art with specific reference to these constraints.

A. Motivation and Scope

This survey is motivated by the absence of a comprehensive review that simultaneously addresses: (i) control theory advances, (ii) hardware implementation on embedded platforms, (iii) stability and safety constraints unique to two-wheelers, and (iv) standardised benchmarking. The survey covers literature from 2005 through early 2025, with emphasis on works published after 2015 which reflect the commercialisation era of E2Ws.

B. Survey Methodology

A systematic literature search was conducted on IEEE Xplore, ScienceDirect, and Google Scholar using the keywords: 'regenerative braking electric two-wheeler', 'e-scooter energy recovery', 'BLDC regeneration control', 'fuzzy braking EV', and 'two-wheeler ABS regeneration'. After de-duplication and relevance filtering, 47 papers were selected for detailed review.

II. PHYSICS OF REGENERATIVE BRAKING

A. Energy Flow Principles

When a vehicle decelerates, kinetic energy $KE = (1/2)mv^2$ must be dissipated. In conventional vehicles this is entirely converted to heat via brake pads. In EVs, the traction motor is operated as a generator: the motor's back-EMF drives current through the power electronics into the battery, producing a braking torque $\tau_{\text{regen}} = k_e \cdot I_{\text{regen}}$, where k_e is the motor's back-EMF constant and I_{regen} is the regenerative current.

The theoretical maximum recoverable energy is bounded by the Ragone relationship of the battery (power vs. energy density) and the motor's rated continuous current in generating mode. Practically, regenerative efficiency $\eta_{\text{total}} = \eta_{\text{motor}} \times \eta_{\text{inverter}} \times \eta_{\text{battery}}$, typically ranging from 55% to 82% at optimal operating points.

B. Two-Wheeler Specific Dynamics

During braking, the normal force on the rear wheel of a two-wheeler decreases significantly due to pitch-forward load transfer: $F_{\text{rear}} = mg \cdot (L_b/L) - (h/L) \cdot ma_x$, where L is wheelbase, L_b is rear axle to CoG distance, h is CoG height, and a_x is deceleration. This means the maximum friction force sustainable at the rear wheel diminishes during heavy braking, imposing an upper bound on rear-wheel regenerative torque below which wheel-lock must not occur.

For a typical 100 kg (vehicle + rider) scooter at 50 km/h braking at 5 m/s^2 , the rear-wheel normal force reduces by approximately 30%, limiting permissible regenerative braking torque to roughly 40 Nm — a constraint that must be embedded in the control logic.

III. MOTOR AND POWER ELECTRONICS TOPOLOGIES

A. Motor Types for E2W Regeneration

Brushless DC (BLDC) hub motors dominate E2W applications due to their compact form factor and elimination of mechanical transmission losses. Permanent-magnet synchronous motors (PMSM) with field-oriented control (FOC) offer superior torque linearity and regeneration efficiency but require more complex drive electronics. Switched reluctance motors (SRMs) have been

explored for their ruggedness but exhibit torque ripple challenges during regeneration.

TABLE I
MOTOR TYPE COMPARISON FOR E2W REGENERATION

Motor Type	Regen Eff.	Control Complexity	Control Strategy
BLDC (Hub)	65–75%	Medium	Conventional MPC (AN)
PMSM (FOC)	72–82%	High	Advanced MPC (AN)
Induction Motor	58–70%	High	DRP
SRM	60–72%	Very High	Low

B. Power Electronics

Two-quadrant and four-quadrant voltage-source inverters (VSIs) using SiC or GaN MOSFETs enable regenerative operation. Bidirectional DC-DC converters between the motor drive bus and battery allow voltage regulation independent of SoC, improving usable regeneration range. Recent work (Li et al., 2023) demonstrated Z-source inverter topologies achieving 3% higher peak regenerative efficiency at low vehicle speeds.

IV. CONTROL STRATEGIES — A SYSTEMATIC REVIEW

A. Rule-Based Control

Rule-based (RB) control was the earliest and remains the most widely deployed approach in commercial E2Ws. The regenerative torque is mapped as a piecewise linear function of brake lever position. Gao et al. (2015) formalised a parallel braking force distribution model that combines regenerative and mechanical braking in proportion to requested deceleration, with a fixed split ratio.

Advantages: zero computational overhead, deterministic behaviour, easy certification. Disadvantages: non-adaptive to battery SoC, speed, or road conditions; sub-optimal energy recovery; potential for discomfort at transition points between regenerative and friction braking.

B. Fuzzy Logic Control

Fuzzy logic controllers (FLCs) were introduced to E2W braking by Velupillai and Guvenc (2007) and have gained significant research attention. FLCs approximate human reasoning using linguistic rules, eliminating the need for precise system models. Inputs typically include: speed, SoC, deceleration demand, and gradient. Output: regenerative torque command.

Cho et al. (2019) demonstrated an FLC achieving 19.4% more energy recovery than rule-based control on a 48 V scooter test cycle. Fuzzy-PID hybrid controllers (Zhao et al., 2021) further improve steady-state accuracy. Adaptive fuzzy systems (Huang & Lin, 2022) update membership functions in real-time using gradient descent, achieving self-tuning across varying load conditions.

C. Sliding Mode Control (SMC)

SMC offers robustness to parametric uncertainty and disturbances. Tanelli et al. (2009) applied SMC to two-wheeler braking, combining slip-ratio control with deceleration regulation. The sliding surface is defined on the error between actual and desired wheel-slip, enabling aggressive yet stable energy recovery near the adhesion limit. A limitation is the chattering phenomenon, which causes high-frequency torque oscillations uncomfortable for riders; boundary layer approaches mitigate this at the cost of reduced robustness.

D. Model Predictive Control (MPC)

MPC optimises a cost function over a receding prediction horizon, naturally handling multi-objective trade-offs between energy recovery, comfort, and safety. Zhang et al. (2022) implemented an MPC with a 500 ms horizon on an FPGA-accelerated processor, achieving near-optimal braking torque allocation. The primary barrier to embedded E2W deployment is computational demand; PC variants running on ARM Cortex-M7 with 8 ms cycle times (Sun et al., 2023).

E. Reinforcement Learning (RL)

RL has emerged since 2020. Hu et al. proposed a Q-network (DQN) on 1,000 hours of data, achieving state-of-art energy recovery on a driver style. Twin Delayed DDPG

(TD3) agents (Chen & Zhao, 2024) demonstrated superior sample efficiency. Challenges include: large training data requirements, real-time inference latency on embedded processors, and safety guarantees in edge-case scenarios.

TABLE II
CONTROL STRATEGY COMPARISON

Strategy	Regen Improv.	Embedded	Adaptability
Rule-Based	Baseline	Very High	None
Fuzzy Logic	+15–22%	High	Medium
Sliding Mode	+18–25%	High	Low
MPC	+20–28%	Medium	High
Deep RL	+25–35%	Low	Very High

V. BATTERY AND ENERGY STORAGE CONSIDERATIONS

A. SoC-Aware Regeneration

Regenerating into a full battery is either impossible (BMS blocks charging) or damaging (lithium plating). SoC-aware control tapers regenerative torque as SoC approaches 100%, transitioning load to mechanical brakes. Lee et al. (2020) proposed a SoC prediction model using an Extended Kalman Filter (EKF) to anticipate battery acceptance current, pre-reducing regenerative torque before hard limits are reached.

B. Thermal Management

Continuous regenerative braking increases battery charging current and motor winding temperature. Ko et al. (2021) showed that exceeding 2C regenerative charge rate accelerates lithium-ion capacity fade by 18% over 500 cycles. Thermal-aware regeneration policies that reduce current when cell temperature exceeds 40°C have been proposed and validated experimentally.

C. Supercapacitor Hybridisation

To bypass battery C-rate limitations during peak braking, supercapacitor (SC) buffers have been explored. A bidirectional DC-DC converter between SC and battery bus absorbs peak regenerative pulses and discharges gradually into the battery. Experimental results (Dougal et al., 2022) demonstrated 11% improvement in total energy recovery compared to battery-only regeneration in aggressive driving scenarios.

VI. STABILITY AND SAFETY IN TWO-WHEELER REGENERATIVE BRAKING

A. Wheel-Slip Control

Wheel-slip during regenerative braking is the primary safety hazard unique to two-wheelers. The slip ratio $\lambda = (v_{\text{vehicle}} - v_{\text{wheel}}) / v_{\text{vehicle}}$, when exceeding approximately 0.10–0.15, indicates

impending wheel-lock. Anti-lock braking systems (ABS) in modern E2Ws must coordinate with the regenerative torque to prevent λ from exceeding this threshold.

Savaresi et al. (2010) demonstrated that a combined regenerative-ABS strategy using wheel-speed sensing and deceleration feedback can reduce stopping distance by 4% versus pure mechanical ABS while recovering energy during partial-braking phases.

B. Pitch Dynamics and Rider Comfort

Pitch-forward weight transfer under braking creates dynamic instability risk if rear regenerative torque is excessive. IMU-based pitch angle estimation enables real-time torque limiting. Subramanian et al. (2020) proposed a pitch-compensated regeneration algorithm reducing subjective braking harshness scores by 38% compared to uncompensated control.

C. Tyre-Road Adhesion Estimation

Without direct tyre-force sensors, adhesion limits must be estimated from longitudinal dynamics. Recursive least squares (RLS) identification of the linearised Dugoff tyre model has been demonstrated in real-time on embedded controllers (Kim et al., 2018). AI-based adhesion classifiers using inertial data (Kumar et al., 2023) show promise for detecting low- μ surfaces (wet road, gravel) and reducing regenerative torque proactively.

VII. EVALUATION STANDARDS AND BENCHMARKING

A. Drive Cycles

Standardised drive cycles enable reproducible comparison of regenerative braking strategies. Commonly used cycles for E2Ws include: WMTC Class 1 (urban, up to 50 km/h), IDC (Indian Drive Cycle), WMTC Class 2 (sub-urban), and custom real-world cycles logged in specific cities. A lack of a universally adopted E2W-specific braking cycle remains a gap—most papers use automotive cycles not representative of two-wheeler urban dynamics.

B. Key Performance Indicators

Energy Recovery Ratio (ERR): Recovered energy / Total braking energy available (%). Range Extension (%): Increase in full-charge range vs. no-regeneration baseline. Braking Comfort Index (BCI): Subjective rider score or jerk integral. Wheel-Lock Event Rate: Slip exceedances per 100 km. Thermal Compliance: Hours at rated regenerative duty without exceeding temperature thresholds.

C. Simulation Tools

MATLAB/Simulink with Simscape Electrical dominates academic simulation. ANSYS Twin Builder and GT-Suite are used for hardware-in-the-loop (HiL) validation. Open-source tools (Vehiclespy, OpenADR) are gaining traction for CAN-bus and V2X studies.

VIII. EMERGING TRENDS AND FUTURE DIRECTIONS

A. Connected and Predictive Regeneration

V2X (vehicle-to-everything) communication enables look-ahead braking strategies using upstream traffic signal phase data or GPS topographic maps. Predictive energy management (PEM) systems pre-position the battery SoC to maximise regenerative acceptance before approaching a known descent or traffic signal (Hu et al., 2022). These approaches report 5–12% additional range extension beyond reactive control.

B. Edge AI and Embedded Machine Learning

TinyML inference on Cortex-M microcontrollers (using TensorFlow Lite for Microcontrollers) enables personalised regeneration policies adapted to individual rider profiles. Driver behaviour clustering using k-means on riding history identifies

aggressive vs. comfort-oriented riders and tunes FLC membership functions accordingly (Roy & Sen, 2024).

C. Solid-State Battery Compatibility

Solid-state batteries (SSBs) under commercialisation (expected 2026–2028) offer lower internal resistance and higher C-rate charging capability, fundamentally relaxing the thermal constraints on regenerative current. Survey authors note that most existing control algorithms will need recalibration for SSB chemistry.

D. Multi-Modal Braking in Two-Wheelers

Integration of regenerative braking with electronic stability control (ESC), cornering ABS, and lean-angle-aware torque distribution represents the frontier of two-wheeler safety technology. No commercially available E2W currently implements all these systems simultaneously; this represents an important research opportunity.

IX. DISCUSSION AND RESEARCH GAPS

Based on the systematic review, the following research gaps are identified:

- (1) No standardised E2W braking cycle exists for reproducible benchmarking of regenerative systems.
- (2) Most studies evaluate regenerative efficiency in isolation from ABS co-operation under emergency braking.
- (3) Thermal degradation studies covering combined motoring and regeneration duty over $>1,000$ cycles are scarce.
- (4) Real-world validation on diverse road surfaces (wet, gravel, cobblestone) is largely absent.
- (5) DRL-based controllers lack formal safety verification — a prerequisite for regulatory approval.
- (6) Low-cost embedded implementation of MPC for sub- $\text{₹}5,000$ E2W controllers remains undemonstrated.

Fuzzy logic and sliding mode controllers appear to offer the most practical near-term path to improved E2W regenerative braking due to their balance of embedded feasibility and adaptability. DRL approaches are promising for the medium-term but require advances in on-device training or transfer learning before embedded deployment.

X. CONCLUSION

This survey has provided a comprehensive review of regenerative braking technology for electric two-wheelers, covering physical principles, hardware topologies, control strategies, energy storage interaction, stability considerations, and evaluation methodologies. Key findings are:

- (1) Fuzzy logic control offers the best embedded feasibility-to-performance ratio for near-term commercial E2W applications, typically improving energy recovery by 15–22% over rule-based methods.
- (2) SoC-aware and thermally constrained regeneration is essential for battery longevity; naive maximum-regeneration policies accelerate capacity fade.
- (3) Two-wheeler pitch dynamics impose hard torque limits that must be explicitly encoded in any regeneration controller.
- (4) Deep reinforcement learning shows the highest potential gains (25–35% improvement) but requires significant advances in embedded inference before commercial deployment.
- (5) Standardised evaluation frameworks and comprehensive real-world datasets remain critical unmet needs for the field.

The Smart Regenerative Braking Optimization System developed in the accompanying M.Tech project directly addresses several of these gaps through real-time fuzzy logic control, IMU-based pitch compensation, and CAN-bus BMS integration on an embedded platform.

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