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Study on Regenerative Braking Systems in Electric Vehicles: Principles, Control, Power Electronics and Open Challenges

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ABSTRACT

Regenerative braking allows the traction motor of an electric vehicle (EV) to operate as a generator during deceleration, returning part of the vehicle's kinetic energy to the battery or another storage element instead of dissipating it as heat in friction brakes. This review examines ten studies that together span the basic motor-generator and inverter principle, vehicle-level energy recovery, hybrid-powertrain coordination, intelligent and adaptive braking control, bidirectional converters and power-electronic conditioning, and brake-by-wire system integration. Using a structured, qualitative and comparative methodology, the review extracts the contribution, method, evidence and stated limitations of each study, classifies them into five themes, and synthesises their quantitative findings. The evidence shows measurable gains: a real-world converted-vehicle case study reported 9.53 Wh/km (about 6.16%) lower energy consumption with regenerative braking, and an adaptive strategy based on naturalistic driver behaviour reported regeneration-efficiency improvements of 39.6%, 16% and 26% for three driver models. The evidence also shows that practical recovery is bounded by motor capability, battery charging limits, converter and transmission losses, vehicle speed and braking demand, so regenerative braking cannot replace friction braking in all conditions. The review identifies seven research gaps, chiefly real-time control that respects hardware and safety limits, the separate treatment of power electronics and braking control, limited real-world validation, and battery-health and driver-acceptance issues, and proposes directions for future work.

Keywords: Electric vehicle (EV), Regenerative Braking System (RBS), Traction Motor, Generator, Inverter, Bidirectional Converter, Battery, Energy Recovery, Braking Control, Neural Network, Literature review

1. INTRODUCTION

1.1 Background and Motivation

Electric vehicles use electrical energy to drive one or more traction motors, so their energy consumption depends on battery capacity, driving behaviour, road conditions and the efficiency of the electric drive system. Limited driving range and the need to use stored electrical energy efficiently are therefore important motivations for energy-recovery technologies.

Conventional friction braking slows a vehicle by converting kinetic energy into heat at the brake pads and discs. During repeated urban deceleration, a significant portion of the vehicle's available energy is dissipated rather than reused. A regenerative braking system (RBS) changes this energy path: the traction motor operates in generating mode, creates an opposing torque, and the generated electrical power is processed by the power electronics and directed toward the battery or another energy-storage device [1]. The reviewed papers describe batteries, capacitors and ultracapacitors as possible destinations for the recovered energy. The central objective is to reduce the irreversible loss of kinetic energy, which can reduce the energy drawn from the grid over a drive cycle and increase the useful distance obtained from a battery charge. The reviewed literature associates regenerative braking with the following benefits:

1. improved overall energy efficiency by recovering energy that would otherwise be dissipated as heat;
2. reduced dependence on friction brakes, which can lower mechanical brake wear;
3. controlled negative motor torque for smooth deceleration when operating conditions permit;
4. particular benefit in urban stop-and-go driving, where frequent acceleration and deceleration create repeated opportunities for recovery, in contrast to steady highway travel with little braking; and
5. longer effective driving range without increasing battery size solely for range.

As regenerative braking becomes more widespread, it becomes both more valuable and more constrained. Practical recovery is limited by motor capacity and battery-current limits [2], and mechanical braking remains necessary when regeneration cannot supply the required stopping torque or when the battery cannot accept additional charging current [3]. The brake controller is therefore a central element: it monitors vehicle or wheel speed and braking demand, determines the regenerative torque that can be accepted, and coordinates the electrical braking command with the battery and the mechanical braking system.

2. LITERATURE REVIEW

2.1 Foundations of Regenerative Braking

Abhale and Nigam [1] explain the fundamental regenerative-braking principle, the role of the brake controller, three-phase inverter operation and alternative energy-storage approaches. During normal driving, electrical power flows from the battery through the inverter to the traction motor, producing positive torque at the wheels. When the driver requests deceleration, the motor is commanded to produce negative torque; the wheels, kept turning by the vehicle's kinetic energy, drive the electric machine as a generator, and the inverter controls the generated current before the energy is returned to the storage system (Fig. 1). The authors report that regenerative braking can improve driving range and is particularly effective in urban conditions, and they discuss flywheels, DC-DC converters, ultracapacitors and supercapacitors as methods for improving energy recovery.

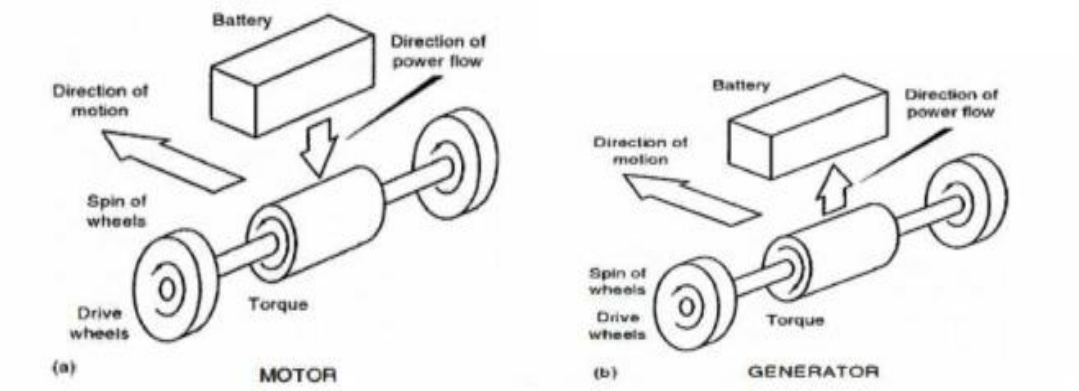


Figure 1. Normal motor operation and regenerative action during braking. Source: Abhale and Nigam [1], Figs. 1–2.

The reviewed studies describe five main components of an RBS:

6. **Traction motor/generator:** produces positive torque during propulsion and negative torque during regenerative braking.
7. **Power inverter:** controls motor current and voltage during both motoring and generating operation.
8. **Brake controller:** determines the available regenerative torque and coordinates braking commands.
9. **Battery or energy-storage system:** receives recovered electrical energy within voltage, current and state-of-charge limits.
10. **Mechanical brake:** supplies additional braking torque when regeneration is insufficient or unavailable.

Malode and Adware [3] present the basic operating principle of regenerative braking, brushless-DC (BLDC) motor operation, inverter switching and the need for a controller. In a BLDC or permanent-magnet machine, the switching devices are controlled according to rotor position and the desired torque; during regenerative operation the switching pattern is changed so that the machine's generated electrical energy can be transferred back toward the DC source (Figs. 2 and 3). They emphasise that mechanical braking remains necessary when regenerative braking cannot supply the required stopping torque or when the battery cannot accept additional charging current.

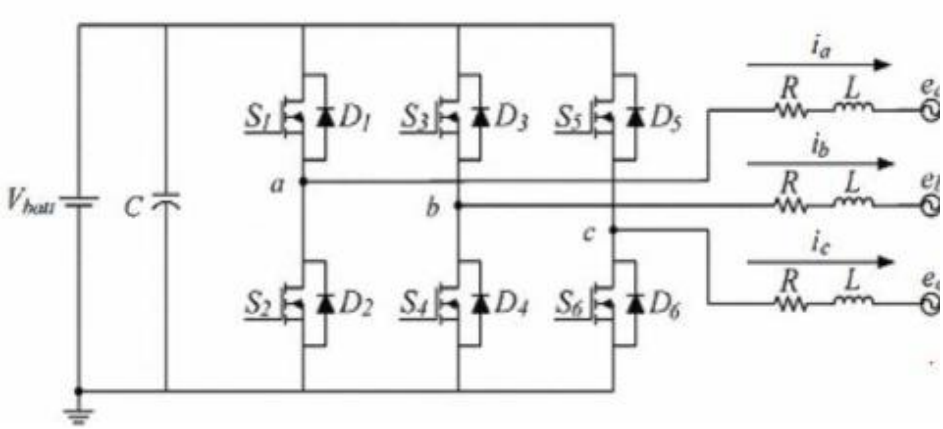


Figure 2. Three-phase inverter structure used for regenerative motor operation. Source: Abhale and Nigam [1], Fig. 3.

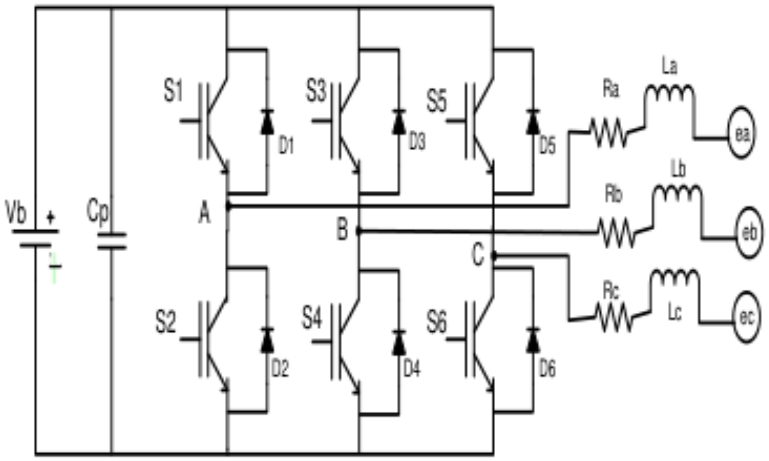


Figure 3. Inverter-driven three-phase PM-BLDC motor circuit. Source: Malode and Adware [3], Fig. 3.

The energy path can be summarised as vehicle kinetic energy → wheels → traction motor/generator → inverter and DC link → battery or energy storage. Losses occur in the motor, inverter, transmission and battery, so the recovered battery energy is always lower than the original kinetic energy; the adaptive study [5] explicitly uses real inverter, transmission and motor-to-battery efficiency data to evaluate the practical recovery process. Fig. 4 shows the simplified regenerative/mechanical braking architecture reported in [2].

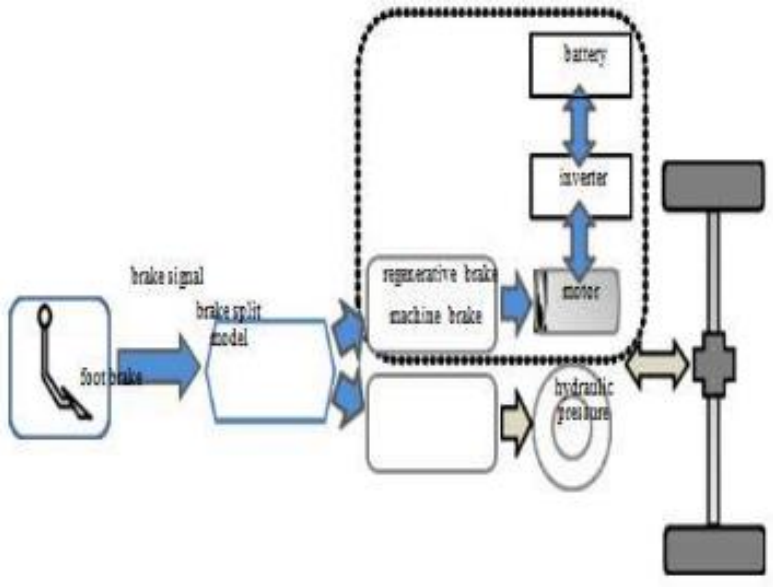


Figure 4. Simplified regenerative/mechanical braking architecture and the brake split used in the case study. Source: Shrivastav and Patel [2].

2.2 Vehicle-Level Energy Recovery and Hybrid Powertrains

Shrivastav and Patel [2] combine a review of RBS technology with a real-world case study of a converted electric vehicle. They identify motor capacity and battery-current limits as practical restrictions on absorbed regenerative energy, which become more important for heavy vehicles because a large amount of kinetic energy is involved during deceleration. A two-boost approach is proposed for a BLDC-motor EV, and the study reports improved regeneration and system efficiency compared with a single-boost approach. The case study used a 1994 Toyota Kijang Super converted from gasoline to electric propulsion and tested over a 12.4 km route in Bandung City; the numerical results are given in Section 4.2.

Xu et al. [4] study regenerative braking in an electrical-variable-transmission hybrid electric vehicle (EVT-HEV). The EVT provides multiple mechanical and electrical ports, allowing more flexible power-flow management than a conventional single-motor regenerative path (Fig. 5). The paper divides braking operation into four modes, including engine-motor coordinating braking (EMCB) and dual-motor braking (DMB), intended to make better use of the available energy paths. A hierarchical controller uses rule-based logic to select the braking mode and a neural-network algorithm for efficiency-oriented control. Simulation was performed on the New European Driving Cycle (NEDC) using CRUISE and MATLAB, and the authors conclude that the proposed strategy improves regenerative-braking performance in the EVT-HEV.

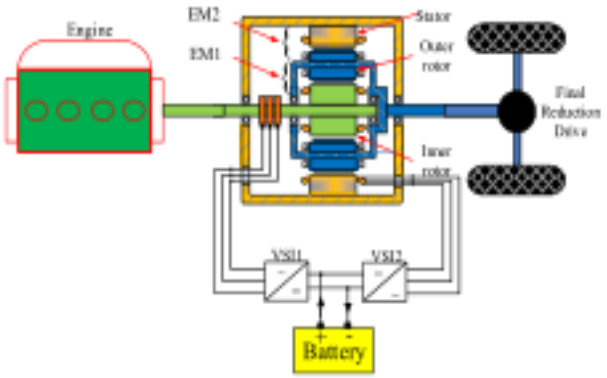


Figure 5. Separated electrical-variable-transmission hybrid electric vehicle structure. Source: Xu et al. [4], Fig. 1.

The reviewed literature points to several application settings: battery-electric passenger vehicles (recovery during traffic stops and downhill deceleration); hybrid electric vehicles (coordinated energy management between engine, motor and battery); electric buses and heavy vehicles (repeated braking involves substantial kinetic energy, although battery and motor limits become more demanding); intelligent and autonomous vehicles (predictive braking can use traffic and driver information to improve recovery); and two-wheelers and compact EVs (regenerative braking can reduce energy consumption when motor and battery limits permit).

2.3 Intelligent and Adaptive Braking Control

Regenerative braking is not an independent replacement for the complete braking system; it is coordinated with mechanical braking so that the total braking force follows the driver's demand. A practical controller receives inputs such as accelerator/brake demand, wheel speed, vehicle speed, battery state and motor operating condition, calculates an allowable regenerative torque, commands the inverter, and allocates any remaining braking demand to the mechanical brake. Regenerative braking is preferred when the motor and battery can accept the requested power, and mechanical braking supplements it when the requested torque exceeds the regenerative limit or the storage cannot accept further charge. Effective braking-force distribution is a compromise between energy recovery, braking stability, battery protection and driver comfort:

11. low-to-moderate deceleration: regenerative torque can provide a large part of the requested braking force;
12. high deceleration demand: regenerative braking is combined with friction braking;
13. high battery state of charge or charging-current limitation: regenerative torque must be reduced;
14. low vehicle speed: the available regenerative power may fall, requiring greater mechanical braking; and
15. wheel-slip or stability event: braking control must prioritise safety over energy recovery.

The reviewed literature contains several levels of braking control [6], [8], [9], [7], [10]. Rule-based controllers are simple and computationally efficient, while fuzzy, sliding-mode and model-predictive approaches can manage nonlinear constraints more explicitly; the literature also describes coordination with ABS and other vehicle systems. Neural-network approaches are used for efficiency optimisation and for estimating or selecting suitable operating conditions. In summary, the strategies are:

16. **Rule-based control:** switches between braking modes using predefined conditions.
17. **Fuzzy control:** distributes regenerative and mechanical braking using rule-based inference under uncertain conditions.
18. **Model predictive control:** considers future behaviour and constraints while optimising braking force.
19. **Neural-network control:** learns nonlinear relationships for efficiency-oriented power distribution.
20. **LSTM/NARX prediction:** forecasts regenerated power or driving behaviour over a future horizon.
21. **Dynamic programming:** optimises a deceleration trajectory when sufficient future information is available.

Ziadia et al. [5] focus on intelligent vehicles and the influence of naturalistic driving behaviour on regenerative energy recovery. LSTM and NARX models predict regenerated power over a 30-second horizon, and dynamic programming then optimises the deceleration profile using long, medium and short planning horizons selected according to the predicted regeneration performance (Fig. 6). The approach explicitly considers driver speed preference and behaviour instead of maximising regeneration without regard to driver acceptance. The method can be understood as a four-stage process:

22. **Prediction:** estimate future regenerated power using driver and vehicle data.
23. **Performance estimation:** determine how close the driver's naturalistic regeneration is to the achievable recovery level.
24. **Horizon selection:** choose long, medium or short deceleration planning according to the estimated regeneration performance.
25. **Optimisation:** use dynamic programming to determine a deceleration profile that increases recoverable energy while respecting speed and powertrain constraints.

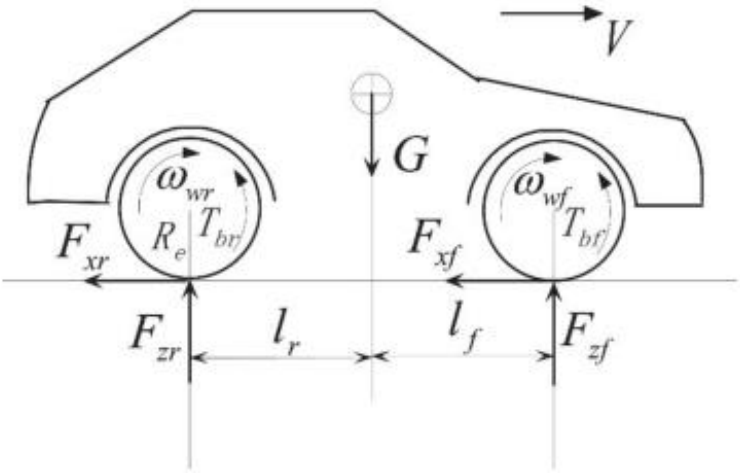


Figure 6. Vehicle braking model used in the adaptive strategy study. Source: Ziadia et al. [5], Fig. 1.

The study emphasises that coasting and anticipation of the braking phase can create more favourable conditions for energy recovery. It also notes that regeneration is technically limited by motor generation capability and deceleration constraints, so a control strategy must optimise within those physical limits rather than assume that all kinetic energy can be recovered. This work is an example of the shift from reactive braking control, which acts only after the brake pedal is pressed, to predictive energy management, in which an intelligent controller anticipates upcoming stops and optimises the deceleration trajectory as part of a broader eco-driving system.

Zhu et al. [10] review brake-by-wire and regenerative-braking control strategies, including conventional control, fuzzy control, neural-network control and intelligent optimisation methods. They explain that electronic brake-by-wire architectures improve response and control precision and can coordinate regenerative and mechanical braking, and they identify real-time performance, subsystem coupling and safe torque distribution as important engineering challenges.

2.4 Power Electronics, Converters and Energy Storage

Naseem and Seok [6] review bidirectional DC-DC converter topologies and their role in regenerative braking. The paper covers non-isolated and isolated converters, buck, boost and buck-boost derived configurations, interleaved and multilevel structures, and the use of wide-bandgap SiC and GaN devices. It also discusses fuzzy logic, neural networks, sliding-mode control, battery degradation and hybrid energy storage, and links efficient two-way power conversion with higher energy recovery and improved power density. Buck, boost and buck-boost derived converters allow electrical power to move in both directions between the storage system and the traction drive; interleaved and multilevel configurations can support higher power density and lower electrical stress; and SiC and GaN devices are identified as promising for higher switching performance and improved thermal behaviour.

Agrawal et al. [7] describe a regenerative-braking architecture in which a DC motor operates as a motor during driving and as a generator during braking. The recovered electrical energy is conditioned using a rectifier, MOSFET-based switching, filtering and a DC-DC converter before battery storage, which illustrates the connection between the mechanical braking event, the electrical conversion stage and the battery-management requirements. The paper emphasises controlled switching between driving and braking modes, energy conditioning, and the continued need for mechanical braking when regeneration is insufficient.

The amount of energy that can be recovered is ultimately limited by the receiving storage system and by the drive hardware. The reviewed studies identify the following constraints:

26. battery voltage and charging-current limit;
27. battery state of charge and temperature;
28. motor maximum generating torque and speed range;
29. inverter voltage/current and switching limits;
30. transmission and electrical conversion losses;
31. vehicle speed, road slope and available braking distance; and
32. driver comfort, tyre-road adhesion and vehicle stability.

2.5 System Integration and Comprehensive Reviews

Huang et al. [8] present a system-level review covering vehicle architecture, drive and energy-storage hardware, intelligent control and evaluation methods. The review compares fuzzy logic, neural networks, model predictive control, sliding-mode control, adaptive control and learning-based methods. It highlights four-wheel independent-drive (4WID) EVs, brake-by-wire systems and hybrid energy storage, which give additional freedom for distributing braking force, and identifies low-speed recovery, battery thermal safety and real-time optimisation as challenges. Intelligent algorithms can use this freedom to balance energy recovery, vehicle stability, battery constraints and driver comfort.

Szumska [9] provides a systematic review of regenerative-braking research from 2005 to 2024. The paper emphasises the transition from conventional PID control toward model predictive control and machine-learning methods. It also reviews brake-by-wire, in-wheel motors, hybrid energy storage and the effects of vehicle speed, external conditions and operating parameters on recovery efficiency. The review identifies computational cost, component reliability, lack of standardised testing, battery degradation and autonomous-vehicle integration as important research challenges.

2.6 Synthesis Across the Studies

Four themes recur when the studies are read together. The first is the progression from motor-level principle to system-level coordination. Early work concentrates on the physical principle and inverter-controlled motor operation [1], [3]. Later work adds measured vehicle-level energy results [2], more sophisticated hybrid-powertrain architectures [4] and intelligent optimisation [5], and the most recent reviews treat the vehicle, converter, storage and brake-by-wire architecture as one system [8], [9].

The second is the shift from reactive to predictive and learning-based control. Rule-based logic gives way to fuzzy, sliding-mode and model-predictive methods and then to neural-network, LSTM/NARX and dynamic-programming approaches [5], [10], [9]. The experiments in [5] show that a NARX model can be attractive where computation time matters, which links control sophistication directly to real-time feasibility.

The third is that hardware and control must be considered together. Bidirectional converter design is fundamental to efficient regenerative energy transfer [6], and power conditioning is essential in a practical motor-generator arrangement [7]. Increasing motor or battery size can raise the theoretical recovery capability, but this also increases cost and power-electronics requirements; intelligent control can improve the utilisation of existing hardware by selecting better braking conditions and distributing torque more effectively.

The fourth is that safety bounds everything. Every study that addresses blending concludes that friction braking remains necessary [3], [7], and the literature consistently indicates that regenerative braking should be viewed as a controlled energy-recovery subsystem within the complete braking system, not as a universal substitute for mechanical brakes. Taken together, these themes indicate that regenerative-braking performance now depends as much on integration, real-time coordination and validation as on any single component.

2.7 Comparative Summary

Table 1 summarises the ten studies, their type, principal contribution and the limitation that matters most for this review.

TABLE 1. Summary of the reviewed studies

Ref.	Theme / domain	Study type	Principal contribution	Key limitation
[1]	RBS foundations	Review	Operating principle, brake controller, three-phase inverter, storage options (flywheel, DC-DC, ultracapacitor)	Qualitative; benefit mainly in frequent-braking operation
[2]	Vehicle-level recovery	Review + real-world case study	Two-boost BLDC approach; with/without-RBS energy comparison on a converted EV	Motor capacity and battery-current limits restrict absorbed energy
[3]	RBS foundations	Principle and implementation paper	BLDC operation, inverter switching and the need for a controller	Mechanical braking still needed when regeneration is insufficient
[4]	Hybrid powertrain (EVT-HEV)	Simulation study	Four braking modes; rule-based + neural-network hierarchical controller	Simulation-based evidence (NEDC; CRUISE and MATLAB)
[5]	Adaptive intelligent braking	Prediction and optimisation study	LSTM/NARX prediction; dynamic programming with adaptive planning horizon	Recovery bounded by motor generation capability and deceleration constraints
[6]	Bidirectional converters	Review	Bidirectional DC-DC topologies, SiC/GaN devices, intelligent control	Battery degradation and storage integration remain constraints
[7]	Power conditioning	Architecture description	DC motor-generator with rectifier, MOSFET switching and DC-DC converter	Mechanical braking still needed when regeneration is insufficient
[8]	System integration	Review	4WID, brake-by-wire, hybrid energy storage, intelligent-control comparison	Low-speed recovery, battery thermal safety, real-time optimisation
[9]	Comprehensive RBS review	Systematic review (2005–2024)	PID to MPC/ML trend; brake-by-wire; in-wheel motors; hybrid energy storage	Computational cost, reliability, no standard testing, battery degradation, AV integration
[10]	Brake-energy control	Review	Brake-by-wire and RBS control strategies; coordinated torque control	Real-time performance, subsystem coupling, safe torque distribution

2.8 Gaps in the Literature

Reading the ten studies together reveals gaps that no single study addresses. The following gaps are the reviewer's synthesis, grounded in the limitations and challenges the reviewed studies themselves identify.

Real-time, constraint-aware control. A continuing gap is control that simultaneously respects battery and motor limits, maintains braking comfort and safety, and adapts to road and traffic conditions. Predictive and optimisation methods raise computational cost [9], and real-time performance remains a stated challenge [8], [10].

Power electronics and braking control developed separately. Converter topology, bidirectional power flow, brake-by-wire architecture, energy-storage selection, battery thermal limits and low-speed recovery must be considered together [6], [8], [10], yet they are largely studied in isolation. A coordinated system in which power electronics and braking control are designed together is still to be demonstrated.

Limited real-world validation and testing standards. Evidence rests on one real-world case study of a single converted vehicle on one route [2], a simulation on one driving cycle [4], and an evaluation on three driver models [5]; the lack of standardised testing is itself identified as a challenge [9].

Battery health, thermal limits and storage. Battery degradation [6], [9] and thermal safety [8] constrain recovery, but battery health and temperature are rarely built into brake-force optimisation.

Low-speed recovery and finite hardware limits. Regenerative power falls at low speed [8], and motor generating capability and battery-current limits bound recovery, particularly for heavy vehicles [2].

Driver acceptance, brake blending and safety. Driver behaviour is the focus of only one study in this corpus [5], excessive or unexpected deceleration can reduce user confidence in intelligent braking, and safe torque distribution and component reliability remain open in brake-by-wire systems [10], [9].

Integration with autonomous and connected vehicles. Autonomous-vehicle integration is listed as an open research challenge [9], and predictive braking that uses traffic and driver information has so far been demonstrated only for driver-behaviour prediction [5].

3. METHODOLOGY

3.1 Research Design

This review uses a qualitative, comparative and structured narrative review design. It does not report new experiments. Instead, it treats the ten selected studies as the evidence base, extracts comparable information from each, and synthesises it thematically. This design suits a corpus that mixes reviews, architecture descriptions, a case study and model-based evaluations, because their outcomes are heterogeneous and cannot be pooled statistically in a formal meta-analysis.

3.2 Corpus and Selection

The corpus comprises ten papers: five initial studies [1], [2], [3], [4], [5] and five recent studies added in the expanded review [6], [8], [9], [7], [10]. The ten papers were fixed as the evidence base; no systematic database-search protocol is claimed. By type, five are reviews [1], [6], [8], [9], [10]; two describe operating principle or a practical architecture [3], [7]; one combines a review with a real-world case study [2]; and two report original simulation or model-based evaluation [4], [5]. By date, three were published in 2015–2019, two in 2022–2023 and five in 2025–2026. The papers appeared in IEEE Access (two), Energies (three), Actuators (one) and four other journals.

3.3 Data Extraction Framework

A common extraction template, shown in Table 2, was applied to every paper so that findings could be compared on the same dimensions.

TABLE 2. Data extraction framework

Dimension	What was recorded
Domain and theme	Application area (principle, vehicle-level recovery, hybrid powertrain, control, converters, system integration) and the review theme it maps to
Study type	Review, principle or architecture description, case study, simulation or model-based evaluation
Technologies	Motor and machine type, inverter or converter topology, energy storage, brake architecture and control algorithm used
Evidence	Quantitative results exactly as reported by the authors (energy consumption, efficiency improvement, prediction error)
Challenges	Battery and storage limits, motor and inverter limits, brake blending and safety, real-time computation, driver acceptance and road conditions discussed
Limitations	Limitations, constraints and future work stated by the authors or evident in the reviewed text

3.4 Analysis Procedure

The analysis followed five steps (Fig. 7):

Corpus selection: the ten papers were fixed as the evidence base.

Data extraction: each paper was reviewed and the template in Table 2 completed.

Thematic classification: papers were assigned to five themes (RBS foundations; vehicle-level energy recovery and hybrid powertrains; intelligent and adaptive braking control; power electronics, converters and energy storage; system integration and comprehensive reviews).

Cross-paper comparison: results, challenges and limitations were compared across themes, and quantitative values were tabulated.

Gap analysis and synthesis: recurring limitations and unaddressed questions were consolidated into the gaps in Section 2.8 and the future directions in Section 5.



Figure 7. Review methodology workflow.

3.5 Validity and Limitations of the Method

Three limitations apply. First, the corpus is small and drawn from several different journals over 2015–2026, so it is illustrative and not exhaustive of the regenerative-braking literature, and the studies differ in depth and in the detail of evidence they give. Second, all quantitative values are reported as published and were not independently reproduced; where this review states a derived figure (such as a difference calculated from two reported values) it is identified as calculated. Third, the studies differ in vehicle type, scale, metrics and test conditions, so numerical results are compared within a study and between scenarios, not ranked across unrelated studies.

4. RESULTS AND FINDINGS

4.1 Profile of the Corpus

The ten studies cover five themes. Seven are reviews or descriptions of operating principle and architecture and three contain original evaluation results, which means that most of the evidence base in this corpus is synthesis and a smaller part is measured or simulated performance. Only one study reports measured vehicle-level energy consumption [2]; one reports improved performance in simulation [4]; and one reports efficiency improvements for three driver models [5]. Fig. 8 summarises the corpus by study type and publication period.

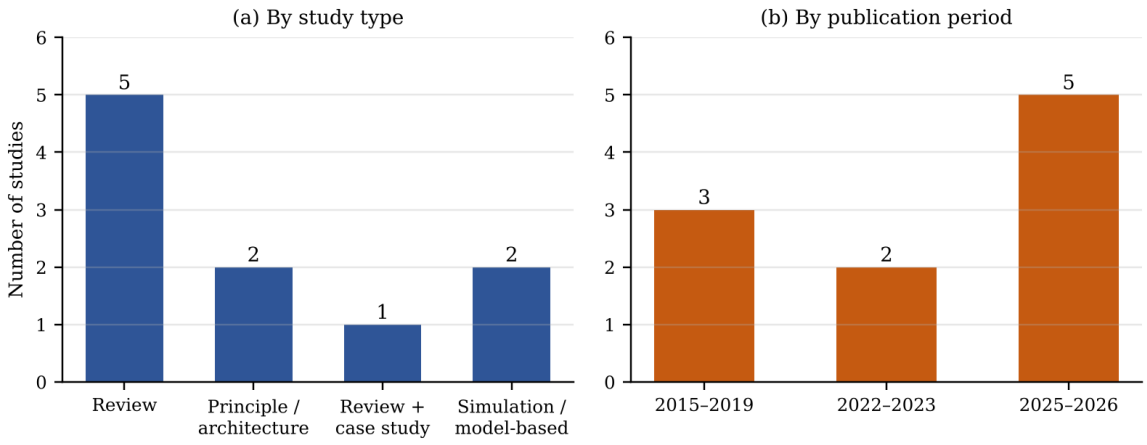


Figure 8. Profile of the reviewed corpus: (a) number of studies by type and (b) by publication period.

4.2 Quantitative Evidence

Table 3 consolidates the numerical evidence reported by each study. Reviews and descriptions with no new numerical results are summarised by their main qualitative conclusion.

TABLE 3. Principal evidence reported by each study

Ref.	Domain	Principal reported evidence
[1]	RBS foundations	Range benefit and energy recovery discussed; most effective in urban conditions; flywheels, DC-DC converters and ultracapacitors identified as ways to improve recovery.
[2]	Vehicle-level recovery	12.4 km route, converted 1994 Toyota Kijang Super: 143.94–146.58 Wh/km with RBS versus 153.30–156.27 Wh/km without; average difference 9.53 Wh/km, about 6.16% lower consumption. Two-boost approach improves regeneration and system efficiency over single-boost.
[3]	RBS foundations	Regenerative mode, BLDC operation, inverter switching and controller operation described; mechanical braking needed when regeneration is insufficient.
[4]	EVT-HEV	Four braking modes (including EMCB and DMB); NEDC simulation in CRUISE and MATLAB; improved RBS performance reported.
[5]	Adaptive braking	Regeneration-efficiency improvement of 39.6%, 16% and 26% for drivers 1, 2 and 3; 30 s prediction horizon; NARX RMSE about 0.4402 kW with substantially less computation time than the compared LSTM.
[6]	Converters	***Efficient bidirectional power conversion linked to higher energy recovery and improved power density; SiC/GaN devices and interleaved/multilevel topologies promising.***
[7]	Power conditioning	Controlled energy recovery and conditioning (rectifier, MOSFETs, DC-DC) for battery storage; mechanical braking still required when regeneration is insufficient.
[8]	System integration	Higher recovery potential with integrated hardware and intelligent control; low-speed recovery, battery thermal safety and real-time optimisation are challenges.
[9]	Comprehensive review	Review of 2005–2024 research; identifies computational cost, component reliability, lack of standardised testing, battery degradation and AV integration as challenges.
[10]	Brake-energy control	Brake-by-wire improves response and control precision; real-time performance, subsystem coupling and safe torque distribution identified as challenges.

Shrivastav and Patel [2] compared energy consumption with and without regenerative braking, and the reported average difference of 9.53 Wh/km corresponds to about 6.16% lower consumption. Taking the midpoints of the two reported ranges (calculated) gives a difference of about 9.5 Wh/km, consistent with the reported average. The result shows that the benefit is measurable at vehicle level and is not limited to a theoretical motor-level calculation. It also shows the importance of operating conditions: energy recovery occurs when the vehicle is decelerating and the traction motor can accept negative torque, so the actual benefit depends on how frequently braking occurs and how much of the requested braking torque can be regenerated.

Ziadia et al. [5] evaluated three naturalistic driving behaviours. The adaptive deceleration-planning strategy improved regeneration efficiency by 39.6% for driver 1, 16% for driver 2 and 26% for driver 3, and the different improvements demonstrate that braking behaviour has a direct effect on the energy that can be recovered. The NARX prediction configuration achieved an RMSE of about 0.4402 kW while requiring substantially less computational time than the compared LSTM configuration, so the authors identify NARX as attractive when computational time is important. Fig. 9 redraws these two sets of reported results.

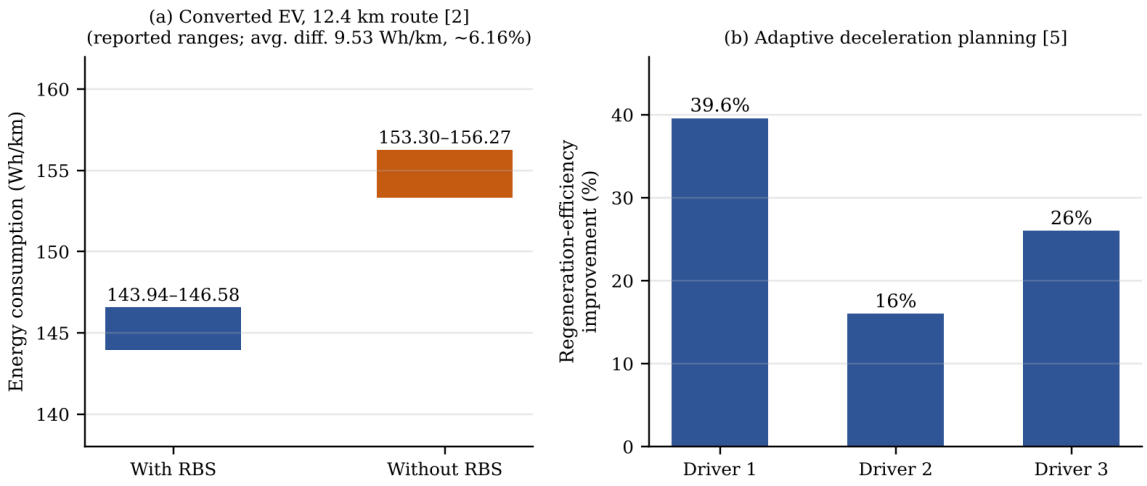


Figure 9. Reported energy-consumption ranges for the converted-EV case study [2] and reported regeneration-efficiency improvements for three driver models [5], redrawn from the published values.

For the EVT-HEV [4], the source summary reports improved regenerative-braking performance under NEDC simulation but gives no numerical value, so none is quoted here.

4.3 Cross-Cutting Challenges

Table 4 records which challenges each study explicitly discusses. It reflects this review's reading of each paper and indicates emphasis, not the strength of evidence. Fig. 10 presents the same information as a matrix, and Fig. 11 counts how many studies discuss each challenge.

TABLE 4. Challenges explicitly discussed (● = discussed)

Ref.	Battery / storage	Motor / power electronics	Brake blending / safety	Real-time / computation	Driver behaviour	AI / ML control
[1]	●	●				
[2]	●	●	●			
[3]	●	●	●			
[4]		●	●			●
[5]		●		●	●	●
[6]	●	●				●
[7]	●	●	●			
[8]	●	●	●	●		●
[9]	●	●	●	●		●
[10]			●	●		●

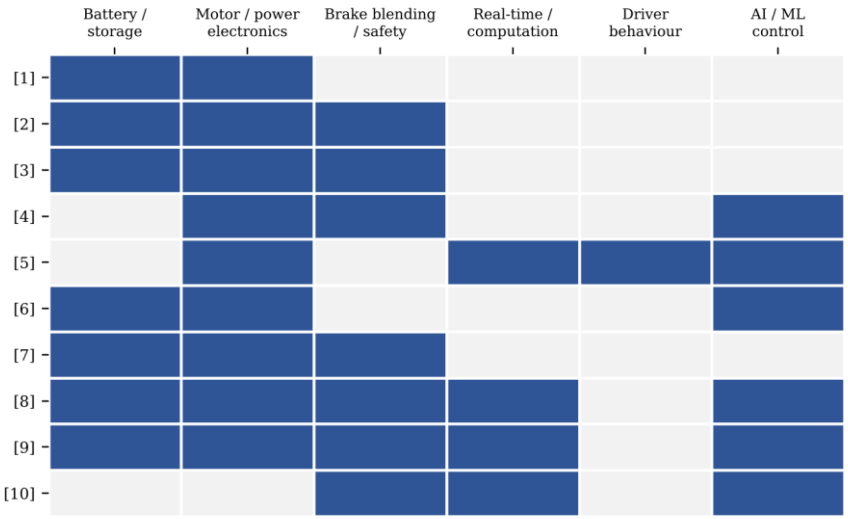


Figure 10. Matrix of challenges discussed by each reviewed study (filled cell = discussed), drawn from Table 4.

Motor and power-electronics limits are the most frequently discussed challenge (9 of the 10 studies), followed by battery/storage and brake blending/safety (7 each), AI/ML control (6) and real-time computation (4); driver behaviour is the focus of only one study [5] (Fig. 11).

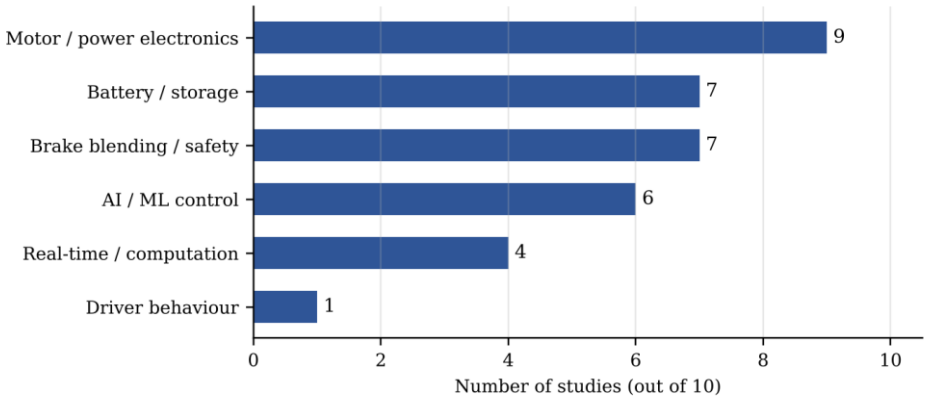


Figure 11. Number of reviewed studies (out of 10) that discuss each challenge, counted from Table 4.

The literature consistently shows the following advantages and limitations of regenerative braking:

33. **Advantages:** recovery of otherwise wasted kinetic energy; lower battery energy demand; reduced friction-brake use; improved efficiency in frequent-deceleration operation.

34. **Limitations:** finite motor generating capability; battery charging-current and state-of-charge constraints; inverter and transmission losses; reduced regeneration at low speed; need for friction braking when high deceleration is required.

The key engineering challenges that follow from these limitations are:

35. **Battery acceptance:** the storage system must safely absorb the recovered current without exceeding electrical or thermal limits.

36. **Torque and speed limits:** the traction machine has a finite generating region.

37. **Brake blending:** regenerative and friction braking must transition smoothly without compromising stability or comfort.

38. **Real-time computation:** predictive and optimisation algorithms must execute fast enough for practical vehicle control.

39. **Driver acceptance:** excessive or unexpected deceleration can reduce user confidence in intelligent braking systems.

40. **Variable road conditions:** slope, traffic, speed and weather change the available recovery opportunity.

4.4 Key Findings

Vehicle-level recovery is measurable. A converted EV consumed about 6.16% less energy with regenerative braking over a 12.4 km route [2], so the benefit is not only a theoretical motor-level calculation.

Driver behaviour changes the recoverable energy. Adaptive, driver-aware deceleration planning improved regeneration efficiency by 39.6%, 16% and 26% for three driver models [5]; longer, better-anticipated deceleration can increase recoverable energy, but the controller must balance recovery with speed preference and comfort.

Recovery is bounded by hardware and safety. Motor generating capability, battery charging limits, converter and transmission losses and low speed all limit regeneration, so friction braking must supply the remainder and must take priority in a wheel-slip or stability event [2], [3], [7].

Control is moving from reactive rules to prediction. Rule-based logic is simple and efficient, while fuzzy, sliding-mode and model-predictive methods handle constraints explicitly, and neural-network, LSTM/NARX and dynamic-programming methods add prediction; NARX offered a low-computation option in [5].

Power electronics are central. Bidirectional converters, interleaved and multilevel topologies and SiC/GaN devices are linked to higher energy recovery and power density [6], and power conditioning is needed before battery storage [7].

Integrated architectures add freedom but also coupling. Four-wheel independent drive, brake-by-wire and hybrid energy storage give more freedom to distribute braking force [8], [9], while subsystem coupling and safe torque distribution become engineering challenges [10].

The evidence base is thin in places. Many results rest on a single vehicle, a simulation or three driver models, so the reported figures indicate potential and are not guaranteed performance in the field.

5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

This review compared ten studies that together describe regenerative braking in electric and hybrid vehicles from its operating principle to power electronics, intelligent control and system integration. Three conclusions follow. First, regenerative braking delivers measurable benefit: a real-world case study reported 9.53 Wh/km, about 6.16%, lower energy consumption, and an adaptive strategy reported regeneration-efficiency improvements of 39.6%, 16% and 26% for three driver models. The greatest opportunities occur during repeated deceleration, particularly in urban stop-and-go driving. Second, practical recovery depends on the coordinated operation of the traction motor, inverter, brake controller, battery and mechanical brakes, and is limited by motor capability, battery charging limits, electrical conversion losses, vehicle speed and braking demand, so safe brake blending remains essential. Third, the main opportunities and obstacles are common across the studies: bidirectional converters, wide-bandgap power devices, brake-by-wire architectures, hybrid energy storage and intelligent control can improve energy recovery and response, but they must operate within battery, motor, thermal, stability and safety constraints.

The review also shows that future regenerative-braking systems must be designed as integrated electromechanical systems. Designing power electronics and braking control together, rather than optimising them independently, is the main opportunity identified.

5.2 Future Scope

Predictive regenerative braking: develop real-time predictive control using vehicle-to-vehicle and vehicle-to-infrastructure information.

Battery-aware optimisation: integrate battery health, temperature and state-of-charge prediction into brake-force optimisation.

Driver-adaptive control: improve driver-adaptive control while preserving predictable pedal feel and safety.

Integrated chassis control: combine regenerative braking with advanced ABS, traction control and model-predictive control.

Hybrid storage: investigate high-power storage combinations such as batteries with ultracapacitors for high-frequency braking energy.

Validation: validate intelligent strategies through larger real-world datasets and hardware-in-the-loop testing.

Co-designed power electronics and control: design converter topology, energy storage and braking control together as one coordinated system.

Standardised testing: develop common test procedures so that regenerative-braking strategies can be compared fairly across vehicles and studies.

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