

Energy Recovery Analysis of Regenerative Braking Systems in Electric Vehicles Under Real-World Driving Conditions

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Abstract: *Regenerative braking is a key energy-recovery technology in battery electric vehicles because it converts part of the vehicle's kinetic energy during deceleration into electrical energy that can be stored in the traction battery. However, the recoverable energy under real-world driving is strongly dependent on vehicle speed, deceleration intensity, traffic conditions, road gradient, battery state of charge (SOC), battery temperature, motor operating limits and driver behaviour. This article develops a practical framework for analysing regenerative-braking energy recovery using real-road driving data. The proposed methodology combines vehicle longitudinal dynamics, motor-generator efficiency, battery charging limits and braking-event segmentation. Energy available during deceleration is estimated from vehicle mass, speed and acceleration, while recovered electrical energy is obtained by integrating measured regenerative power at the DC bus or battery terminals. Urban, suburban and highway operation are treated separately because their braking frequency and speed distributions differ substantially. A data-acquisition architecture based on CAN/OBD-II, GPS, inertial measurements and battery signals is proposed. Illustrative calculations and charts are included solely to demonstrate the analysis workflow; they are not claimed as measured vehicle results. Recent literature indicates that real-world traffic, speed and regenerative-braking level materially affect net energy consumption, and recent reviews identify battery constraints, low-speed recovery, safety and standardized evaluation as continuing challenges. The framework therefore provides a reproducible basis for quantifying recovered energy, regenerative contribution, recovery efficiency and the influence of driving conditions without relying on artificial optimization objectives.*

Keywords: electric vehicle; regenerative braking; energy recovery; real-world driving; battery SOC; vehicle dynamics; CAN data; braking energy; energy efficiency.

I. INTRODUCTION

Electrification of road transport has increased interest in technologies that improve the useful energy obtained from every unit of stored battery energy. Regenerative braking is important because a conventional friction-braking event converts kinetic energy mainly into heat, whereas an electric traction machine can operate as a generator and return part of that energy to the battery. Recent reviews describe regenerative braking as a central technology for improving electric-vehicle energy efficiency and driving range, while emphasizing that recovery is constrained by motor speed/torque, battery SOC and temperature, braking-system architecture and vehicle safety requirements.

The practical recovery potential is not constant over a journey. A real-world study of a passenger electric SUV reported that regenerative-braking stage, speed and traffic conditions influenced both recovered energy and net battery consumption, and argued that real-road testing is necessary because laboratory conditions do not fully represent traffic and route variability. Recent research has also moved toward intelligent control and real-vehicle validation, while identifying safety, comfort, battery limitations and low-speed recovery as continuing technical issues.



The objective of this article is therefore not to rank or optimize alternative braking strategies, but to establish a transparent energy-recovery analysis methodology. The central questions are: (i) how much kinetic energy is available during real braking events, (ii) how much of that energy reaches the electrical storage system, (iii) how recovery varies between urban, suburban and highway conditions, and (iv) which measurable variables explain unsuccessful or limited regeneration.

II. LITERATURE REVIEW AND RESEARCH GAP

Regenerative braking architecture

A typical regenerative-braking system contains a traction motor/generator, inverter, battery and battery-management system, brake sensors and a controller coordinating regenerative and friction braking. The controller must meet the driver's requested deceleration while respecting motor, inverter and battery limits. Recent reviews identify this coordinated architecture as a major focus of current research.

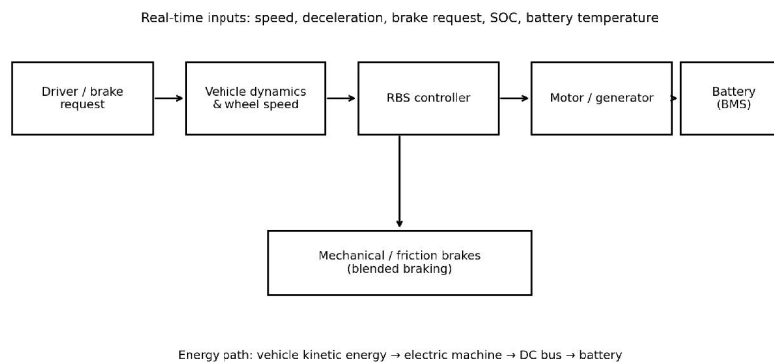


Figure 1. Proposed real-world regenerative-braking energy-flow architecture.

Real-world operating factors

Factor	Effect on energy recovery	Recommended measurement
Vehicle speed	Determines available kinetic energy and motor operating point	GPS/CAN wheel speed
Deceleration	Controls instantaneous braking power	IMU + wheel speed
Traffic density	Changes braking frequency and stop duration	Video/GPS route annotation
Road gradient	Changes net longitudinal energy demand	GPS altitude / map data
Battery SOC	Limits charge acceptance near high SOC	BMS/CAN
Battery temperature	Changes allowable charging power	BMS/CAN
Motor speed/torque	Determines generator operating region	CAN/inverter
Driver behaviour	Changes braking intensity and frequency	Brake-pedal/CAN + event segmentation
Vehicle mass	Scales kinetic energy	Vehicle specification + payload estimate

These factors are consistent with published evidence that real-world traffic, speed, route and vehicle conditions influence EV energy consumption and regenerative recovery.



Research Gap

Three practical gaps motivate the proposed study. First, many analyses report overall energy consumption without separating energy available at the wheels from energy actually recovered at the battery. Second, laboratory drive cycles can mask route-specific effects such as frequent short stops, gradients and traffic interactions. Third, energy-recovery efficiency is sometimes discussed as a single number even though the underlying conversion chain contains multiple losses. Recent reviews also note the absence of fully standardized evaluation frameworks and continued challenges involving low-speed recovery, battery thermal safety and real-time control.

III. OBJECTIVES AND SCOPE

- Quantify kinetic energy available during regenerative-braking events under real-world driving.
- Calculate recovered electrical energy at the motor/DC-bus or battery level.
- Compare recovery characteristics for urban, suburban and highway operation.
- Examine the influence of vehicle speed, deceleration, SOC, battery temperature and road gradient.
- Separate regenerative losses from the total vehicle energy balance.
- Develop a repeatable data-processing procedure that can be implemented using CAN/OBD-II and GPS/IMU data.
- Provide a validation protocol suitable for a real EV road-test campaign.

IV. METHODOLOGY

A. Vehicle longitudinal-energy model

For a road vehicle of mass m and instantaneous longitudinal speed v , the translational kinetic energy is:

$$E_k = 1/2 \cdot m \cdot v^2$$

The theoretical kinetic-energy change between two speed samples is $\Delta E_k = 1/2 m(v_1^2 - v_2^2)$. During downhill or accelerating conditions, gravitational potential-energy and rolling/aerodynamic terms must also be included in the longitudinal balance.

$$F_{total} = m \cdot a + F_{roll} + F_{aero} + m \cdot g \cdot \sin(\theta)$$

$$F_{aero} = 1/2 \cdot \rho \cdot C_d \cdot A \cdot v^2$$

$$F_{roll} = C_{rr} \cdot m \cdot g \cdot \cos(\theta)$$

B. Regenerative electrical energy

If DC-bus voltage V and regenerative current I are measured at a sufficiently high sampling rate, instantaneous electrical power is:

$$P_{reg}(t) = V_{dc}(t) \cdot I_{reg}(t)$$

The recovered electrical energy for a braking event is obtained by numerical integration:

$$E_{reg} = \int P_{reg}(t) dt$$

For battery-terminal measurements, sign convention must be fixed before processing. A positive regenerative-power value should correspond to charging power entering the battery. Where only motor torque and speed are available, mechanical generator power can be estimated from $P_m = T_m \omega_m$ and then corrected using measured or mapped conversion efficiency.

C. Energy-recovery indicators

Indicator	Expression	Interpretation
Available kinetic energy	$\Delta E_k = 0.5m(v_1^2 - v_2^2)$	Upper-level mechanical energy available from speed reduction
Regenerative energy	$E_{reg} = \int P_{reg} dt$	Electrical energy recovered during event
Recovery ratio	$\eta_{rec} = E_{reg} / \Delta E_k \times 100$	Fraction of speed-reduction energy reaching measured electrical point



Regenerative share	$E_{reg}/E_{traction} \times 100$	Contribution relative to propulsion energy over a trip
Braking-event rate	$N_{events} / \text{distance}$	Frequency of regenerative opportunities
Average recovered power	$E_{reg} / \text{event duration}$	Intensity of energy recovery

D. Real-world data acquisition

Signal	Typical source	Suggested sampling	Purpose
Vehicle speed	CAN / wheel-speed ECU	10–100 Hz	Kinetic-energy calculation
Motor speed	CAN / inverter	10–100 Hz	Generator operating point
Motor torque	CAN / inverter	10–100 Hz	Mechanical regenerative power
Battery voltage	BMS/CAN	10–100 Hz	Electrical power
Battery current	BMS/CAN	10–100 Hz	Electrical power and SOC cross-check
SOC	BMS/CAN	1–10 Hz	Charge-acceptance constraint
Battery temperature	BMS/CAN	1–10 Hz	Thermal constraint
Brake-pedal position	CAN	10–100 Hz	Driver braking demand
GPS speed/position	GNSS	1–10 Hz	Route classification
Acceleration	IMU	50–200 Hz	Braking-event segmentation
Road gradient	GNSS/map	1–10 Hz	Potential-energy correction

Braking-event segmentation

A braking event can be defined using a negative longitudinal acceleration threshold together with positive brake demand or negative motor power. A practical algorithm should merge closely spaced samples into one event, remove very short sensor glitches, and retain event duration, initial/final speed, maximum deceleration, regenerative power, SOC and temperature. Events should then be classified by route type and braking intensity

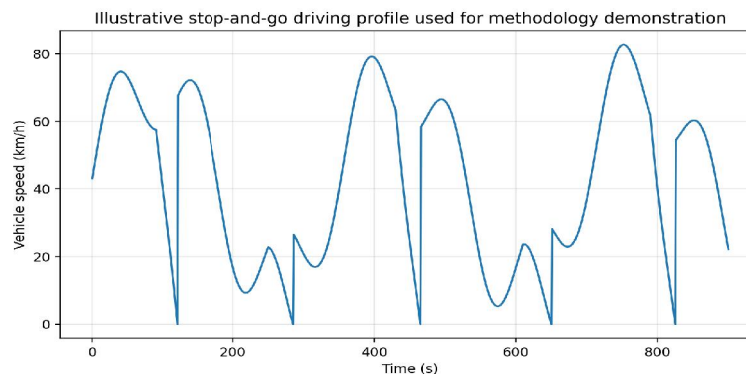


Figure 2. Illustrative stop-and-go speed profile for demonstrating event segmentation; not measured vehicle data.

Analytical energy balance

A trip-level balance can be expressed conceptually as:

$$E_{batt,net} = E_{propulsion} + E_{auxiliaries} + E_{losses} - E_{reg}$$

The exact sign convention depends on whether the battery terminal is treated as positive discharge or positive charge. For publication-quality analysis, the selected convention should be explicitly stated and checked using a known charging/discharging event.



V. ILLUSTRATIVE ANALYSIS AND REPORTING FORMAT

The following figures demonstrate how results can be presented. They are intentionally labelled illustrative because no real vehicle dataset was supplied in the request. They should not be copied into a manuscript as experimental evidence. The same plots can be regenerated from measured data using the equations and acquisition plan above.

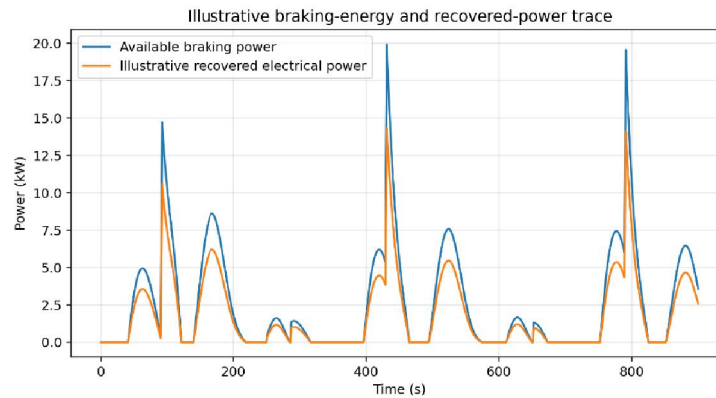


Figure 3. Illustrative braking-power trace showing available and recovered power; demonstration only.

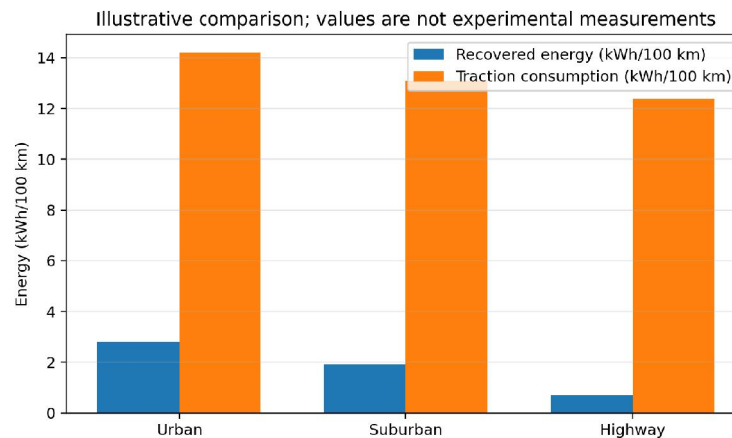


Figure 4. Illustrative route comparison. Values are placeholders for the final measured dataset.

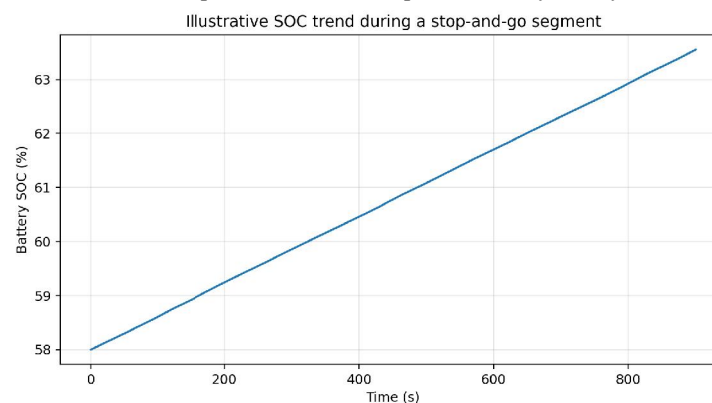


Figure 5. Illustrative battery-SOC trend during a stop-and-go segment.



Example calculation

Consider a hypothetical 1800 kg EV decelerating from 60 km/h to 20 km/h. The speed reduction corresponds to 16.67 m/s to 5.56 m/s. The change in translational kinetic energy is:

$$\Delta E_k = 0.5 \times 1800 \times (16.67^2 - 5.56^2) \approx 222.2 \text{ kJ} \approx 0.0617 \text{ kWh}$$

If the complete conversion chain delivered 60% of this event-level kinetic-energy change to the battery, the illustrative recovered energy would be about 0.0370 kWh. This is a physics example, not a claim about a particular EV. In real testing, road gradient, rolling resistance, aerodynamic drag, motor limits, battery charge acceptance and friction braking would change the result.

Expected physical trends

Driving condition	Expected regenerative opportunity	Reason
Dense urban stop-and-go	High	Frequent deceleration and low-to-moderate speed
Moderate suburban traffic	Moderate	Fewer braking events than dense urban traffic
Highway cruising	Low	Long periods of near-constant speed and fewer braking events
Long downhill	Potentially high	Sustained negative grade can produce prolonged generator operation
High SOC	Potentially reduced	Battery charge acceptance can become constrained
Low speed near standstill	Reduced	Motor/generator operating region and control limits
Cold battery	Potentially reduced	BMS may restrict charging power to protect cells

These are physical expectations rather than measured findings for the present article. Published real-world work similarly reports differences with speed and traffic conditions and recommends route-specific testing.

VI. REAL-WORLD TEST PROTOCOL

A robust experimental campaign should use the same vehicle and battery state window across repeated runs wherever possible. At minimum, each route should be driven in both directions to reduce systematic effects from road grade and traffic. Ambient temperature, tyre pressure, payload, HVAC usage and battery SOC at route start should be recorded.

Stage	Procedure	Output
1. Vehicle preparation	Record mass, tyre pressure, SOC, battery temperature and ambient conditions	Test-condition sheet
2. Instrumentation	Synchronize CAN/OBD-II, GPS and IMU clocks	Time-aligned dataset
3. Route definition	Urban, suburban and highway segments; record gradient	Route metadata
4. Repeated runs	Perform multiple runs under comparable conditions	Replicate measurements
5. Event detection	Identify deceleration/regeneration intervals	Braking-event table
6. Energy calculation	Integrate electrical regenerative power	E_{reg} per event
7. Classification	Group by speed, deceleration, SOC and route	Condition-wise results
8. Validation	Cross-check battery energy and trip energy balance	Measurement consistency

VII. DATA PROCESSING PROCEDURE

1. Import synchronized CAN/OBD-II, GPS and IMU records.
2. Remove duplicate timestamps and identify missing samples.



3. Apply physically justified signal filtering; retain raw data separately.
4. Convert speed to SI units and align sensor timestamps.
5. Calculate longitudinal acceleration and identify braking events.
6. Determine whether motor power is regenerative, friction-brake dominated, or mixed.
7. Integrate regenerative electrical power over each event.
8. Calculate kinetic-energy change and event-level recovery ratio.
9. Group events by route, speed band, deceleration band, SOC and temperature.
10. Perform uncertainty and repeatability analysis.
11. Report mean, median, standard deviation and confidence intervals rather than a single recovery number.

VIII. UNCERTAINTY AND ERROR ANALYSIS

Energy-recovery analysis is sensitive to sensor bias, time synchronization, current/voltage measurement uncertainty and incomplete accounting of road-gradient effects. If regenerative energy is calculated as the product of voltage and current, uncertainty should be propagated rather than omitted.

$$u_{P/P} \approx \sqrt{[(u_{V/V})^2 + (u_{I/I})^2]}$$

Integration introduces additional error when sampling is sparse or signals contain noise. GPS-derived speed can also differ from wheel speed, particularly during rapid acceleration or braking. Therefore, wheel/CAN speed should preferably be used for instantaneous kinetic-energy calculations, while GPS is used for route position and gradient verification.

IX. DISCUSSION

The central engineering issue is that regenerative braking is an energy-conversion chain rather than a single efficiency parameter. Mechanical kinetic energy must first be made available through deceleration, then transmitted through the drivetrain, converted by the electric machine and inverter, and finally accepted by the battery. Losses and constraints at each stage reduce the energy that can be stored.

Real-world driving adds another layer of variability. Urban driving creates many braking opportunities, but each event may be short and occur at low speed. Highway driving generally offers fewer regenerative events despite higher vehicle speed. A long downhill section can produce a different pattern because braking may be sustained rather than intermittent. Published road-test evidence supports treating traffic, speed and regenerative-braking level as explicit variables rather than assuming a fixed recovery percentage.

Battery charge acceptance is equally important. A high SOC or restrictive temperature condition can reduce the power that can safely be absorbed, causing the friction brakes to dissipate energy that would otherwise be recoverable. Recent reviews identify battery temperature, SOC, motor speed/torque and control architecture as important constraints, while current research is increasingly examining predictive and learning-based control.

Comfort and safety should be treated as essential engineering constraints. Recent 2026 research using real-road testing has examined the interaction of energy recovery with SOC, wheel slip and ride comfort, illustrating the movement from purely energy-focused analysis toward integrated vehicle behaviour.

X. CONCLUSION

Regenerative braking provides a direct pathway for recovering part of the kinetic energy that would otherwise be dissipated during deceleration. However, the recoverable amount under real-world operation depends on the frequency and intensity of braking events, vehicle speed, route gradient, traffic, motor-generator characteristics and battery charge acceptance. The literature confirms that real-road conditions can materially change energy-recovery behaviour and that standardized, route-aware evaluation remains important.

This article has presented a complete methodology for a real-world regenerative-braking energy study, including vehicle dynamics equations, data acquisition, event segmentation, energy integration, route classification, uncertainty



analysis and reporting formats. The illustrative plots demonstrate the intended presentation style but must be replaced with measured vehicle data before the manuscript is submitted as an experimental research article. A properly instrumented road-test campaign using CAN/OBD-II, GPS and IMU signals can provide the evidence required to quantify energy recovered per braking event, recovery ratio, regenerative share and the influence of operating conditions.

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