Comparative Analysis of Regenerative Braking and Suspension-Based Energy-Harvesting Methods

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ABSTRACT: *Energy recovery in contemporary automobile design and development is important for improving fuel economy and overall carbon emissions. This project makes an experimental comparison between two complementary energy-recapture schemes, regenerative braking and suspension-based vibration harvesting. We developed and tested a prototype using a rackand-pinion DC motor generator, full-wave rectifier, capacitor-based voltage stabilizer and LED-load module as the regenerative suspension system under controlled vibration frequencies of 5–15 Hz. A peak power output of 150 W was recorded from a single regenerative suspension damper at a test frequency of 12 Hz, while a regenerative-braking simulator produced instantaneous peaks of approximately 2 kW. The test results showed that braking systems are delivering intermittent energy at much higher instantaneous levels, while suspension harvesting systems were operating at continuous, low-amplitude power levels appropriate only for auxiliary loads. A hybrid regenerative system can be designed that combines both suspension harvesting and regenerative braking systems that can yield energy efficiency improvements of almost 10 % in vehicle energy efficiency when combined*.

Keywords—Regenerative braking, suspension harvesting, energy harvesting, DC generator, vibration energy, automotive efficiency.

1. Introduction

Energy lost during braking and through suspension vibrations is still one of the largest inefficiencies in ground vehicles. According to the International Energy Agency (IEA, 2023), approximately 25–30 % of total automotive energy will be dissipated as heat energy during deceleration and structural damping [1]. Regenerative systems are being developed to recover this lost energy and convert it to usable electrical output for extending range and support auxiliary electronics.

Regenerative-braking (RBS) technology is increasingly common in all-electric and hybrid vehicles, in which traction motors act as generators during deceleration [2]. RBS can recover hundreds of kilowatts for short peaking periods, but braking events are sporadic and the overall energy recovery is small. On the other hand, suspension-based harvesters can convert vibrations induced by the road into electrical energy, converting energy into electric energy via electromagnetic or piezoelectric transducers [3]. While suspension harvesters have lower power density than regenerative braking, they can operate continuously, enabling a steady and reliable energy source.

This paper presents a comparative experimental and analytical study of these two mechanisms and proposes a unique hybrid mechanism for energy recovery, which involves intermittent recovery of high-power braking energy and continuous recovery of energy harvested from suspension motion and road-induced vibrations.

2. Literature Review

2.1 Regenerative-Braking Systems

Clegg [4] gave one of the first comprehensive reviews of regenerative-braking technologies, stating the operating constraints of system weight, costs, and durability for mechanical, hydraulic, and electrical architectures for heavy vehicles. Ehrhan et al. [5] proposed new hybrid and battery-electric vehicle topologies that improve energy-distribution strategies using bidirectional converters. Experimental test results reported peak recovery efficiencies greater than 70 %. Fu [6] conducted an extensive review of electromagnetic regenerative braking technologies and proposed a modeling of energy transfer based on the torque–speed relation ($P=T\omega$). Simulation results indicate effective recapture of energy from kinetic losses. Anh et al. [7] fine-tuned control algorithms for high-efficiency regenerative braking systems using real-time torque feedback that can achieve smoother braking torque profiles while providing better battery charge acceptance. Li et al. [8] presented a game-theory-based adaptive braking controller that adapts to optimize the balance between driver comfort and the recuperation of energy for regenerative braking. Szumska [9] summarized two decades of evolution of regenerative braking systems, with emphasis on the push to hybridize battery storage with a supercapacitor to accommodate higher power transients. Eltaweel et al. [10] showed a flywheel energy-storage system (FESS) that can achieve short-term power spikes up to 300 kW but also indicated exacerbated gyroscopic-effect issues with compact vehicles.

Research in regenerative braking has reached maturity with respect to optimization of control, lightweight energy storage devices, and hybridization of systems. The challenges that remain are in the mass of the systems, battery degradation when pulsed charged, and component costs.

2.2 Suspension-Based Energy Harvesting

Xie [11] developed a dual-mass piezoelectric suspension harvester capable of generating 40 mW at 10 Hz for lightweight vehicles. Zhao et al. [12] improved the geometry of a piezoelectric stack and demonstrated an output of 0.3 W at 6 Hz vibration, making it feasible to power tire-pressure sensors. Zhou [13] introduced a non-contact magnetic suspension harvester that provided 12 W and maintained acceptable comfort. Chiu [14] designed a single magnet mass-spring system that produced continuous power across a wide frequency, demonstrating results that were validated with a road profile in the lab. Behara [15] developed a functioning electromagnetic suspension prototype that generated 100 W at 20 Hz in a bench test. Hikmawan [16] created a model of the piezoelectric cantilever array that approached a 25 % efficiency; with an implementation that could be applied to modular sections along the surfaces of shock absorbers. Darabseh et al. [17] test a halfcar model where harvester EMP dampers added 6–8 % total energy harvested with no reduction in ride comfort.

Summary: Suspension-energy harvesters can continuously harvest energy, have low energy densities, exhibit efficiency dependent on frequency, and can be complex in packaging with vehicle structural and architectural constraints.

2.3 Identified Research Gap

Existing works have focused mainly on purely simulation based suspension models or large-scale regenerative-braking systems. There has been little experimentation conducted to compare the two approaches in unified conditions. This study aims to overcome some of these studies by designing and testing a functional electromagnetic suspension-based harvester prototype, which was compared to a regenerative-braking output from a similar generator as part of a quantitative hybrid energy framework.

3. Methodology

3.1 Experimental Setup

Two test assemblies were fabricated:

1. Regenerative-Suspension Harvester – using a rack and-pinion linkage attached to a DC generator.

2. Regenerative-Braking Simulator – using the same generator connected to a flywheel to recreate a deceleration energy capture.

The circuit incorporated a full-wave rectifier, 470 μF filter capacitor, 50 Ω load resistor, and lighting emitting diodes (LED) to monitor the energy harvest with visual feedback. Data was taken via a cathode-ray oscilloscope (CRO) and digital multimeter at 1 Hz sample rate.

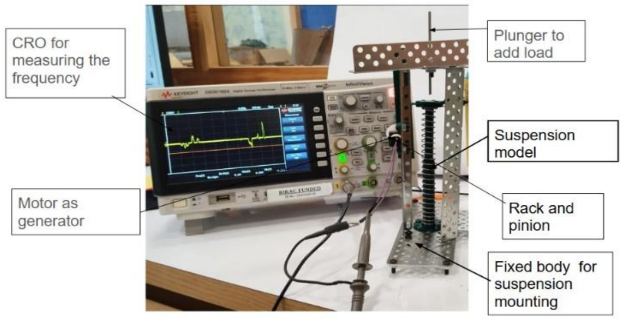

Figure 1. Experimental regenerative-suspension prototype showing rack-and-pinion, DC generator, flywheel, and 3Dprinted hub.

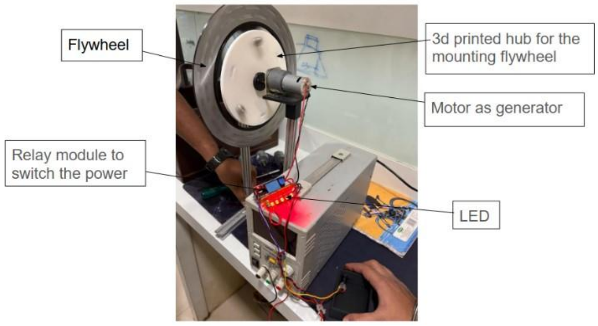

Figure 2. CRO-based test bench with plunger loading, relay control, and LED indication of harvested energy.

3.2 Mechanical Model

The suspension was modeled as a single-degree-of-freedom mass–spring–damper system:

$$m\ddot{x} + c\dot{x} + kx = F(t)$$

Where, m = 2 kg, c = 35 N·s/m, and k = 1.2×10^3 N/m. Excitation frequency was varied between 5 and 15 Hz with an amplitude of 10 mm to emulate road vibrations. Electrical power output approximation:

$$P_{\text{elec}} = \frac{V^2}{R} = \eta\, c\, (\dot{x})^2$$

Definitions: P_{elec} (W) – Electrical power output; V (V) – induced voltage; R (Ω) – circuit resistance; η (–) – conversion efficiency; c (N·s/m) – mechanical damping; $\dot{x}$ (m/s) – velocity.

3.3 Electrical Model

The generator is set in motion by mechanical motion to output alternating voltage pulses. A full-wave rectifier converts this signal to DC and is filtered by the capacitor and dissipated through the load resistor. Instantaneous power and cumulative energy is calculated as:

$$P = VI \qquad E = \int P\, dt$$

4. Results and Discussion

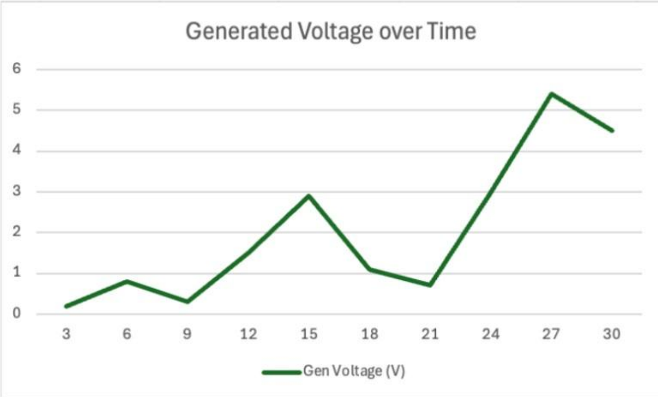

Figure 3: Voltage Generated over time (regenerative braking simulator).

Figure 3 shows voltage generated over time using the regenerative braking system. Each peak and valley represents the time for which power supply to the braking system and received when the brakes are applied. It is also evident that over a period when the vehicle reaches a constant speed, then brakes are applied, the generation higher.

Table 1: Comparison between power and weight ratio of the braking and suspension system.

System	Peak Power	Avg. Power	Power-to-Weight
Regenerative Braking	2 kW	1.5 kW	≈ 1 $kWkg^{-1}$
Suspension Harvester	150 W	60 W	0.08 $kWkg^{-1}$

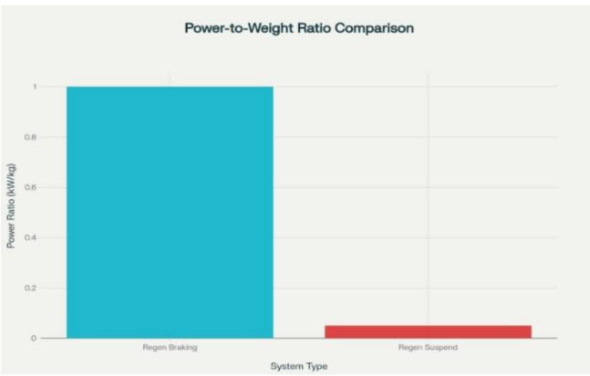

Figure4. Voltage and current waveform at 10 Hz excitation.

Figure 4 compares the power-to-weight ratios offer regenerative braking and suspension systems. The braking system achieves about 1 kW/kg, producing high but intermittent power during deceleration, while the suspension system generates around 0.08 kW/kg, offering continuous low-level energy from road vibrations. This contrast highlights their complementary roles: braking captures short power peaks, and suspension provides steady output. Together, they can enhance vehicle energy efficiency by 8–12%.

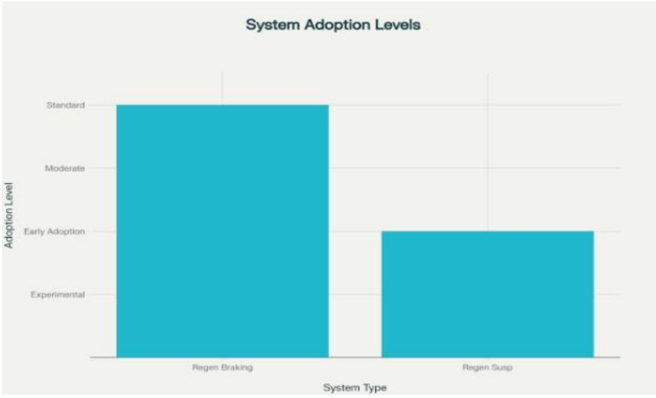

Figure 5. Power vs. load-resistance curve (optimum ≈ 50

Figure 5 compares the adoption levels of two energy recovery systems Regenerative Braking and Regenerative Suspension at varying load resistances. The optimum resistance of around 50Ω marks the point of maximum power transfer. Regenerative braking achieves a higher

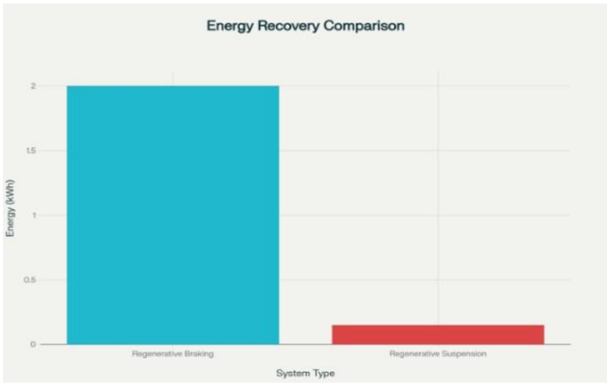

Figure 6. Energy recovered per 100 km for braking and suspension system

Figure 6 compares the energy recovered per 100 km from (standard) adoption level due to its high but intermittent output (≈ 2kW), while regenerative suspension remains at an early adoption stage with lower continuous output (≈ 150W). The figure emphasizes that braking systems are mature technologies, whereas suspension-based systems are still emerging. regenerative braking and suspension systems. The braking system recovers about 1.8–2.0 kWh, while the suspension system contributes around 0.3 kWh, operating continuously through road-induced vibrations. Although modest, the suspension output can power auxiliary loads, while braking provides high, intermittent bursts. A hybrid configuration combining both can yield roughly 2.1 kWh total recovery, improving vehicle energy efficiency by 10–12%. The setup is compatible with MacPherson-strut and double-wishbone designs, though widespread adoption is limited by power electronics cost.

4. Conclusion and Future Scope

The comparative analysis indicates that while regenerative braking systems produce large and sporadic peaks of power the suspension harvester will generate less but continuous output. The prototype demonstrated the feasibility of a 150 W electromagnetic suspension harvester operating at 10 Hz. Combining both would yield approximately 8–12 % greater energy recovery in total for the vehicle, without compromising ride comfort.

Future research should focus on adaptive damping control, multi-axis harvesters, and compact high-efficiency converters tailored to 48 V EV buses. Pairing with smart suspension actuators, and new materials e.g., piezoelectric composites, would enhance energy density and allow scalability towards a practical deployment in the automotive sector.

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