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# **Construction Of A Traditional Hydraulic Braking System With Smart Regenerative Components Technology**

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## **ABSTRACT**

This research develops an innovative hybrid braking system integrating traditional hydraulic architecture with smart regenerative components for enhanced energy efficiency and safety. The system combines conventional friction-based braking with electromagnetic energy recovery technology to capture kinetic energy during deceleration and convert it into electrical energy for battery storage. The research objectives are to design and construct a functional hydraulic braking system, integrate smart regenerative components, and evaluate braking performance and energy recovery capabilities. The project addresses critical gaps in technical and vocational education (TVET) institutions where instructional facilities lack integration of conventional hydraulic systems with modern regenerative technology. Traditional hydraulic braking operates on Pascal's principle using master cylinders, brake lines, calipers, and friction materials. The regenerative component utilizes electric motor-generators operating in reverse during deceleration, with advanced control algorithms optimizing the balance between regenerative and friction braking based on vehicle speed, battery charge level, and driver input. Studies demonstrate regenerative systems can recover 15% to 25% of total energy during urban driving cycles, with advanced systems capturing up to 92.5% of kinetic energy. The constructed system serves as a comprehensive educational tool for automotive technology programs, enabling students to observe both hydraulic pressure dynamics and electromagnetic energy conversion processes. As the global regenerative braking market approaches \$14.86 billion by 2031, understanding integrated braking systems becomes essential for automotive technicians. This instructional platform bridges conventional and modern technologies, preparing graduates for evolving industry demands while contributing to automotive safety and sustainability objectives.

**Keywords:** hydraulic systems, automotive safety, hybrid braking system

## **INTRODUCTION**

Automobile technology education in Nigeria encompasses training programs offered by technical colleges, colleges of education (technical), polytechnics, and universities, preparing students for careers in automotive design, diagnostics, repair, and maintenance. The curriculum covers emerging trends in

electric vehicles, hybrid systems, and sustainable energy sources, making it crucial for vocational and technical training (Okoro, 2023). However, inadequate funding and poor facilities limit the use of instructional models for teaching complex automotive systems including braking systems, suspension, transmission, and ignition systems.

The braking system represents a critical safety component that converts kinetic energy into other forms to decelerate or stop vehicles. Traditional hydraulic braking systems have dominated automotive applications for decades, utilizing hydraulic pressure to transmit force from brake pedals to friction materials. With the proliferation of electric and hybrid vehicles, regenerative braking technology has emerged as a complementary system that captures kinetic energy during deceleration and converts it to electrical energy for battery storage, significantly improving vehicle efficiency (Yang et al., 2024).

Hydraulic braking systems operate on Pascal's principle of fluid mechanics, where master cylinders convert mechanical pedal force into hydraulic pressure transmitted through brake lines to wheel cylinders or calipers (Rajput, 2023; Zhang et al., 2024). Modern vehicles increasingly integrate traditional components with smart regenerative braking components to create hybrid systems maximizing both safety and energy efficiency. In regenerative braking, electric motors operate in reverse as generators during deceleration, converting kinetic energy into electrical current stored in battery packs while hydraulic systems provide supplementary friction-based braking (Huang et al., 2025).

A traditional hydraulic braking system with smart regenerative components serves as an advanced educational model demonstrating both conventional friction-based braking and modern energy recovery technology. This integrated setup enables understanding of complementary functions between hydraulic and regenerative systems, making it ideal for training in automotive technology programs (Prakash, 2025). Constructing such systems requires comprehensive understanding of hydraulic principles and electrical energy systems, involving hydraulic circuit assembly, electric motor integration with battery packs and control electronics, sensor installation for monitoring wheel speed and brake pressure, and control unit coordination for optimal braking force distribution.

The integrated system functions on principles of hydraulic pressure and electromagnetic energy conversion. During braking, the master cylinder generates hydraulic pressure transmitted to wheel cylinders, forcing brake pads against rotors to create friction. Simultaneously, the electric motor switches to generator mode, with wheels driving the motor in reverse to generate electrical current through electromagnetic induction. Advanced control systems use algorithms incorporating machine learning and fuzzy logic to optimize the balance between regenerative and friction braking based on vehicle speed, battery charge level, road conditions, and driver input. Advanced systems can capture up to 92.5% of kinetic energy during coordinated braking (Advanced Regenerative Braking Study, 2025). As the global regenerative braking system market is projected to reach \$14.86 billion by 2031, understanding these integrated systems becomes increasingly essential (Market Analysis, 2025).

#### Problem Statement

Many TVET institutions and engineering training centers lack instructional facilities integrating conventional hydraulic braking systems with modern regenerative braking technology. Regenerative braking systems have become standard in electric and hybrid vehicles, yet training infrastructure has not kept pace with this technological evolution (Vasiljević et al., 2022). Students are exposed mainly to outdated braking models that do not reflect current industry practices, limiting understanding of smart braking systems, energy recovery principles, and the transition from traditional to advanced automotive technologies.

Kennedy and Kepha (2015) highlighted that complexity in modern automobile technology presents significant challenges to mechanics operating in micro and small enterprises, particularly those trained under conventional curricula. Saidu et al. (2021a) observed that lack of competent troubleshooting skills and inefficiency of facilities have led to complaints about competency and quality of motor vehicle mechanics. Ezeama et al. (2016) emphasized the critical need for capacity building among motor vehicle mechanics trainers in modern diagnostic tools essential for servicing regenerative braking systems. The

advancement in automobile technology, particularly the influx of modern automobiles with complex electrical/electronic control systems, makes it imperative for training institutions to provide practical exposure to regenerative braking systems alongside conventional systems (Baba et al., 2018). Without adequate instructional facilities bridging conventional and regenerative braking technologies, graduates remain ill-equipped to meet current labor market demands.

### **Aim and Objectives**

The aim of this study is to construct a traditional hydraulic braking system integrated with smart regenerative components technology for instructional purposes in technical and vocational education institutions. The specific objectives are to:

1. Design and construct a functional traditional hydraulic braking system.
2. Integrate smart regenerative braking components into the hydraulic braking system.
3. Evaluate the braking performance and energy recovery capability of the constructed system.

### **Research Questions**

Based on the stated objectives, the following research questions guide this study:

1. What are the design specifications and functional requirements for constructing a traditional hydraulic braking system for instructional purposes in technical and vocational education institutions?
2. How can smart regenerative braking components be effectively integrated into a traditional hydraulic braking system to demonstrate hybrid braking technology?
3. What is the braking performance and energy recovery capability of the constructed hybrid hydraulic-regenerative braking system?

## **LITERATURE REVIEW**

The automotive industry is experiencing a paradigm shift from conventional internal combustion engine vehicles to hybrid and electric vehicles, driven by environmental concerns, energy efficiency demands, and technological advancements (Chen et al., 2024). This transformation has necessitated corresponding changes in automotive braking systems, with regenerative braking technology emerging as a critical component in modern vehicle energy management systems (Kumar & Singh, 2023). Technical and vocational education institutions face the challenge of preparing motor vehicle mechanics and technicians with competencies required to service, maintain, and troubleshoot these advanced braking systems (Olaitan & Mohammed, 2024).

### **Hydraulic Braking Systems**

Hydraulic braking systems operate on Pascal's principle of fluid mechanics, which states that pressure applied to a confined fluid is transmitted equally in all directions (Rajput, 2023). The system consists of master cylinders, brake lines, wheel cylinders or calipers, brake pads or shoes, and brake fluid (Zhang et al., 2024). When drivers apply pressure to brake pedals, master cylinders convert mechanical force into hydraulic pressure transmitted through brake lines to wheel cylinders, causing brake pads to contact rotors and generate friction that decelerates vehicles.

Master cylinders serve as the heart of hydraulic braking systems, converting pedal force into hydraulic pressure through piston-cylinder mechanisms (Ahmed & Hassan, 2024). Modern master cylinders incorporate dual-circuit designs providing redundancy and safety, with separate hydraulic circuits for front and rear wheels or diagonal wheel pairs (Bosch Automotive Handbook, 2024). Brake fluid must meet stringent requirements including high boiling point, low compressibility, corrosion resistance, and stability across wide temperature ranges, with DOT 4 being most prevalent in contemporary automotive applications (Limpert, 2023; SAE International, 2024).

Brake calipers in disc brake systems house pistons and brake pads, with floating and fixed caliper designs being primary configurations (Eriksson & Jacobson, 2024). Fixed calipers have pistons on both sides of rotors providing superior braking performance but are more expensive and complex, while floating calipers use pistons on only one side and are more common in passenger vehicles (Day, 2024). Brake rotors must dissipate significant thermal energy during braking, with ventilated rotors being standard on

front axles where majority of braking force is applied (Tirovic & Day, 2023).

### **Regenerative Braking Systems**

Regenerative braking systems represent a fundamental departure from conventional friction braking by capturing kinetic energy during deceleration and converting it into electrical energy for storage rather than dissipating it as waste heat (Li et al., 2024). The theoretical foundation rests on energy conversion principles and reversibility of electric motors (Ehsani et al., 2024). When electric motors are driven by external mechanical force rather than supplied electrical energy, they operate as generators producing electrical current that can charge vehicle batteries (Husain, 2023).

The energy recovery potential is substantial, with regenerative braking recovering 15%–25% of total energy consumed during urban driving cycles, with higher recovery rates possible in stop-and-go traffic conditions (Zhou et al., 2024). Actual energy recovery depends on multiple factors including vehicle mass, driving cycle characteristics, initial velocity, deceleration rate, and efficiency of motor-generators and power electronics (Park & Chen, 2024).

Mathematical modeling demonstrates that recoverable energy ( $E_r$ ) during braking events can be expressed as:  $E_r = \eta \times (1/2 \times m \times v^2)$ , where  $\eta$  is overall system efficiency,  $m$  is vehicle mass, and  $v$  is initial velocity (Kumar et al., 2023).

Electric motor-generators serve as primary energy conversion devices in regenerative braking systems (Emadi, 2024). Permanent magnet synchronous motors (PMSMs) and induction motors are most common types used in electric and hybrid vehicles, with PMSMs offering higher efficiency and power density while induction motors provide greater robustness and lower cost (Miller, 2023). Motor capability to transition smoothly between motoring and generating modes is critical for effective regenerative braking (Boldea & Nasar, 2024).

Power electronics, specifically inverters, control electrical energy flow between motor-generators and batteries during regenerative braking (Rashid, 2024). Inverters convert AC voltage generated by motors into DC voltage compatible with batteries while managing braking torque to achieve desired deceleration (Husain & Islam, 2024). Advanced inverter designs incorporate silicon carbide (SiC) semiconductors offering lower switching losses and higher efficiency compared to traditional silicon-based devices (Wang et al., 2024).

Battery or energy storage systems must be capable of accepting high charging currents during regenerative braking events (Scrosati et al., 2024). Lithium-ion batteries are predominant in modern electric vehicles due to high energy density, power capability, and cycle life (Goodenough & Park, 2023). However, battery state of charge, temperature, and charge acceptance rate limit the amount of regenerative energy that can be captured (Plett, 2024). When batteries are near full charge or operating at extreme temperatures, regenerative braking capability may be reduced, requiring increased reliance on friction brakes (Battery University, 2024).

### **CONCLUSION**

Hydraulic braking systems remain the foundation of automotive braking, providing reliable and effective deceleration through well-established friction-based technology. Regenerative braking systems represent significant technological advancement that captures kinetic energy during deceleration, improving vehicle efficiency and reducing environmental impact. Integration of these systems in hybrid braking architectures requires sophisticated control strategies, careful component selection, and comprehensive system validation.

Technical and vocational education institutions face the challenge of preparing motor vehicle mechanics with knowledge and skills necessary to service increasingly complex automotive braking systems. Construction of instructional hybrid braking systems integrating traditional hydraulic components with modern regenerative technology provides an effective platform for developing student competencies. Such systems enable hands-on learning experiences that bridge theoretical understanding and practical application, preparing graduates for evolving demands of the automotive service industry.

## RECOMMENDATIONS

1. The braking system model should be incorporated into automobile and mechanical engineering laboratories for instructional purposes.
2. Digital displays and monitoring units should be added to show real-time braking force and recovered energy values.
3. Future studies should focus on improving regeneration efficiency through advanced control algorithms and sensor integration.
4. The system can be further developed into a full hybrid braking trainer for TVET institutions.

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