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Application of Theory of Inventive Problem Solving (TRIZ) and Quality Function Deployment (QFD) Methodologies for Design and Manufacturing of a Regenerative Braking System

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Abstract

Regenerative braking systems represent an innovative technology in automotive engineering, offering enhanced energy efficiency and sustainability through the recovery of kinetic energy during braking. Compared to traditional braking mechanisms, regenerative braking is particularly useful for electric vehicles due to its ability to recharge batteries recharging with restored kinetic energy. This paper is structured to present a problem definition, literature review, and engineering design, along with a discussion of regenerative braking system (RBS) working principles, types, and applications. Additionally, the application of the Theory of Inventive Problem Solving (TRIZ) methodology in the design and optimization of regenerative braking systems is evaluated. TRIZ provides a systematic approach to innovation by identifying contradictions and resolving them through inventive principles and solutions. This paper aims to perform a detailed analysis through a case study to enhance the efficiency, reliability, and performance of regenerative braking systems for sustainable transportation solutions. The conceptual design of a regenerative braking system was performed and a small-scale prototype replicating the dynamics of the system was manufactured to validate the proposed design methodology. Experimental validation of the proposed design showed that almost 14 percent of the kinetic energy can be easily recovered during braking and reused for recharging the battery of an electric or hybrid vehicle.

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1. Introduction

In recent years, the automotive industry has witnessed a paradigm shift towards sustainable transportation solutions driven by environmental concerns and technological advancements. Central to this transformation is the development and implementation of regenerative braking systems that aim to optimize energy efficiency, decrease emissions, and promote sustainability. Traditional braking systems dissipate kinetic energy as heat through friction, resulting in energy loss and increased wear on braking components. The loss of energy in this system opens doors for potential improvements toward more sustainable transportation. Regenerative braking systems play a pivotal role in modern vehicles, converting kinetic energy into electrical energy for storage or immediate reuse, thus improving energy efficiency and reducing reliance on traditional braking mechanisms. This transformative technology not only enhances energy efficiency, but also reduces emissions and extends vehicle range in electrified and hybrid propulsion systems.[1,2] The design and optimization of regenerative braking systems present complex engineering challenges, including maximizing energy recovery, minimizing system weight, and ensuring safety and reliability. In addressing these challenges, the Theory of Inventive Problem Solving (TRIZ) offers a systematic methodology for innovation and problem-solving.[3]

The subject matter of design and production in regenerative braking system projects has great significance since it directly impacts the system's performance and efficiency. A properly designed and manufactured regenerative braking system can achieve efficient energy recovery, limit energy dissipation, and enhance overall brake efficiency. Furthermore, the cost-effectiveness and feasibility of including regenerative braking in vehicles are directly influenced by the design and manufacturing process, which is crucial for the successful integration of this technology in the

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automotive industry. Regenerative braking systems' importance comes from improving vehicle energy efficiency and sustainability by capturing and reusing energy dissipated during braking, reducing fuel consumption and greenhouse gas emissions. They also enhance electric and hybrid vehicle range and performance by recovering energy lost during braking. Discussing regenerative braking opens opportunities for innovation and technological advancements in the automotive industry, encouraging collaboration among researchers, engineers, and manufacturers to develop more efficient technologies.[4,5]

Before the use of regenerative braking systems, several attempts had been made to mitigate the constraints of conventional braking systems. These innovations included improvements in brake pad materials and designs to promote friction and heat dispersion, along with the installation of larger brake discs to improve braking performance.[6-8] In addition, hydraulic braking systems were developed to provide enhanced precision and response. Nevertheless, these systems had limitations in their capacity to recover and utilize the energy dissipated during braking, leading to inefficiencies and increased fuel consumption.[9]

Regenerative braking systems represent a revolutionary advancement in automotive technology, enabling the recovery and utilization of kinetic energy during braking maneuvers.[10] The core principle behind regenerative braking systems lies in the utilization of electric motors or generators integrated into the vehicle's drivetrain. During braking, these motors operate in reverse mode, functioning as generators to capture kinetic energy and convert it into electrical energy. This energy is then stored in batteries or capacitors for subsequent use, such as powering auxiliary systems, providing acceleration assistance, or refilling the vehicle's energy reserves. However, to ensure driving safety, regenerative braking systems are coupled with mechanical braking systems into a hybrid braking system, as shown in the schematic diagram presented in Fig. 1. Both types of braking are controlled by the single pedal in which the initial part of the breaking maneuver is for regenerative braking and last part is for mechanical braking, based on the angle of the brake pedal.[11] The distribution of braking force between regenerative and mechanical braking is significantly essential.

1.1 Advantages and disadvantages of regenerative braking systems

This section highlights the significant advantages offered by regenerative braking systems. It discusses improvements in energy efficiency, reduced environmental impact, extended vehicle range, enhanced braking performance, and overall system reliability. The advantages of a regenerative braking system can be summarized as follows.[12]

- Energy Efficiency: One significant advantage of regenerative braking is that it allows the recovery and reuse of energy that would otherwise be lost as heat during traditional braking. This significantly increases the overall energy efficiency of the vehicle, thereby reducing fuel consumption and extending the range of electric and hybrid vehicles.
- Reduced Emissions: By recovering and storing energy during braking, regenerative braking systems help to reduce the reliance on conventional frictional braking, which generates more heat and contributes to increased emissions. This technology contributes to a decrease in greenhouse gas emissions and enables a more environmentally friendly mode of transportation.
- Extended Brake Life: Regenerative braking systems can help extend the life of braking components by reducing the amount of frictional energy dissipated and heat generated during braking. This can result in reduced wear on brake pads, discs, and other components, leading to longer-lasting and more cost-effective braking systems.

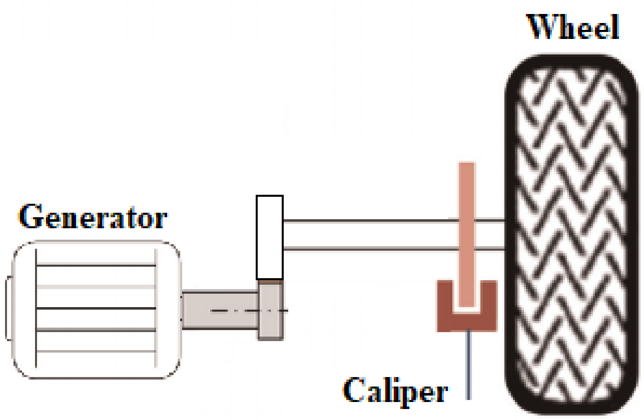

Fig. 1 Schematic representation of hybrid braking system.

Despite their advantages, regenerative braking systems also face certain limitations and challenges. This section examines factors such as energy conversion efficiency, system complexity, cost, weight, thermal management, and integration with existing vehicle architectures. The disadvantages of a regenerative braking system can be summarized as follows.[13]

- Weight and Space Requirements: Regenerative braking systems occasionally require auxiliary components, like energy storage devices that contribute to the overall weight of the vehicle. The additional weight might have an impact on the overall performance and mobility of the vehicle. Likewise, the need for more room to accommodate energy storage devices might influence the vehicle's design and packaging, perhaps leading to a decrease in interior space.

• Cost and Complexity: The incorporation of a regenerative braking system may introduce complexity and costs to the entire vehicle design and manufacturing process, particularly when upgrading current vehicles. Additional components, such as electric generators and energy storage systems, may raise the initial cost of vehicles and require specialized control systems for smooth integration.

1.2 Types of regenerative braking system

As the automotive industry continues to embrace electrification and sustainable practices, the importance of regenerative braking systems cannot be overstated. From electric vehicles to hybrid powertrains, regenerative braking represents a fundamental component of the green mobility ecosystem, driving innovation, efficiency, and environmental stewardship. This section presents the fundamental principles underlying regenerative braking systems. It categorizes regenerative braking systems based on mechanisms used to convert kinetic energy into electrical energy. Hamada and Orhan[14] presented a detailed overview of regenerative braking systems, where they provided a concise and holistic evaluation of regenerative braking system (RBS) fundamentals from history, competing technologies, types, and characteristics perspectives. Among various RBS configurations, the following commonly used types can be allocated:

1. Electromagnetic regenerative braking system utilizes electromagnetic forces to convert the kinetic energy of the vehicle into electrical energy. It involves the use of magnets and conductors to generate an electromagnetic field. When the brakes are applied, the kinetic energy turns the wheels and rotates the conductors within the magnetic field, producing an electrical current that can be stored or fed back into the vehicle's electrical system.[15]

2. Flywheel regenerative braking system utilizes a rotating flywheel to store the kinetic energy. When brakes are engaged, the energy is transferred to a spinning flywheel, which stores the energy as rotational motion. This energy can be recovered later by transferring it back to the drivetrain during acceleration, reducing the strain on the main powertrain.[16]

3. Spring regenerative braking system utilizes the energy stored in mechanical springs to recover and reuse energy. When the brakes are applied, the kinetic energy is transferred to a set of springs, which are compressed and store the energy. The stored energy can then be released and used during acceleration, assisting the main power source and enhancing overall energy efficiency.[17]

4. Hydraulic regenerative braking system utilizes hydraulic fluid to convert kinetic energy into potential energy, which can be stored and reused. When the brakes are applied, hydraulic pressure is generated by a pump/motor system. This pressure is then used to compress a fluid or a gas in an accumulator, storing the energy. The stored energy can be subsequently returned to the wheels or used to assist the main powertrain system during acceleration.[18]

Each of these regenerative braking systems offers unique advantages and disadvantages, catering to specific vehicle applications and requirements. The selection of the appropriate system depends on factors such as the vehicle type, size, powertrain configuration, and desired energy recovery capabilities. A comparative analysis of regenerative braking system technologies can provide insights and lead to the selection of the most suitable RBS technology for particular application. The following points can be derived from the literature review:

• Electro-Mechanical systems tend to be more efficient in converting kinetic energy to storable forms.
• Mechanical systems are highly efficient, but face practical challenges in automotive applications.
• Mechanical systems could be less expensive, but have higher maintenance costs.
• Electric systems have higher initial costs, but lower operational costs.
• Hydraulic systems are better suited for heavy vehicles.
• Electric systems are ideal for passenger vehicles and hybrids.
• Electric and Electro-Mechanical systems are more complex due to integration with vehicle electronics.
• Mechanical and Friction-based systems are simpler, but have limitations in energy recovery.

As a result, the choice of regenerative braking technology depends on the specific requirements of the vehicle, including cost, efficiency, weight, and complexity. Electric regenerative braking is the most commonly used in modern electric and hybrid vehicles due to its efficiency and integration capabilities. However, other systems like mechanical and hydraulic regenerative braking offer unique advantages for specific applications, such as heavy-duty vehicles and performance cars.[19]

2. Experimental

The primary objective of a regenerative braking system is to improve the energy recovery efficiency during braking maneuvers while minimizing system complexity and weight. Additionally, the system should maintain safety standards and ensure seamless integration with the vehicle's dynamics and control systems.[15] Attaining efficient regenerative braking while simultaneously ensuring adequate vehicle stability and control is a rather difficult task.[20] Therefore, the use of TRIZ and Quality Function Deployment (QFD) design methodologies was selected to solve this complex engineering design problem.

TRIZ provides a structured framework for innovation and problem-solving in engineering systems.[21] At its core, TRIZ is founded on the premise that inventive solutions to technical problems are not arbitrary, but rather governed by identifiable patterns and principles. Altshuller's extensive study of thousands of patents and innovative solutions led to the formulation of TRIZ, which embodies a synthesis of engineering principles, psychology, and system theory. The overarching goal of TRIZ is to enable individuals and organizations to overcome barriers to innovation and achieve breakthroughs in product design, process optimization, and problem-solving. Key components of TRIZ include contradiction analysis, inventive principles, and the utilization of a comprehensive database of inventive solutions.[22] Many engineering problems, such as the design of a regenerative braking system, involve multiple contradictions. These contradictions manifest as conflicts between desirable attributes or parameters. The first step in applying TRIZ to regenerative braking system design involves identifying inherent contradictions within the system. The following contradictions were identified:

Energy Recovery Efficiency vs. System Complexity: Increasing the energy recovery efficiency often entails adding complexity to the system, potentially compromising reliability and increasing maintenance requirements.

System Weight vs. Structural Integrity: Reducing system weight to enhance vehicle performance conflicts with the need to ensure structural integrity and safety standards.

Regenerative Braking Activation vs. Driver Experience: Optimizing regenerative braking activation to maximize energy recovery may impact the driver's braking experience and comfort.

TRIZ provides systematic methods for resolving these contradictions by identifying inventive principles that enable the simultaneous optimization of conflicting factors. These inventive principles were derived from the analysis of successful patents and innovations across various industries and serve as heuristic guidelines for generating creative solutions to engineering problems.[23] Following inventive principles may be applied:

Principle of Segmentation (Division): Divide the regenerative braking system into modular components to simplify maintenance and troubleshooting while maintaining overall system integrity.

Principle of Intermediary: Introduce an intermediary mechanism between the braking pedal and the regenerative braking system to provide variable braking force and improve the driver's braking experience.

Principle of Dynamics: Utilize dynamic adjustments in regenerative braking activation based on real-time driving conditions, such as vehicle speed, road gradient, and traffic patterns, to optimize energy recovery without compromising safety.

Principle of Replacement of Mechanical System: Utilize electronic sensors and control algorithms to define the proper braking activation based on real-time driving conditions in order to maximize energy recovery without compromising safety.

Principle of Pneumatic or Hydraulic Constructions: Utilize hydraulic system to store kinetic energy generated during braking maneuvers and use it during takeoff.

By following these inventive principles, multiple solutions and ways of implementing regenerative braking can be designed. Redesigning regenerative braking system with modular components, allowing for easier maintenance and repair, implementation of an intermediary mechanism to provide variable braking force, and dynamic adjustments in regenerative braking activation optimize energy recovery without compromising safety or driving experience are some of them. With these insights, second step of design methodology – QFD can be applied in order to come up with conceptual design of RBS prototype.[24,25] QFD is a comprehensive methodology that became a pivotal tool in the realms of product development, project management, and quality assurance across various industries worldwide. At its core, QFD is a systematic approach designed to translate customer requirements, preferences, and expectations into specific product or service characteristics by aligning customer needs with engineering design and manufacturing processes. Quality Function Deployment serves as a bridge between customer expectations and product realization, fostering excellence, innovation, and customer satisfaction as a result of design process.[26]

The specific objectives of research on the design and manufacturing of regenerative braking systems(see Fig. 2) may include:

1. Enhancing Energy Efficiency: The research aims to optimize the design and manufacturing processes to maximize energy recovery during braking. This involves identifying the most effective methods, materials, and components for capturing and storing the dissipated energy, and minimizing energy losses.

2. Improving System Performance: The objective is to develop regenerative braking systems that provide seamless integration with conventional braking systems, resulting in

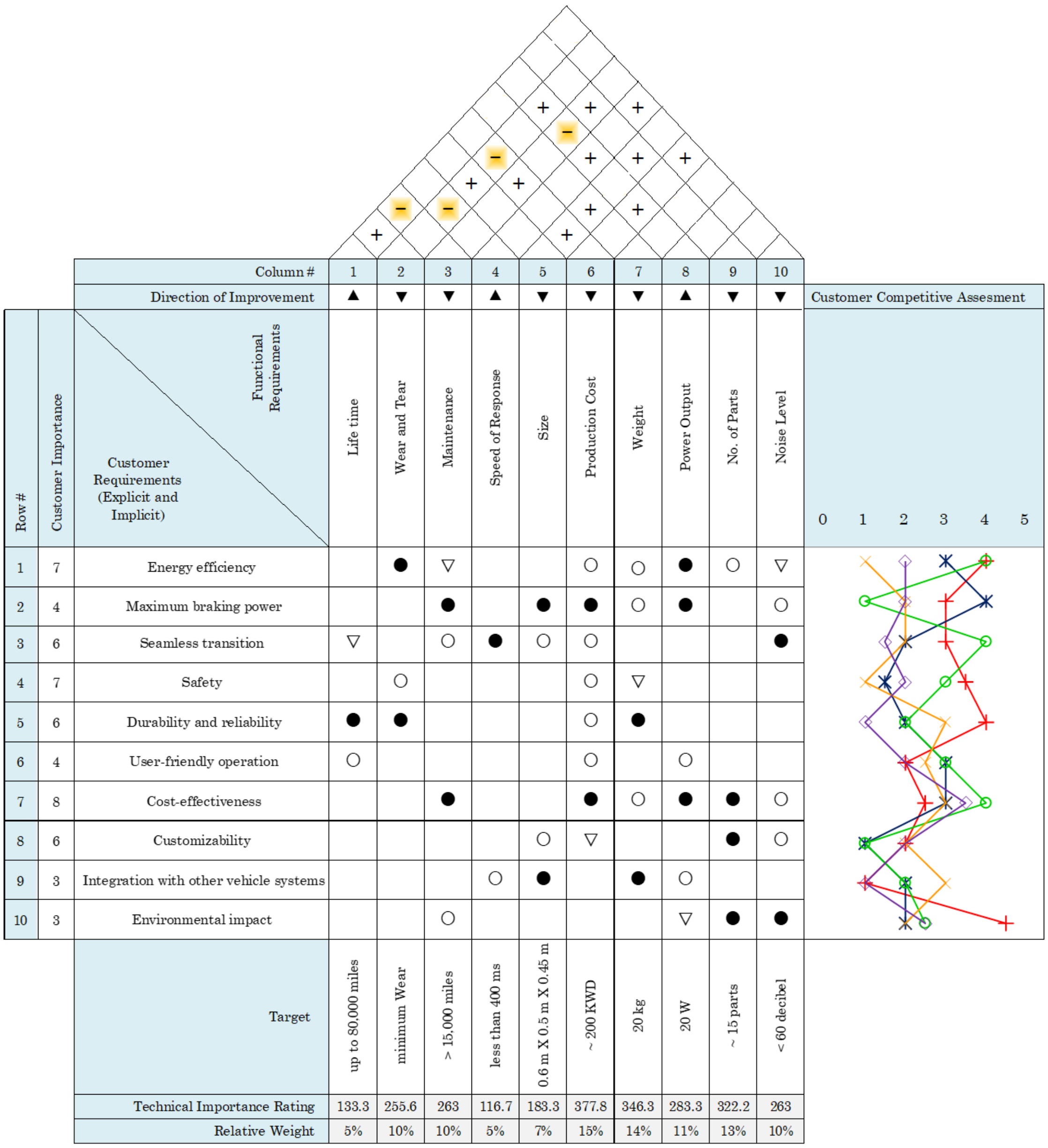

Fig. 2 House of Quality for QFD analysis of regenerative braking system design.

smooth and responsive braking performance. This may involve studying the dynamics of the braking system and optimizing control algorithms to ensure optimal operation.

3. Ensuring Safety and Reliability: The research focuses on designing and manufacturing regenerative braking systems while upholding the highest safety standards. This includes evaluating the durability and reliability of system components, such as generators and energy storage devices, to ensure their long-term functionality and safe operation.

4. Reducing Manufacturing Costs: The objective is to explore cost-effective manufacturing techniques without compromising quality and performance. This may involve identifying efficient production processes, materials, and manufacturing methods that can streamline the assembly of regenerative braking systems, making them more economically viable for mass production.

3. Results and discussion

This paper presents an approach to the design and manufacturing of regenerative braking systems by integrating the Theory of TRIZ and QFD methodologies. Conducted as a student project, this research aims to provide a proof of concept for the innovative technology. Unlike traditional design processes, the presented approach integrates the systematic problem-solving capabilities of TRIZ and the customer-centric focus of QFD to create a more efficient and user-oriented regenerative braking system design. The conclusions from this research can enhance vehicle efficiency, reduce manufacturing costs, and improve customer satisfaction in the automotive industry. Similar design approaches can also be applied to public transportation, railway systems, industrial machinery, and renewable energy systems, driving technological advancements and sustainable solutions across multiple fields.

The concept of a flywheel regenerative braking system is selected as it offers several benefits in relation to reduced manufacturing expenses, simplified maintenance procedures, and the ready availability of spare components, making it a highly functional and economically efficient option. The selected design enhances both the overall performance of the vehicle and its fuel consumption due to its rapid responsiveness and decreased weight. The conceptual design of RBS and the manufactured prototype are presented below in Fig. 3.

To construct a small-scale prototype replicating the dynamics of a regenerative braking system, the following procedural steps were undertaken: Initially, the required materials were acquired, including a base serving as the foundational platform for accommodating various components, a metallic shaft facilitating linkage between the motor and flywheel, bearings providing support for the shaft, and flange coupling ensuring a robust connection between the shaft and motor. An alternating-current (AC) electric motor was selected to power the system and serve as an energy input, a caliper and brake disk were attached to the rim as a conventional friction based braking system to ensure timely and safe braking. The braking pedal was coupled with a generator for simultaneous activation of conventional and regenerative braking systems. Functionality assessment involved verifying secure connections and correct component positioning. A motor was activated to provide input to the system and then switched off before braking operation started. The kinetic energy stored in the flywheel is then partially recovered through RBS and partially dissipated during conventional braking. The electrical output from the generator was measured using a multimeter to calculate the efficiency of the hybrid braking system.

3.1 Design calculations

Calculation of kinetic energy stored in flywheel:

Rotational speed: $N = 1350\ rpm$

Angular velocity: $\omega = \frac{2\pi N}{60} = \frac{2\pi(1350)}{60} = 141.37\ rad/s$

Moment of inertia of the flywheel: $I = MR^2 = 0.75 \cdot 0.12^2 = 0.0108\ kg \cdot m^2$

Kinetic energy of the flywheel: $KE_{stored} = \frac{1}{2} I\omega^2 = \frac{1}{2} \cdot 0.0108 \cdot 141.37^2 = 108\ Joule$

Electrical energy recovered from the generator:

Average output voltage: $V = 12V$

Average output current: $I = 0.5A$

Average braking time: $t = 2.5\ s$

Recovered energy: $E_{recovered} = V \cdot I \cdot t = 12V \cdot 0.5A \cdot 2.5s = 15\ Joule$

Efficiency: $\eta = \frac{E_{recovered}}{KE_{stored}} = \frac{15\ J}{108\ J} \cdot 100 = 13.89\%$

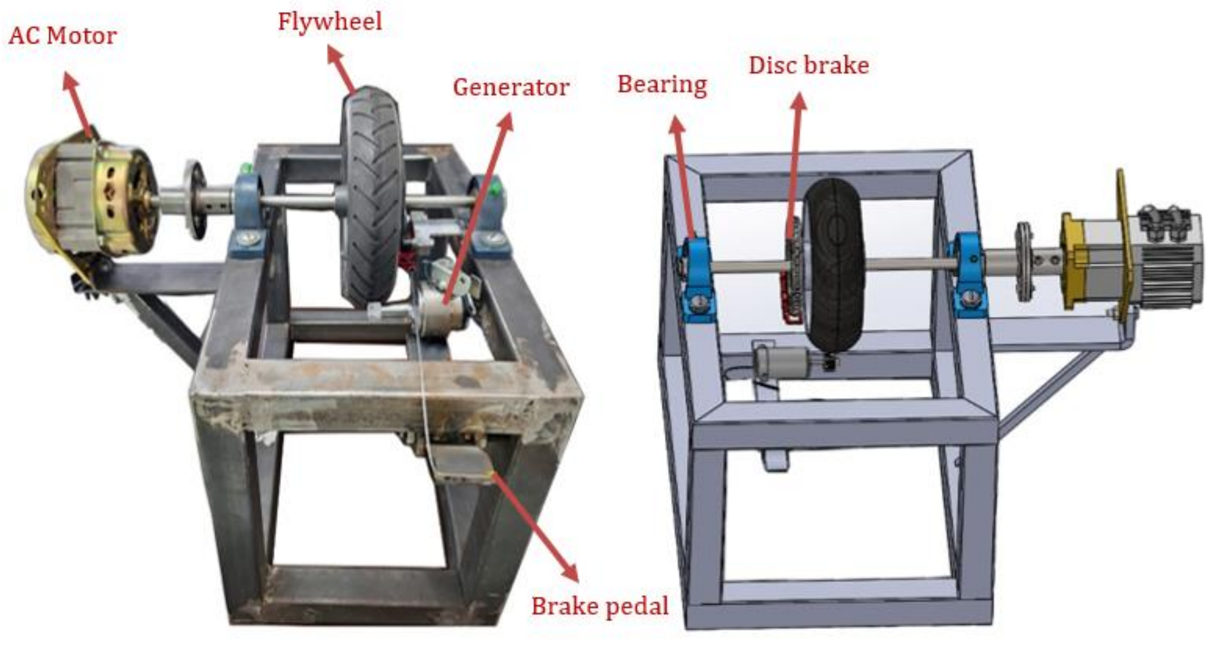

Fig. 3 Conceptual design and manufactured prototype.

4. Conclusion

This paper explores the principles, design considerations, challenges, and future prospects of regenerative braking systems. By engaging in problem definition, conducting a comprehensive literature study, and performing conceptual design, the project has successfully established the basic foundation for the evolution of an effective regenerative braking system while also targeting a competitive specification. A comprehensive analysis of technological advancements and engineering innovations was applied through a simplified prototype design to evaluate the applicability of the proposed methodology. Experimental validation of the proposed design showed that almost 14 percent of the kinetic energy could be easily recovered and reused. Additionally, the paper shows that TRIZ methodology offers a structured approach to innovation and problem-solving in the design and optimization of regenerative braking systems. This paper, while presenting a case study, has limitations due to its scope as a student project aimed at providing a proof of concept for the application of TRIZ and QFD methodologies in the design and manufacturing of regenerative braking systems. The research is constrained by limited resources and time, which may impact the comprehensiveness and scalability of the proposed solutions. Therefore, further research and development in this domain are essential to advance the state-of-the-art in regenerative braking technology. Future research may focus on integrating AI and machine learning algorithms to enable autonomous optimization of regenerative braking systems in real-time, further enhancing energy efficiency and driving experience.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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