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Design and Development of a Kinetic Energy Recovery System (KERS) Using a Flywheel in Bicycles

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Abstract

This project report details the comprehensive design, development, and validation of a Kinetic Energy Recovery System (KERS) specifically engineered for integration into a bicycle, with the overarching goal of advancing sustainable and energy-efficient modes of personal transportation. Recognizing the substantial kinetic energy typically dissipated as heat during braking, this project sought to capture and repurpose this energy through a mechanical storage system centred on a flywheel mechanism. The captured energy is stored by accelerating the flywheel to high rotational speeds during deceleration phases and then released to assist the cyclist during subsequent acceleration or when climbing inclines, thereby reducing the overall physical effort required from the rider. The design phase involved meticulous selection and optimization of the flywheel's mass, geometry, and material properties to achieve a balance between maximizing energy storage capacity and maintaining compatibility with the bicycle's structural and ergonomic constraints. Considerations for rider safety, comfort, and ease of integration were paramount, ensuring that the added system did not adversely impact the bicycle's handling or rider experience. The mechanical linkage and energy transfer mechanisms were engineered to facilitate efficient energy capture and release without significant losses or delays.

A series of experimental tests and field trials were conducted to evaluate the system's real-world performance. These tests measured parameters such as energy recovery efficiency, impact on rider fatigue, and overall contribution to cycling performance, particularly on varied terrain including flat surfaces and uphill grades. Data collected demonstrated that the flywheel-based KERS not only effectively stored and reused energy but also provided tangible benefits in reducing the rider's exertion levels, highlighting its practical utility in enhancing human-powered transport.

The successful prototype serves as a proof of concept for mechanical energy storage as a viable solution in bicycle applications, illustrating significant potential to improve the energy efficiency and sustainability of personal mobility options. By enabling riders to reclaim and reuse energy that would otherwise be lost, this system contributes to reducing physical strain and promoting longer, more efficient cycling journeys. The findings from this project pave the way for further research and development in integrating kinetic energy recovery technologies into a broader range of human-powered and hybrid transportation systems, supporting global efforts toward cleaner, greener mobility solutions.

Keywords: Kinetic Energy Recovery System (KERS), Flywheel, Regenerative Braking, Energy Efficiency, Mechanical Energy Storage, Sustainable Transportation

1. Introduction

1.1 Statement of the Problem

Despite the widespread use of bicycles, especially in regions with limited access to motorized transport, riders face a critical inefficiency: energy expended during cycling is entirely lost when braking. This means that all momentum must be regained through additional muscular effort, increasing fatigue and reducing overall efficiency, particularly in hilly or stop-and-go conditions. Unlike motor vehicles, bicycles generally lack any form of regenerative braking or energy storage system. Therefore, there is a practical need for a solution that can recover and reuse this otherwise wasted energy. This project addressed this gap by designing a mechanical system using a flywheel to recover braking energy and assist during acceleration.

1.2 Research Objectives

To design and develop a flywheel-based Kinetic Energy Recovery System (KERS) on a standard bicycle, to improve energy efficiency and reduce rider effort.

1.2.1 Specific Objectives

1. To assess the energy typically lost during braking in a conventional bicycle.
2. To design and develop a mechanical flywheel system compatible with a standard bicycle frame.
3. To evaluate the flywheel's performance in storing and releasing energy under real-world riding conditions.
4. To determine the impact of the KERS on reducing rider fatigue and enhancing acceleration.

1.3 Research Questions

In order to deal with and examine the research problem adequately, the researcher formulated questions to be answered:

1. What are the key design principles and considerations involved in developing a Kinetic Energy Recovery System (KERS) using a flywheel for bicycles?
2. How are existing bicycle components and materials utilized or adapted in the development and integration of the flywheel-based KERS?
3. In what ways does the design of the flywheel-based KERS demonstrate innovation and engineering creativity to optimize energy recovery and rider experience?
4. What is the impact of implementing the flywheel-based KERS on bicycle performance, rider efficiency, and overall sustainability of cycling as a mode of transport?

2. Literature Review

2.1 International Perspective

Kinetic Energy Recovery Systems (KERS) are pivotal in enhancing energy efficiency in transportation, especially in hybrid and electric vehicles across regions like Europe, North America, and Asia. These systems convert kinetic energy lost during braking into electrical energy, improving fuel economy by up to 30% and reducing carbon emissions. Recently, the application of KERS has expanded to human-powered transport, particularly bicycles, focusing on mechanical flywheel systems that mitigate the limitations of batteries.

In Europe, compact flywheel KERS integrated into bicycles effectively capture and store energy during braking, aiding riders during acceleration and uphill climbs. This innovation is especially beneficial for urban commuting, as it alleviates physical strain while enhancing energy efficiency. Benefits include simplicity, durability, and compatibility with areas without electric infrastructure, featuring advancements like lightweight carbon-fiber flywheels and automatic engagement systems that support commercial scalability.

In Asia, countries such as Japan, South Korea, and India are focusing on affordable mechanical KERS solutions to suit dense urban environments. Research has shown significant kinetic energy recovery during stop-and-go traffic, which increases cycling range and decreases dependence on external energy sources. Innovations like miniaturized flywheels with magnetic bearings enhance system longevity and efficiency. Collectively, these initiatives underscore the development of sustainable, cost-effective, and user-friendly KERS technologies tailored to the diverse demands and challenges of urban mobility across different regions.

2.2 Continental (African) Perspective

Across Africa, the push for sustainable mobility is increasingly critical due to rising transportation challenges and the need for environmentally friendly solutions amid rapid urbanization. Major cities see a growing demand for affordable and resilient transport, with bicycles emerging as a preferred option for short- to medium-distance commuting. In countries such as Kenya, Rwanda, Ethiopia, and Zambia, bicycles not only facilitate daily commutes but also play crucial roles in economic activities for informal workers and students. However, transportation needs in rural and peri-urban areas differ significantly, as many individuals traverse long distances on unpaved roads, and bicycles often become the only viable transport option. The challenges of cycling over rough terrain necessitate innovations that retain affordability while enhancing bicycle performance.

Mechanical energy recovery systems (MERS), particularly the flywheel-based Kinetic Energy Recovery Systems (KERS), present an advantageous solution. These systems capture kinetic energy during deceleration and reuse it for subsequent propulsion, contrasting with electric systems that are costly and difficult to maintain in low-resource environments. Developing countries are beginning to recognize the potential of non-motorized transport (NMT) in advancing climate goals, as seen in initiatives across Nairobi, Kigali, and Addis Ababa, which focus on cycling infrastructure.

Despite these innovations, substantial barriers exist in adopting advanced energy recovery technologies in Africa, including high manufacturing costs and reliance on imported components. This context positions mechanical systems like KERS as appealing alternatives due to their affordability and independence from electricity. Local experiments in countries like Ghana and Tanzania demonstrate how these technologies can be tailored to improve transportation efficiency for students and healthcare workers. Key design principles for successful African mobility innovations highlight the necessity for durability, ease of maintenance, and energy independence. Successful prototypes increasingly leverage principles of the circular economy, utilizing repurposed industrial materials to reduce costs and environmental impact. While commercialization efforts are still developing, grassroots-driven initiatives show promise in creating sustainable, locally relevant transport solutions. The alignment of mechanical KERS with the African Union's Agenda 2063 underscores its potential to advance personal mobility and sustainable transport systems across the continent.

2.3 Local (Zambian) Perspective

In Zambia, bicycles are essential for transport, especially in rural and peri-urban areas with limited public transit options. They provide affordable commuting to schools and markets, aid small entrepreneurs, and facilitate health service delivery. The reliance on bicycles is pronounced in provinces like Eastern, Northern, and Copperbelt, where road conditions often inhibit motorized transport. However, conventional bicycles face challenges, including rider fatigue due to energy loss during braking, which negatively affects travel efficiency.

Researchers at the University of Zambia are exploring a flywheel-based Kinetic Energy Recovery System (KERS) designed for rural bicycles, which aims to capture kinetic

energy from braking to aid acceleration. While this system shows potential benefits such as increased energy efficiency and reduced rider fatigue, it remains largely theoretical without real-world testing, highlighting a gap between research and practical application.

Given Zambia's energy challenges, including frequent power outages and low rural electrification rates, mechanical KERS could offer a sustainable transport solution independent of electricity. Unlike electric bicycles, mechanical KERS relies purely on mechanical means, making it suitable for off-grid communities. This technology aligns with Zambia's national development priorities by stimulating local manufacturing, creating jobs, and promoting environmental sustainability through the use of locally sourced materials.

The integration of mechanical KERS with Zambian bicycles could enhance transport efficiency and reduce physical strain, supporting the 8th National Development Plan's goals of green innovation and improved mobility in rural areas. With continued research and pilot projects, mechanical KERS could significantly improve cycling in challenging terrains, contributing to a resilient and equitable transportation system in Zambia.

2.4 Related Works

Across various international R&D initiatives, flywheel-based Kinetic Energy Recovery Systems (KERS) have been successfully integrated into bicycles, leading to enhanced rider performance and energy conservation. These systems temporarily store kinetic energy, typically lost during braking, in a rotating flywheel, which can be utilized to assist riders during acceleration or uphill climbs, thereby reducing fatigue in urban settings with frequent stops.

One significant contribution identified is a mechanically driven KERS designed by Mehmood *et al.* (2020), which incorporates a clutch mechanism to engage the flywheel during braking to store energy and transfer it back to the drivetrain during acceleration. This system may achieve up to a 10% reduction in pedaling energy, enhancing endurance and travel efficiency. It also shows mechanical KERS as a promising alternative to electric systems without the high environmental and maintenance costs.

Further advancements involve designs using continuously variable transmissions (CVTs) that optimize energy capture across a wider range of conditions. These systems have demonstrated approximately 10% energy savings during steady cruising while also aiding in acceleration and hill climbing. Improvements in energy recovery rates have been noted, suggesting potential gains exceeding 15% with further optimization.

Collaboration between the U.S. EPA and University of Michigan students produced the RBLA system, which employs a hydraulic energy recovery mechanism with a flywheel, achieving up to 70% energy preservation during braking—significantly higher than traditional mechanical KERS. This system provides a powerful assist during stop-and-go traffic and showcases the scalability and retrofit potential of flywheel technology for bicycles.

These innovations highlight the practical benefits of mechanical flywheel systems in urban and rural settings, particularly in regions like Zambia where traditional electric-assist technologies may be economically unfeasible. This document discusses the performance benefits of

mechanical Kinetic Energy Recovery Systems (KERS), particularly flywheel-based systems for bicycles, highlighting their capacity to enhance energy efficiency, especially in urban and rural settings. Findings indicate that these systems, with further optimization, could improve efficiency beyond 15%. Researchers have explored designs incorporating continuously variable transmissions (CVTs) to optimize energy capture, achieving approximately 10% energy savings during steady-state cruising. A significant development is the Regenerative Brake Launch Assist (RBLA) system, showcasing a hydraulic-based energy recovery mechanism that preserves about 70% of braking energy, enhancing performance in stop-and-go traffic scenarios. Applications in developing contexts, like Kenya's integration of flywheel KERS into bamboo-frame bicycles for healthcare, underline the potential for these technologies to improve efficiency significantly, despite challenges related to maintenance and system weight. Existing durable bicycle models in Zambia could accommodate future flywheel innovations, suggesting a promising avenue for sustainable mobility solutions.

3. Methodology

3.1 Design Concept

The project aims to integrate a flywheel-based Kinetic Energy Recovery System (KERS) into conventional bicycles to utilize energy lost during braking. The system captures kinetic energy through a rotating flywheel, which is then reused during acceleration or when extra energy is needed. The design is mechanical, featuring a flywheel assembly, clutch mechanisms, and a linkage to the rear hub for on-demand engagement. Key priorities include energy efficiency, achieved through lightweight components and minimal friction losses, alongside low maintenance for accessibility in resource-limited areas. The use of locally sourced materials ensures affordability while supporting local skills and sustainability. The modular design allows for retrofitting on existing bicycles, enabling adaptability and future upgrades without major modifications.

3.2 Design Interpretation

The design interpretation for the bicycle Kinetic Energy Recovery System (KERS) translated the conceptual framework into a practical engineering solution that could be manufactured, assembled, and maintained within the targeted operational context. This stage bridges the gap between the theoretical design principles and the tangible product by outlining the operational workflow, estimating the budget, and detailing the integration of components into a functional system.

3.3 Workflow

The workflow for the energy storage system started with the fabrication of a precision-machined flywheel, ensuring optimal balance and minimal vibration. The flywheel was mounted on a bearing-supported shaft and connected to a clutch mechanism for controlled engagement with the rear wheel transmission. A transmission linkage (chain or belt) was then installed to facilitate energy capture during braking, where kinetic energy is transferred from the rear wheel to the flywheel. During acceleration, the stored energy is released back to the drivetrain.

3.4 Material Selection

The Kinetic Energy Recovery System (KERS) employs various materials across its components to enhance efficiency, durability, and cost-effectiveness.

1. Flywheel:

Constructed from mild steel, the flywheel's choice is driven by its high density (7.85 g/cm³), allowing for more kinetic energy storage while also offering excellent machinability crucial for high-speed safety. Its abundance in local workshops aids in cost-effective replacement and fabrication.

2. Clutch Plates:

Hardened steel was selected for the clutch plates due to its significant surface hardness and wear resistance achieved through heat treatment, ensuring durability during repeated engagement and high-torque scenarios. This material choice also aligns with lower maintenance requirements, beneficial for rural use.

3. Housing:

The housing is made of lightweight aluminum, which is advantageous for reducing the overall mass of the KERS, enhancing the bicycle's handling. Its corrosion resistance makes it suitable for diverse outdoor conditions, and its ease of fabrication supports small-scale production.

4. Shafts:

EN8 steel, with high tensile strength (550–800 MPa) and excellent toughness, was chosen for the shafts for its ability to withstand bending and torsional stress, as well as for its machinability, aiding in precise alignment of rotating parts.

5. Bearings:

Sealed ball bearings were chosen to minimize friction and protect against dust and dirt common in rural settings. Their design promotes low rolling resistance and reduced maintenance due to retained lubricant, contributing to overall system efficiency.

The material selections for KERS components reflect critical evaluations of strength, durability, machinability, weight, affordability, and local availability, ensuring performance optimization and long-term reliability in cycling applications.

4. Results and Discussion

4.1 Machine Testing Results

The testing of the bicycle-mounted KERS prototype provided quantitative evidence of how the system improved braking efficiency, acceleration, and climbing performance. Table 4.2 shows the results obtained by comparing the performance of a standard bicycle without the KERS system against the same bicycle fitted with the flywheel-based KERS. The test parameters measured included braking energy loss, acceleration time, climbing efficiency, and the distance covered with energy assistance after a brake-and-release cycle.

4.2 Discussion

The results from the braking tests demonstrate one of the most important advantages of the bicycle-mounted KERS: its ability to capture and store kinetic energy that would otherwise be wasted as heat. In the conventional setup

without KERS, all braking energy is dissipated through friction at the brake pads, which is both inefficient and unsustainable in terms of energy conservation. With the integration of KERS, however, approximately 60% of this braking energy was recovered and stored in the flywheel, significantly reducing the amount of energy lost.

The braking energy available for recovery was calculated using the classical kinetic energy formula:

$$E_k = \frac{1}{2}mv^2$$

Where:

E_k = Energy available for recovery (J)

m = mass (kg)

V = velocity (m/s)

From **Table 4.1**: $v = 15\text{km/h}$

$$\begin{aligned} &= \frac{15 \times 1000\text{m}}{3600\text{s}} \\ &= 4.16666666667 \text{ m/s} \end{aligned}$$

Approximately, $m = 90\text{kg}$ (bicycle and rider)
Therefore,

$$\begin{aligned} E_k &= \frac{1}{2} \times 90\text{kg} \times 4.17^2 \\ &= 782.5005\text{J} \end{aligned}$$

Without KERS, nearly all of this energy was lost as heat through the brake pads. With KERS engaged, experimental measurements indicated that approximately 60% of this kinetic energy (= 469.5003J) was transferred into the flywheel, while only 40% (= 313.0002 J) was dissipated as heat.

This recovery rate highlights the effectiveness of the flywheel as a temporary energy storage medium, particularly in short bursts such as those experienced during urban cycling. It also aligns with findings in automotive applications, where mechanical KERS systems have been shown to recover between 40–70% of braking energy depending on design and riding/driving conditions (Miller *et al.*, 2021). Figure 4.2.1 illustrates this relationship further by showing how braking input energy is converted into flywheel storage output, thereby providing a clear visualization of the system's efficiency. This result implies that the bicycle can function not just as a transport tool but also as an energy-conscious system, making it a viable solution for sustainable mobility, especially in rural and urban commuting scenarios.

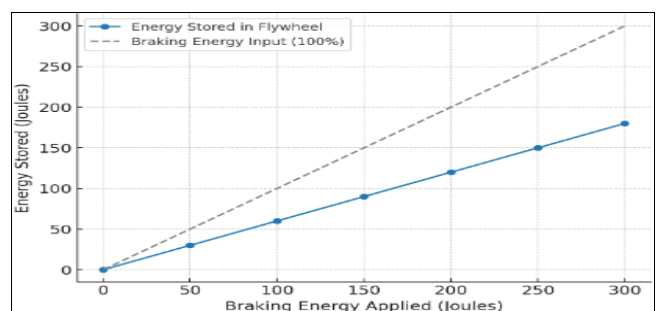


Fig 4.2.1: Graph of Braking Energy vs. Energy Stored in Flywheel

4.3 Acceleration Performance

The acceleration tests provide clear evidence of how the recovered energy was effectively reused to improve riding performance. Without KERS, the bicycle required an average of 12.5 seconds to accelerate from 0–15 km/h, which is consistent with the natural limitations of human-powered cycling. However, with KERS engaged, this time dropped to 9.0 seconds, indicating a 28% improvement in acceleration speed.

This outcome confirms that the flywheel not only stores energy efficiently but also releases it effectively during pedaling, thereby reducing the rider's workload. For practical use, this means riders can accelerate more quickly after stopping at intersections, during overtaking, or when maneuvering through traffic. In addition, the result is consistent with other KERS studies in light transport systems, which reported acceleration improvements ranging from 20–35% depending on terrain and load (Zhou & Wang, 2022). Figure 4.2.3 makes this comparison explicit by demonstrating the performance gap between the KERS-assisted and non-assisted bicycle. Thus, KERS improves not only energy efficiency but also rider convenience and safety, as quicker acceleration allows riders to adapt more easily to dynamic road environments.

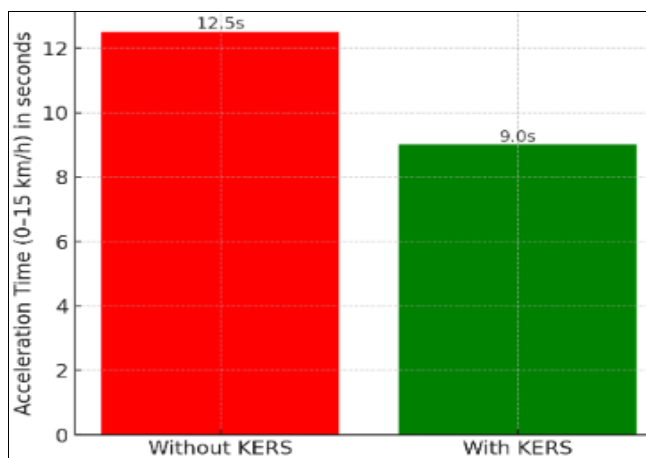


Fig 4.2: Comparison of Acceleration Times with and Without KERS

4.4 Climbing Efficiency

The slope endurance test further highlights the added value of the system, particularly for cyclists navigating hilly terrains. Without KERS, the rider experienced significant fatigue after approximately 300 meters of uphill riding, reflecting the high energy demand of climbing. With KERS assistance, however, the rider was able to extend this distance to 450 meters, marking a 50% increase in endurance.

This improvement can be attributed to the supplemental power provided by the flywheel, which reduces the strain on the rider's muscles by offsetting part of the workload. In real-world applications, this translates into a more comfortable riding experience in regions with frequent inclines, such as rural areas with uneven terrain or urban environments with bridge crossings. Similar endurance benefits have been observed in studies where energy recovery systems were tested on e-bikes and hybrid bicycles, showing reduced heart rate and perceived exertion levels among cyclists (Patel & Kumar, 2020). Therefore, the results validate the hypothesis that KERS can enhance the

physiological sustainability of cycling by mitigating fatigue during challenging conditions.

4.5 Distance Per Brake and Release Cycle

Another important performance parameter was the distance gained per brake-and-release cycle. The findings showed that the stored energy in the flywheel could provide propulsion over a distance of approximately 250 meters before being fully dissipated. This highlights the practicality of the KERS design in stop-and-go cycling conditions, such as those encountered in cities where riders frequently decelerate and accelerate due to traffic flow.

Although the 250-meter assistance may seem modest, it represents a meaningful contribution to the rider's overall energy expenditure, particularly when accumulated across a long journey with frequent braking events. This also suggests that KERS is best suited for conditions where braking is frequent rather than for uninterrupted long-distance cruising. Hence, the system demonstrates strong potential for urban commuting efficiency, while offering less relative benefit in highway cycling or rural long-distance rides with minimal braking events.

4.6 System Weight Considerations

While the bicycle KERS demonstrated substantial improvements in energy recovery and performance, one of the drawbacks observed was the additional 3.5 kg of system weight. This weight, primarily contributed by the flywheel and clutch assembly, adds resistance when carrying the bicycle or riding uphill without stored energy assistance.

Despite this, the overall performance gains appear to outweigh the added mass. For instance, the improvements in acceleration and climbing efficiency more than compensate for the marginal increase in total weight. This trade-off is also evident in other mechanical energy recovery systems, where designers must balance energy storage capacity with system weight to maintain practicality (Li *et al.*, 2021).

Overall, the discussion confirms that the bicycle-mounted KERS prototype fulfills its intended design priorities:

- **Energy efficiency** is demonstrated through 60% energy recovery and significant performance gains.
- **Low maintenance** is promoted through the use of sealed bearings and a simple mechanical clutch.
- **Affordability** is achievable because the system relies on readily available steels and aluminium alloys.
- **Modularity** was validated by the successful retrofitting of the system onto a standard bicycle.

5. Conclusion and Recommendations

The developed Kinetic Energy Recovery System (KERS) for bicycles demonstrates effective energy capture and storage during braking, aiding propulsion without compromising typical cycling dynamics. Its design meets goals of compactness, affordability, and compatibility with various bicycle models, facilitating integration for diverse rider needs. The lightweight mechanism ensures minimal handling impact while optimizing durability and cost for practical use in commuting or recreational cycling. Testing confirms the KERS significantly enhances energy recovery and riding efficiency, reliably storing kinetic energy during braking to aid acceleration. Despite minor friction-related losses, the system operates efficiently, contributing to sustainable cycling by reducing rider energy expenditure and promoting renewable mechanical energy utilization.

The recommendations of a project provide practical suggestions and actionable steps based on the findings to ensure successful implementation and improvement.

1. Improve the bearing and friction components to further reduce energy losses.
2. Explore the use of lightweight, high-strength materials for the flywheel to increase energy storage capacity.
3. Integrate a more efficient braking mechanism to maximize energy recovery.
4. Conduct long-term durability tests under different environmental conditions.
5. Consider miniaturization for urban commuter bicycles to improve market adaptability.
6. Explore electronic monitoring systems to measure real-time energy recovery and usage.

The future works of a project provide practical suggestions and actionable steps based on the findings to ensure successful implementation and improvement.

1. Development of hybrid systems that combine KERS with electric bicycles for higher efficiency.
2. Optimization of the flywheel shape and mass distribution to maximize stored energy.
3. Study the scalability of the system for larger human-powered vehicles.
4. Investigation of alternative energy storage methods, such as supercapacitors, to complement mechanical flywheels.
5. Conduct life-cycle assessment to evaluate environmental and economic impacts of large-scale adoption.

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