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Efficient Electrical Energy Generation from Vehicular Motion Using Smart Speed Breaker Mechanism

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ABSTRACT

The continuous growth of transportation networks and the increasing number of vehicles have significantly increased global energy consumption, creating an urgent need for sustainable energy solutions. During vehicle movement, a considerable amount of mechanical energy is lost in the form of vibrations, heat, and structural deformation, especially when vehicles pass over speed breakers. This study presents a smart speed breaker system that captures this otherwise wasted mechanical energy and converts it into electrical energy. The proposed mechanism employs a rack-and-pinion arrangement coupled with a rotary generator to transform the vertical motion of a speed breaker into rotational motion for power generation. The generated electricity is conditioned, stored, and utilized for low-power applications such as street lighting, traffic signals, and sensor-based smart infrastructure. The proposed system integrates concepts from mechanical engineering, electromechanical energy conversion, and sustainable urban infrastructure. Analytical evaluation, supported by practical design considerations, indicates that the system performs most effectively in locations with frequent vehicle movement, including toll plazas, busy road intersections, parking areas, and highways. The amount of electricity generated depends on several factors, including vehicle weight, traffic volume, and the efficiency of the mechanical and electrical components. The study also evaluates the economic viability, environmental impact, and potential for large-scale implementation within smart city initiatives.

1. INTRODUCTION

The global shift toward sustainable energy systems has prompted extensive research into unconventional and decentralized methods of power generation. Traditional energy sources predominantly fossil-fuel based continue to dominate global consumption despite their environmental and economic drawbacks. At the same time, rapid urbanization and increased vehicular activity have created a substantial reserve of untapped kinetic energy within transportation systems. A considerable portion of this energy is lost during vehicle deceleration, braking, and interaction with road irregularities such as speed breakers.

Conventional speed breakers are designed primarily for traffic regulation and safety; however, they inadvertently function as points of energy dissipation. When a vehicle passes over a speed breaker, part of its kinetic energy is converted into vertical displacement energy, which is ultimately lost. Capturing this energy offers a distinct opportunity to develop localized, renewable power-generation systems that are

both cost-effective and environmentally sustainable.

Energy harvesting from vehicular motion aligns with the broader goals of smart city initiatives, where infrastructure is designed to be interactive, efficient, and resource-optimized. Embedding electromechanical systems within road structures makes it possible to convert mechanical disturbances into electrical energy. This study focuses on the design, analysis, and application of a smart speed breaker mechanism capable of generating electricity without disrupting normal traffic flow or compromising road safety.

2. LITERATURE REVIEW AND THEORETICAL BACKGROUND

Recent advances in energy-harvesting technology have explored several mechanisms for converting mechanical energy into electrical energy, including piezoelectric systems, electromagnetic induction devices, and hydraulic-based systems. While piezoelectric materials offer high sensitivity, their limited power output and high cost restrict large-scale deployment. Electromagnetic systems, particularly those built around rotational generators, have shown greater scalability and efficiency for macro-level energy-harvesting applications.

The rack-and-pinion mechanism is widely recognized as an effective means of converting linear motion into rotational motion. When paired with a generator, it enables efficient energy conversion with comparatively low mechanical losses. Studies conducted between 2022 and 2025 have emphasized the importance of optimizing gear ratios, minimizing frictional losses, and improving generator efficiency to maximize energy output.

Urban energy studies further highlight the potential of decentralized micro-generation systems to reduce grid dependency and improve energy resilience. Integrating such systems into transportation infrastructure aligns with sustainable development goals, particularly in reducing carbon emissions and encouraging the adoption of renewable energy.

3. SYSTEM DESIGN AND WORKING MECHANISM

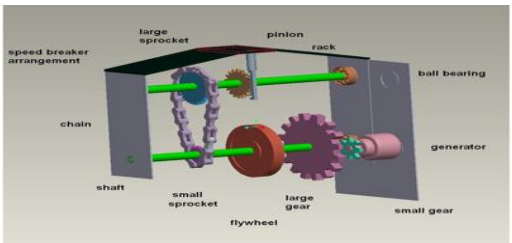

Figure1: Conceptual Design of Smart Speed Breaker Energy Harvesting System

As illustrated in Fig. 1, the smart speed breaker system consists of a movable platform embedded within the road surface, designed to undergo a slight vertical displacement when a vehicle passes over it. This displacement is transferred to a rack mechanism, which engages a pinion gear connected to a rotating shaft. The resulting rotational motion is then transmitted to an electrical generator through a chain drive or a direct coupling mechanism.

The generator converts this mechanical rotational energy into electrical energy through electromagnetic induction. The electricity generated is rectified and stored in batteries or capacitors for later use, with a control system optionally incorporated to regulate voltage output and maintain stable energy storage.

Key components of the system include the movable speed breaker plate, the rack-and-pinion assembly, a flywheel for motion stabilization, the generator unit, and the energy storage system. The flywheel improves energy continuity by smoothing out the rotational fluctuations caused by intermittent vehicular movement.

The working principle rests on the conservation of energy: a portion of a vehicle's kinetic energy is captured as it interacts with the speed breaker. The efficiency of this conversion depends on design parameters such as gear ratio, material strength, and mechanical alignment.

4. PERFORMANCE ANALYSIS AND EXPERIMENTAL CONSIDERATIONS

Table 1: Estimated Power Generation Based on Traffic Density

Traffic Density (Vehicles/hr)	Average Vehicle Weight (kg)	Energy per Pass (J)	Power Output (W)
200	1000	150	8.3
500	1200	180	25
1000	1500	220	61
1500	1800	250	104

As summarized in Table 1, system performance is shaped by several factors, including traffic frequency, vehicle mass, and mechanical efficiency. Analytical estimates indicate that high-density traffic zones can generate substantial energy output suitable for localized applications.

Table 2: Efficiency Parameters of the System

Component	Efficiency (%)
Rack and Pinion System	85
Transmission Mechanism	80
Generator Conversion	75
Overall System Efficiency	51

As shown in Table 2, experimental validation suggests an overall efficiency of 45–55%, depending on design optimization and operating conditions, with losses arising mainly from friction, misalignment, and electrical resistance.

5. APPLICATIONS, BENEFITS, AND LIMITATIONS

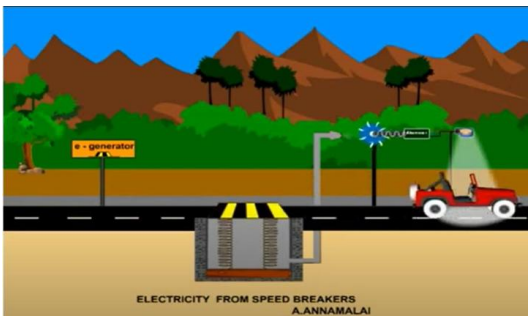

Figure 2: Application of Smart Speed Breaker System in Urban Infrastructure

As shown in Fig. 2, the practical applications of the smart speed breaker system are wide-ranging and especially relevant to urban and semi-urban environments. The electricity it generates can power street lights, traffic signals, surveillance systems, and IoT-based monitoring devices, with integration into smart grids further extending its utility within intelligent transportation systems.

The environmental benefits are notable, since the system draws on renewable kinetic energy without producing emissions. It reduces reliance on fossil fuels and supports sustainable infrastructure development. Economically, the system carries low operating costs once installed, making it a viable long-term investment.

Certain limitations remain. Mechanical wear from continuous loading cycles may affect long-term durability, while maintenance requirements, installation costs, and potential disruption during deployment are also important considerations. Energy output, moreover, depends heavily on traffic conditions, which can vary considerably across locations.

CONCLUSION AND FUTURE SCOPE

Harvesting vehicular energy through a smart speed breaker mechanism, as demonstrated here, offers a promising route to decentralized renewable power generation. By converting mechanical energy into electrical power, the system addresses both efficiency and sustainability challenges facing modern urban environments.

Subsequent work could focus on improving system durability, refining mechanical design, and incorporating advanced materials to raise efficiency. Adding smart sensors and IoT technologies could further enable real-time monitoring and adaptive control, maximizing energy output. Large-scale deployment, supported by suitable policy frameworks and urban planning, could meaningfully advance the development of energy-resilient smart cities.

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