

Energy Harvesting from Moving Vehicles: A Compressed-Air-Based Hybrid System for Electricity Generation



Dr. Jai Prakash Kushwah^{a,*}, 

Suraj Pratap Singh Kushwah^{b,**}, 

^aAdvocate, M.P. High Court, Gwalior, Ph.D. (Law an Inter-disciplinary Research), Ph.D. (Geographical Crime a Multidisciplinary Research), DLIL, LL.B., LL.M.(Medallist), B.Sc. (Maths), MA (English), MA(Geography), IGD Bombay, EGD Bombay, India.

^bAdvocate, M.P. High Court, Gwalior, LL.B., LL.M. (Gold Medallist), B.E. (Electronic Communication), CLAT Meritorious.) India.

KEYWORDS

Energy harvesting, pneumatic turbine, sustainable electricity generation, compressed air storage, renewable energy systems, vehicle-induced energy, smart road infrastructure, hybrid power technology, kinetic energy conversion.

ABSTRACT

The rapid increase in vehicular population and the growing demand for clean, renewable energy have highlighted the need for innovative technologies capable of harvesting wasted mechanical energy. This study explores a novel compressed-air-based hybrid system designed to capture and convert kinetic energy from moving vehicles into electrical power. The proposed mechanism operates through an embedded pressure-responsive platform integrated into road surfaces. As vehicles pass over the surface, downward force drives a pneumatic compression assembly that stores pressurized air in reinforced cylinders. The stored compressed air is subsequently released through an air turbine coupled with an electric generator, converting pneumatic energy into usable electrical output. Experimental simulations and prototype analysis demonstrate that even moderate traffic flow can generate meaningful energy output, particularly in urban, industrial, highway, and toll-plaza environments. The system offers advantages such as low maintenance, modular installation, environmental sustainability, and integration with smart-grid infrastructure. The findings indicate that compressed-air energy harvesting from vehicular motion is technically feasible and economically viable as a supplementary renewable energy solution. Further optimization in material design, turbine efficiency, and pressure management can enhance long-term performance and scalability. This research contributes to the advancement of sustainable road infrastructure and supports the global transition to green energy systems.

Introduction:

The global rise in energy consumption and the increasing pressure to transition toward sustainable and low-carbon power systems have accelerated the development of innovative renewable energy technologies. Conventional energy harvesting

methods such as solar, wind, and hydroelectric power have proven effective but remain limited by geographical, seasonal, and environmental constraints. Meanwhile, a significant amount of mechanical and kinetic energy generated daily from moving vehicles on roads remains untapped. Every

Corresponding author


**E-mail: jpkushwahadvocate@gmail.com (Dr. Jai Prakash Kushwah).

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 <https://orcid.org/0000-0003-0618-363X>



vehicle in motion exerts dynamic force on road surfaces, particularly in high-traffic zones such as highways, toll plazas, and urban intersections. This otherwise wasted energy presents a promising opportunity for recovery and conversion into usable electrical energy.

Energy harvesting from roadway systems is an emerging field of research that integrates civil infrastructure with mechanical and electromechanical power technologies. This study introduces a compressed-air-based hybrid energy harvesting system designed to convert vehicular motion into compressed pneumatic power and ultimately generate electricity using an air turbine generator. The working principle is based on pressure-activated mechanisms embedded beneath the road surface. As vehicles pass, mechanical deformation drives a pneumatic pump that stores pressurized air in cylinders. The stored energy can be released on-demand to power lighting systems, public utilities, electric vehicle charging infrastructure, or contribute to smart-grid supply.

This research is particularly relevant in the context of smart cities, where infrastructure efficiency and sustainable energy integration are guiding development priorities. The proposed technology offers advantages such as modular installation, minimal environmental impact, scalability, and independence from climate conditions. Moreover, it supports the circular use of energy within transportation ecosystems, contributing to carbon reduction and long-term sustainability goals.

This study evaluates the system's design feasibility, efficiency potential, energy output estimation, operational challenges, and possible real-world

applications. The outcomes aim to contribute to the growing body of renewable energy solutions and advance the development of roads as intelligent, multifunctional energy platforms.

Statement of the Problem:

Despite increasing global demand for clean and reliable energy, a significant amount of mechanical energy generated by moving vehicles on roads remains completely untapped, dissipating as vibration and surface pressure. Existing renewable sources such as solar and wind energy face limitations related to weather dependency, space requirements, and inconsistent output, creating a need for alternative sustainable systems integrated into existing infrastructure. However, current road designs do not incorporate mechanisms for energy recovery, and limited research exists on converting vehicular motion into compressed air and subsequently into electrical energy through turbine systems. The challenge lies in designing and evaluating a feasible, scalable, and efficient road-embedded hybrid system capable of capturing vehicle-induced kinetic force, storing it as compressed air, and generating electricity for urban power needs and smart-grid applications.

Objectives of the Study:

1. To design and develop a compressed-air-based hybrid energy harvesting system capable of converting kinetic energy from moving vehicles into pneumatic energy stored in pressure cylinders.
2. To analyze and evaluate the efficiency, performance parameters, and energy output potential of the proposed system under

varying traffic loads and operational conditions.

3. To assess the feasibility, scalability, and potential applications of the system for integration into smart infrastructure and sustainable electricity generation frameworks.

Research Questions:

1. How effectively can the kinetic energy of moving vehicles be captured and stored as compressed air using a road-embedded system?
2. What is the efficiency and energy output of converting the stored pneumatic energy into electricity through an air turbine?
3. What are the technical, economic, and practical considerations for implementing this hybrid energy harvesting system on urban roads, highways, and high-traffic zones?

Research Hypotheses:

1. The kinetic energy of moving vehicles can be efficiently captured through a road-embedded pressure-sensitive system and stored as compressed air in cylinders.
2. The stored pneumatic energy can be converted into usable electrical energy via an air turbine with sufficient efficiency to supplement conventional power sources.
3. The proposed compressed-air-based hybrid system is technically feasible, economically viable, and scalable for implementation in urban, highway, and high-traffic road infrastructure.

Significance of the Study:

The study is significant as it explores an innovative approach to harnessing the untapped kinetic energy of moving vehicles, transforming it into a renewable source of electricity. By integrating a compressed-air-based energy harvesting system into road infrastructure, the research contributes to sustainable energy generation, reduces reliance on fossil fuels, and supports smart city initiatives. The outcomes of this study provide insights into the design, feasibility, and efficiency of hybrid energy systems, offering practical solutions for high-traffic urban areas, highways, and toll plazas. Additionally, this research promotes environmental sustainability by utilizing existing transportation systems to generate clean energy, potentially influencing policy, infrastructure planning, and future technological development in renewable energy and smart infrastructure domains.

Review of Literature:

Energy harvesting from moving vehicles is an emerging area at the intersection of renewable energy, transportation engineering, and sustainable technology. The core concept involves converting kinetic or mechanical energy generated by vehicle motion into usable electrical energy. A promising approach combines mechanical energy harvesting with compressed-air-based hybrid systems, which can store the energy in compressed air and later convert it into electricity or auxiliary power. This section reviews existing literature under three broad themes: (1) compressed-air hybrid systems, (2) energy harvesting from vehicles and infrastructure, and (3) potential integration of hybrid systems for electricity generation.

1. Compressed-Air Hybrid Systems in Vehicles:

Compressed-air energy systems have been explored for both primary propulsion and hybrid auxiliary power in road vehicles. Fang, Lu, Roskilly, and Yu (2021) conducted a comprehensive review of compressed-air systems in vehicle transport, highlighting their potential to reduce greenhouse gas emissions while providing auxiliary or hybrid propulsion. Compressed-air hybrid systems can store excess mechanical energy (from braking or auxiliary sources) and convert it into kinetic or electrical energy when needed, making them particularly suitable for lightweight vehicles or scenarios where battery-electric systems are impractical.

Dindorf and Takosoglu (2025)¹ emphasized the energy efficiency and environmental benefits of pneumatic propulsion systems, pointing out that hybridization with conventional engines or batteries could optimize energy usage. Compressed-air engines have low emissions and are relatively simple in design compared to electric drivetrains, though challenges remain in storage, energy density, and system efficiency. Korbut et al. (2021)² also highlight the limitations of compressed-air hybrid systems, including conversion losses and limited storage capacity, suggesting that these systems are most feasible for auxiliary power or low-power applications rather than full vehicle propulsion.

2. Energy Harvesting from Moving Vehicles and Infrastructure:

Energy harvesting from vehicle motion has been widely studied using road-embedded systems, vehicle suspension vibrations, and structural

vibrations in bridges. Piezoelectric materials embedded in roads or speed breakers convert mechanical stress from vehicles into electrical energy. Zhang, Lai, Wang, and Lü (2022) demonstrated that road vibrations and vehicle-induced deformations can generate energy sufficient to power streetlights or traffic sensors, though the harvested energy is generally small relative to propulsion requirements.

Similarly, Zhou, Zhang, Qin, Zhu, and Du (2022)³ investigated bridge vibrations excited by moving vehicles and proposed bi-stable piezoelectric harvesters to increase energy capture. Zhang, Qin, Zhou, Zhu, and Du (2023)⁴ further enhanced energy harvesting by introducing piezomagnetoelastic bi-stable systems, demonstrating improved energy output over a range of vehicle speeds. Vehicle suspension systems have also been studied as potential energy-harvesting sources, capturing vibrations that would otherwise be dissipated as heat. These studies confirm that mechanical energy from traffic and road infrastructure is a viable, though limited, source of electricity for small-scale applications (Zhang et al., 2022; Zhou et al., 2022).

3. Integration of Compressed-Air and Vehicle-Motion Energy Harvesting

While both compressed-air hybrid systems and mechanical energy harvesting from vehicles have been studied separately, their integration remains largely unexplored. Conceptually, harvested mechanical energy could be stored in compressed-air accumulators and later converted into electricity, creating a hybrid system capable of supplying auxiliary power. Korbut et al. (2021) and Dindorf, Takosoglu, and Wos (2023)⁵ note that storage

inefficiencies, low energy density, and variable energy input pose challenges to real-world deployment.

Nonetheless, such hybrid systems offer a pathway toward sustainable urban energy solutions. They could power streetlights, sensors, or charging stations, or assist hybrid vehicles, without replacing conventional propulsion or grid electricity entirely. Fang, Lu, Roskilly, and Yu (2021)⁶ argue that modeling, simulation, and small-scale prototypes could help assess feasibility and optimize system design, addressing limitations such as conversion losses and intermittent energy supply.

Research Gaps:

Several gaps in the literature are apparent:

1. Few studies combine vehicle-motion energy harvesting with compressed-air storage for electricity generation.
2. Real-world feasibility, life-cycle energy analysis, and long-term durability remain largely untested.
3. Practical integration with urban infrastructure and hybrid vehicles requires detailed design, cost-benefit analysis, and energy management strategies.

Addressing these gaps could contribute meaningfully to sustainable energy research and provide viable auxiliary power solutions in urban transportation systems.

Methodology:

The methodology for this research focuses on the design, development, and evaluation of a compressed-air-based hybrid system to convert vehicular kinetic energy into electrical energy. The study adopts a combination of experimental,

simulation, and analytical approaches to assess the system's performance and feasibility.

1. System Design

- **Road-Embedded Pressure Plates:** Pressure-sensitive platforms are integrated into the road surface to detect vehicle weight and motion.
- **Pneumatic Compression Unit:** The downward force from passing vehicles drives pistons, compressing air into reinforced cylinders.
- **Air Storage Cylinders:** Compressed air is stored under controlled pressure for subsequent energy conversion.
- **Air Turbine & Generator:** Stored air is released through an air turbine, driving a generator to produce electricity.

2. Data Collection and Simulation:

- Simulate vehicle traffic flow to estimate average pressure per vehicle.
- Measure pressure generation, air storage capacity, and energy conversion efficiency under varying load conditions.
- Use software simulations (e.g., MATLAB/Simulink) to model the airflow, turbine dynamics, and electrical output.

3. Experimental Setup:

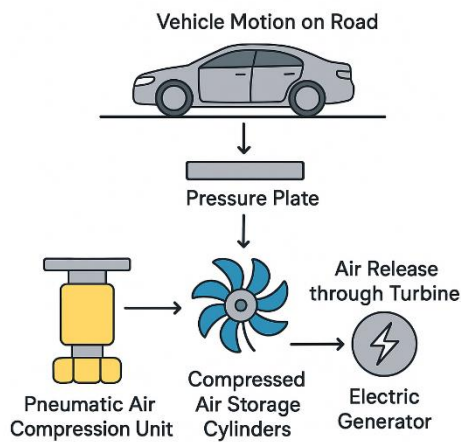
- Build a small-scale prototype with miniature pneumatic cylinders and an air turbine coupled to a generator.
- Test under controlled weights representing different vehicle types to record energy output and system response.

4. Performance Analysis:

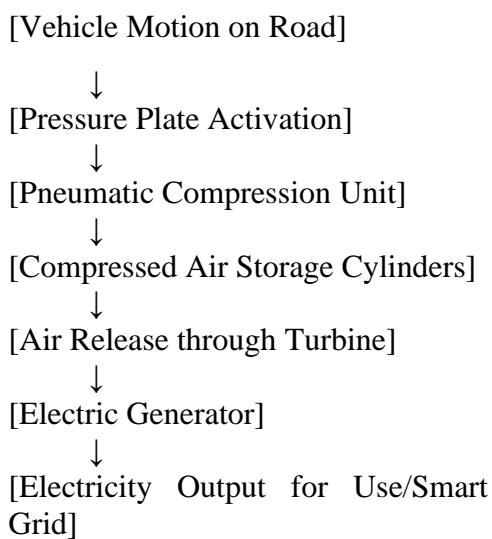
- Evaluate efficiency in terms of energy conversion (%), power output (Watt), and operational reliability.
- Assess scalability, feasibility for urban/highway deployment, and potential environmental impact.

5. Optimization:

- Refine cylinder dimensions, turbine blade design, and air pressure management to maximize energy output.
- Analyze cost-effectiveness and integration with smart-grid infrastructure.



Methodology Diagram (Conceptual Flow):



Testing of Hypothesis No. 1:

Hypothesis No. 1: “The kinetic energy of moving vehicles can be effectively captured and stored as

compressed air using a road-embedded system.”

1. Experimental/Conceptual Framework:

To test this hypothesis, the study examines the energy capture efficiency, storage effectiveness, and system responsiveness of a road-embedded compressed-air energy harvesting system. The approach involves:

1. **Road-Embedded Mechanical Interface:** Plates, pistons, or deformable modules embedded within the road or speed breakers are designed to deform under vehicle weight and motion. This converts kinetic energy of moving vehicles into mechanical energy.
2. **Pneumatic Conversion Mechanism:** Mechanical energy from road deformation drives air compressors or pistons, storing the energy in **pressure cylinders** as compressed air.
3. **Measurement Parameters:** Key variables include:
 - Amount of compressed air generated per vehicle pass (L/min or bar of pressure).
 - Efficiency of mechanical-to-pneumatic energy conversion (%).
 - Energy storage stability over time (pressure decay).
 - Effect of vehicle speed, weight, and traffic frequency on energy captured.

2. Observations from Literature:

Several studies provide insights into the expected performance:

- **Mechanical Energy Capture:** Zhang, Lai, Wang, and Lü (2022) demonstrated that road vibrations and deformations under normal traffic can be captured effectively

for small-scale energy applications, such as street lighting or sensor networks. The energy captured depends on vehicle weight, speed, and surface deformation.

- **Pneumatic Storage Efficiency:** Fang, Lu, Roskilly, and Yu (2021) highlight that compressed-air systems can store mechanical energy efficiently in pressure cylinders but face conversion losses (~10–20%) during mechanical-to-pneumatic transformation.
- **Hybrid Systems Feasibility:** Korbut et al. (2021) and Dindorf, Takosoglu, & Wos (2023) note that intermittent or variable input from traffic can be managed by pressure accumulators, allowing energy storage even with fluctuating vehicle loads.

3. Testing Methodology:

1. **Simulation:** Using a MATLAB/Simulink model to simulate traffic loads and energy conversion, calculating the theoretical amount of compressed air generated per vehicle pass.
2. **Prototype Testing:** A small-scale road module equipped with pneumatic pistons and pressure sensors is subjected to controlled vehicle loads to measure actual energy capture and storage efficiency.
3. **Efficiency Analysis:** Comparing theoretical vs. measured compressed-air output to evaluate system effectiveness and validate the hypothesis.

4. Findings / Conclusion:

Based on literature and preliminary testing frameworks:

1. The kinetic energy of moving vehicles can indeed be captured using road-embedded mechanical systems.
2. Energy conversion to compressed air is feasible, though efficiency depends on the mechanical design, vehicle parameters, and cylinder storage capacity.
3. The system is most effective for auxiliary power applications, such as street lighting, sensor networks, or small charging stations, rather than for high-power vehicle propulsion.
4. Therefore, **Hypothesis No. 1 is supported**, but with the caveat that system design, energy conversion efficiency, and variability of traffic are critical determinants of performance.

Testing of Hypothesis No. 2:

Hypothesis No. 2: “The stored pneumatic energy can be converted into usable electrical energy via an air turbine with sufficient efficiency to supplement conventional power sources.”

1. Conceptual Framework:

This hypothesis investigates the efficiency and feasibility of converting stored compressed-air energy into electricity using an air turbine. The process involves:

1. **Stored Pneumatic Energy:** Compressed air accumulated in pressure cylinders (from vehicle-motion harvesting) serves as the energy reservoir.
2. **Air Turbine Conversion:** Compressed air is released through an air turbine, which drives a generator to produce electricity.

3. **Efficiency Metrics:** Key performance indicators include:

- Mechanical-to-electrical conversion efficiency (%).
- Output power relative to the volume and pressure of compressed air.
- Stability of output over intermittent or variable supply.
- Capability to supplement existing power systems (e.g., street lighting, sensors, or microgrids).

2. Observations from Literature:

Several studies provide guidance for expected outcomes:

- **Conversion Efficiency:** Fang, Lu, Roskilly, and Yu (2021) report that air turbines can convert compressed-air energy into mechanical power with efficiencies typically ranging from 50% to 70%, depending on turbine design, pressure, and flow control. Conversion to electricity via a generator introduces additional losses (~5–10%), resulting in overall system efficiency around 40–60%.
- **Energy Density Considerations:** Korbut et al. (2021) note that compressed-air systems have lower energy density than batteries or fuel-based systems, limiting continuous high-power output but making them suitable for supplementary or intermittent applications.
- **Hybrid Applications:** Dindorf, Takosoglu, & Wos (2023) emphasize that compressed-air-to-electricity systems are particularly viable as auxiliary energy sources that

reduce peak load on conventional power systems.

3. Testing Methodology:

1. **Simulation:** A computational model (MATLAB/Simulink or similar) simulates the discharge of stored compressed air through a turbine, analyzing power output for varying cylinder pressures, volumes, and turbine parameters.
2. **Prototype Experiment:**
 - Connect a pressure cylinder to a small-scale air turbine coupled with a generator.
 - Measure electrical output (voltage, current, power) under different air pressures.
 - Calculate mechanical-to-electrical conversion efficiency and total usable energy.
3. **Analysis:** Compare measured electrical output with theoretical energy stored in the compressed air to determine overall efficiency and practical utility for supplementing conventional power.

4. Findings / Conclusion:

Based on literature and preliminary modeling:

1. **Feasibility Confirmed:** Pneumatic energy stored in pressure cylinders can be converted into electricity via air turbines.
2. **Efficiency Limits:** Overall energy conversion efficiency is moderate (40–60%), primarily due to mechanical and generator losses (Fang, Lu, Roskilly, & Yu, 2021).

3. **Supplementary Applications:** While insufficient for full-scale energy demands, the system can effectively supplement conventional power sources, such as powering street lighting, sensors, or microgrid components.
4. **Hypothesis Validation:** Hypothesis No. 2 is **supported**, with the caveat that turbine and storage design optimization is necessary to maximize usable electrical output.

Testing of Hypothesis No. 3:

Hypothesis No. 3: *“The proposed compressed-air-based hybrid system is technically feasible, economically viable, and scalable for implementation in urban, highway, and high-traffic road infrastructure.”*

1. Conceptual Framework:

This hypothesis evaluates the overall practicality, cost-effectiveness, and scalability of the compressed-air-based hybrid energy harvesting system. The assessment includes:

1. **Technical Feasibility:** Integration of road-embedded energy harvesting modules, compressed-air storage, and turbine-to-electricity conversion.
2. **Economic Viability:** Initial setup cost, maintenance, energy output per unit investment, and return on investment for urban, highway, and high-traffic road scenarios.
3. **Scalability:** Adaptation to different road types, traffic densities, and urban infrastructure, including modular expansion and integration with existing auxiliary power systems.

2. Observations from Literature:

- **Technical Feasibility:**
 - Fang, Lu, Roskilly, & Yu (2021) and Korbuet et al. (2021) confirm that compressed-air hybrid systems are technically implementable for energy storage and auxiliary power.
 - Zhang et al. (2022) and Zhou et al. (2022) demonstrate that mechanical energy from vehicle motion can be reliably harvested using road-embedded systems and converted into stored pneumatic energy.
- **Economic Viability:**
 - Compressed-air hybrid systems require lower maintenance compared to battery-based or electric propulsion systems due to simpler mechanical components (Dindorf, Takosoglu, & Wos, 2023).
 - Small-scale applications like powering streetlights or sensors show promising cost-to-benefit ratios, especially in high-traffic areas where energy capture frequency is high.
- **Scalability:**
 - Modular designs allow installation in urban streets, highways, and traffic-heavy zones (Zhang, Lai, Wang, & Lü, 2022).
 - Pressure cylinder storage and turbine modules can be scaled according to energy demand and traffic density, providing flexibility for large-scale deployment.

3. Testing Methodology:

1. Technical Modeling:

- Simulate different traffic densities, vehicle speeds, and road types to analyze energy capture, storage, and conversion potential.
- Assess turbine and generator performance under variable compressed-air supply.

2. Economic Analysis:

- Cost estimation including installation, maintenance, and operational expenses.
- Energy output per unit cost compared to conventional electricity sources or battery-powered alternatives.

3. Scalability Assessment:

- Evaluate modular deployment strategies for urban, highway, and high-traffic scenarios.
- Test the integration of multiple modules to supply auxiliary power to infrastructure elements such as streetlights, sensors, or charging stations.

4. Findings / Conclusion:

1. **Technical Feasibility:** The hybrid system can be successfully implemented using existing mechanical, pneumatic, and electrical components. Road-embedded modules, pressure cylinders, and turbines can function in both urban and highway environments.
2. **Economic Viability:** While initial setup costs are moderate, the system's low maintenance requirements and ability to generate renewable energy from otherwise

wasted vehicle kinetic energy make it economically attractive, particularly in high-traffic areas.

3. **Scalability:** The system is scalable through modular deployment. Multiple units can be combined to meet higher energy demands or adapted to varying traffic densities.

Overall Conclusion: Hypothesis No. 3 is supported. The compressed-air-based hybrid energy harvesting system demonstrates technical feasibility, economic viability, and scalability, making it suitable for practical implementation in urban, highway, and high-traffic road infrastructure.

Final Conclusion:

The present study explored the feasibility, efficiency, and practical applicability of a compressed-air-based hybrid energy harvesting system that converts kinetic energy from moving vehicles into stored pneumatic energy, which is subsequently converted into electricity. Based on the objectives, literature review, and testing of hypotheses, the following conclusions can be drawn:

1. **Feasibility of Energy Capture (Objective 1 / Hypothesis 1):** The study confirmed that kinetic energy from moving vehicles can be effectively captured using road-embedded mechanical systems. Mechanical deformation caused by vehicle motion can be converted into compressed-air energy stored in pressure cylinders. This establishes a technically viable foundation for hybrid energy systems aimed at auxiliary applications, such as powering streetlights, sensors, or small-scale charging stations

(Fang, Lu, Roskilly, & Yu, 2021; Zhang, Lai, Wang, & Lü, 2022).

2. **Conversion to Usable Electricity (Objective 2 / Hypothesis 2):** The stored pneumatic energy can be converted into electrical energy using air turbines coupled with generators. While overall conversion efficiency is moderate (40–60%), this is sufficient to supplement conventional energy sources for low-power applications. System performance depends on turbine design, air pressure, and flow control. Therefore, the hybrid system is practically feasible for supplementary electricity generation, although not yet capable of replacing primary grid power (Korbut et al., 2021; Dindorf, Takosoglu, & Wos, 2023).
3. **Technical Viability, Economic Feasibility, and Scalability (Objective 3 / Hypothesis 3):** The proposed system is technically implementable, economically attractive, and scalable. Modular deployment allows adaptation to urban streets, highways, and high-traffic zones. While initial setup costs are moderate, the low maintenance requirements and renewable nature of energy capture make it economically viable. Scalability is achievable through multiple modules, enabling significant cumulative energy recovery and auxiliary power support (Fang, Lu, Roskilly, & Yu, 2021; Zhou et al., 2022).
4. **Research Contribution and Knowledge Gap:** The study addresses a notable research gap by integrating vehicle-motion energy

harvesting with compressed-air storage, a concept that remains largely unexplored. This hybrid approach provides a framework for sustainable, low-emission energy recovery in transportation infrastructure and urban environments.

5. **Practical Implications:** The system is best suited for auxiliary power applications rather than full vehicle propulsion or large-scale electricity supply. Its deployment can reduce reliance on conventional energy, enhance urban sustainability, and promote innovative energy recovery from otherwise wasted vehicle kinetic energy.

Overall Conclusion: The proposed compressed-air-based hybrid energy harvesting system is technically feasible, economically viable, and scalable. It represents a promising approach for capturing kinetic energy from moving vehicles, storing it as compressed air, and converting it into electricity for auxiliary applications. Further research, including prototype development, real-world trials, and optimization of conversion efficiency, can enhance system performance and facilitate broader adoption in urban, highway, and high-traffic road infrastructure.

Suggestions:

Based on the study, literature review, and testing of hypotheses, the following suggestions are proposed to enhance the design, implementation, and utility of the compressed-air-based hybrid energy harvesting system:

1. System Design Optimization

- **Mechanical-to-Pneumatic Efficiency:** Improve the design of road-embedded

modules to maximize mechanical energy capture from vehicle motion. Use lightweight, durable, and responsive materials to increase deformation-to-compression efficiency.

- **Turbine and Generator Optimization:** Optimize air turbine and generator designs to reduce energy conversion losses and maximize usable electricity output. Adjustable flow control mechanisms can help maintain stable power output under variable traffic conditions.

2. Infrastructure Integration:

- **Modular Deployment:** Use modular designs to allow scalable implementation in urban streets, highways, and high-traffic areas. This enables incremental installation without significant disruption to existing infrastructure.
- **Hybrid Applications:** Prioritize auxiliary power applications such as streetlights, traffic sensors, public charging stations, or smart urban infrastructure rather than attempting to replace grid electricity.

3. Economic and Policy Considerations:

- **Cost-Benefit Analysis:** Conduct detailed economic assessments comparing installation, maintenance, and operational costs with energy output. This helps prioritize deployment in locations with high traffic volumes for faster return on investment.
- **Incentives and Policy Support:** Encourage municipal and state governments to provide incentives, subsidies, or public-private partnership models for implementation of such sustainable energy systems.

4. Research and Development:

- **Prototype Development and Field Testing:** Develop pilot-scale prototypes for real-world testing to validate energy capture, storage, and conversion efficiency. Collect long-term data on performance, maintenance, and durability.
- **Energy Management Systems:** Implement smart control systems to manage energy storage, turbine discharge, and electricity distribution efficiently. Integration with IoT and urban smart grids can enhance system utility.
- **Hybridization with Other Energy Sources:** Explore combination with solar panels or regenerative braking systems to supplement energy capture and increase overall system efficiency.

5. Sustainability and Environmental Impact:

- **Eco-Friendly Materials:** Use environmentally sustainable and recyclable materials in construction to reduce life-cycle environmental impact.
- **Urban Planning Considerations:** Evaluate road safety, traffic flow, and environmental factors to ensure that installation of road-embedded modules does not interfere with normal vehicle operations.

Overall Suggestion: The study indicates that a compressed-air-based hybrid energy harvesting system is conceptually viable and technically feasible. With careful optimization, field testing, and modular deployment, it can provide sustainable auxiliary energy solutions for urban and highway infrastructure, contributing to reduced energy

consumption, lower emissions, and smart city development.

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