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INTEGRATING PIEZOELECTRIC ENERGY HARVESTING WITH SMART ROAD NETWORKS: A REVIEW OF MATERIAL INNOVATIONS, DESIGN CHALLENGES, AND CIVIL ENGINEERING APPROACHE

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ABSTRACT

The study explores the potential of piezoelectric pavement systems as a sustainable energy-harvesting technology within India's smart city framework. The article delves into the process of converting vehicle stress into electrical energy using implanted piezoelectric materials like PZT, PVDF, and ZnO, and how this invention ties in with the increasing need for sustainable energy solutions in the country. Assessing the engineering configurations, materials, and performance efficiency of worldwide case studies from China, Israel, Japan, and the USA is the purpose of this article. The approach used is a qualitative review that relies solely on secondary data sources such as government publications, smart city documents, and journal articles. Engineering and policymakers can benefit from the analysis's classification of results into three areas: structural integration, smart infrastructure linkages, and material advances.

With the help of Internet of Things (IoT) monitoring, the results show that piezoelectric systems can be incorporated in a way that is both technologically feasible and ecologically beneficial. The suggested integration architecture shows how smart road networks can use AI-enabled predictive maintenance to collect energy and share performance data all at once. According to the research, smart cities in India, especially those with heavy foot traffic like Jaipur, have the necessary infrastructure to test out such systems. It suggests integrating piezoelectric road systems into energy and mobility strategies for smart cities, starting pilot projects, creating standard technical protocols, encouraging academic-industry collaboration, and so on.

1. INTRODUCTION

In the form of pressure exerted on vehicles, vibration, and deformation of roadways, the massive quantities of mechanical energy that is generated by urban transportation networks is quite significant. Although it is common for this type of energy to vanish without being captured, it does, however, provide a significant opportunity for sustainable innovation. The process piezoelectric energy harvesting entails embedding materials that exhibit the piezoelectric effect—such as lead-zirconate-titanate (PZT), polyvinylidene-fluoride (PVDF), and zinc oxide (ZnO)—within the infrastructure of roadways. This allows for the conversion of mechanical stress exerted by passing cars into electrical energy. The application of strain to these materials causes them to produce electric charge as a direct piezoelectric effect, making them a possible source of power that is both continuous and dispersed across transportation corridors (Covaci et al., 2020; Zhang et al., 2022).

The need for energy harvesting in transportation systems is on the rise as a result of the increased traffic on the roads, the growing demand for energy, and the worldwide priority of reducing carbon emissions and boosting sustainability in metropolitan areas. In order to reduce the carbon emissions they produce, improve their energy efficiency, and manage rising traffic volumes, cities all over the world are facing a significant challenge. In the light of the present situation, road infrastructure that merely serves mobility purposes looks to be more ineffective. The incorporation of energy-generation capabilities into road networks is in line with the frameworks of smart cities, which aim to optimize resources and increase the multifunctionality of infrastructure.

Emerging trends that are occurring on a global scale demonstrate that researchers and pilots are making strides in the areas of renewable infrastructure and smart road technology. The importance of piezoelectric harvesting systems is shown by the range of their applications, which include anything from vibrations caused by vehicles to integrated structural harvesters found in highway surfaces (Sezer, 2021; Covaci et al., 2020). In the meanwhile, the Smart Cities Mission and other programs in India are modernizing urban infrastructure and mobility systems, but the projects that are now underway are mostly focused on digital governance, traffic systems, and traditional renewable energy sources, rather than energy harvesting from roadways (Anand et al., 2018; Ministry of Housing and Urban Affairs, 2025). Despite the fact that there are favorable vehicular densities and modernized infrastructure, there remains a significant research issue: the lack of integrated engineering frameworks that link piezoelectric devices with road infrastructure within the settings of smart cities in India. A more thorough comprehension of materials, embedding design, system integration, and localized application circumstances is the key to being prepared for the future.

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The purpose of this study is to consolidate all of the available information about materials, design, and technical integration as they relate to piezoelectric roadways, as well as to put up a model that may be adapted to meet the requirements of smart cities in India. In order to do this, the document made use of a qualitative review approach that was completely founded on sources of secondary data.

The data were gathered from a variety of sources, including peer-reviewed journal papers, government publications, open-access research repositories, international case studies, and engineering reports, all of which were published between the years 2010 and 2024. In order to categorize worldwide research according to three fundamental dimensions—namely, material advances, structural embedding design, and engineering integration—a theme analysis technique was employed. These observations were further analyzed in order to uncover lessons and paths that may be applied to the smart city corridors in India.

2. MATERIAL INNOVATIONS IN PIEZOELECTRIC ENERGY HARVESTING

There has been a significant rise in the development of piezoelectric materials in the realm of energy harvesting. This advancement is particularly significant when it is considered in conjunction with the endeavors of scientists to integrate these systems into the architecture of roadways. As a direct consequence of the high piezoelectric coefficient and electromechanical coupling exhibited by lead zirconate titanate (PZT), this material remains the benchmark against which all other types of core materials are measured. A number of evaluations have shown that, in ideal conditions, PZT exhibits piezoelectric charge coefficients (d_{33}) in the range of 300 to 600 picometers per volt, and it also has a high Curie temperature of around 350 degrees Celsius, which makes it an appropriate material for situations that require high loads and high temperatures. Brusa, Carrera and Delprete (2023) note that PZT's conversion efficiency remains superior to many alternatives, yet they caution that its brittleness, lead content and road-embedded longevity remain concerns.

Polyvinylidene fluoride (PVDF), On the other hand, is a flexible piezoelectric polymer that offers improved compliance and the ability to adjust to deformations of the road surface. According to the findings of Ahbab et al. (2025), polyvinylidene fluoride (PVDF) films achieve a moderate degree of piezoelectric performance; nonetheless, they are capable of performing very well in situations where the flexibility of the substrate, the cycling of heat, and the alteration of the surface are all factors of considerable significance. Despite the fact that the d_{33} of PVDF is substantially lower than that of PZT, PVDF is the more preferable option for the goal of modular road surface embedding or retrofitting. This is due to the fact that PVDF is more durable in situations that are mechanically dynamic and that it has a smaller weight. One more illustration of a novel method of invention, which gives alternatives that do not involve lead and that have improved environmental sustainability, is hybrid ZnO/PVDF composites, in addition to zinc oxide (ZnO).

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According to the observations made by Bhadwal (2023), ZnO Even while the piezoelectric response of nanostructures has a smaller absolute value when compared to that of lead-based ceramics, it is feasible to get improved piezoelectric performance through the use of morphology that has been specifically designed, particularly when these nanostructures are incorporated in the form of a composite.

Ceramic and polymer components can be combined to create designs that are referred to as hybrid composites, and there is a possibility that these designs will be successful. Take, for example, PZT/PVDF composites, which are capable of achieving more flexibility while still preserving a more robust piezoelectric response compared to pure polymer.

ZnO/PVDF combinations, on the other hand, are capable of utilizing wurtzite ZnO to form the electroactive β-phase of PVDF, thereby improving the total output (Brusa et al., 2023). Nanostructured films and flexible ceramics further extend material options by enabling higher energy density via increased surface area, alignment control and phase optimization; Sezer (2021) explains how customized composites, porous ceramics, and nanowire arrays contribute to the enhancement of coupling metrics when applied under field-relevant strain circumstances.

Performance benchmarks drawn from laboratory and limited field trials provide approximate yardsticks. Qabur and Alshammari (2018) It was suggested that, under ideal conditions, certain roadway-embedded piezoelectric devices promised outputs on the magnitude of hundreds of kilowatt-hours per kilometer per day. Despite this, however, actual real-world production remained much lower. The selection of materials is an extremely important factor to consider while making the transition to driving on Indian roads. There are a lot of factors that must be taken into consideration, such as heat cycles (high temperatures during the summer and humidity during monsoon season), mixed axle loads (trucks, buses, and two-wheelers), the frequency of maintenance, local expenses, and the availability of supply chains. As a consequence, the selection matrix for Indian usage lays an emphasis on pricing, the availability of local production facilities, the convenience of maintenance access, durability under abrasion, and temperature. Solutions that are based on modular PVDF or hybrid polymer/ceramic composites may be able to provide the most advantageous tradeoffs between cost, durability, and performance for smart city corridors in India within this context.

As a consequence of this, the landscape of material developments for the purpose of piezoelectric pavement energy harvesting is fairly diversified, evolving from high-performance but brittle PZT to ecologically acceptable ZnO composites by way of flexible PVDF alternatives. The piezoelectric output is not the only parameter that is subject to extra restrictions due to applications that are embedded in roadways; mechanical durability, thermal resilience, and lifespan cost are also affected. Because of this, there is a need for solutions that use composite materials that have been tailored and optimized for specific environments, such as smart cities in India.

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3. DESIGN CHALLENGES AND STRUCTURAL INTEGRATION APPROACHES

The structural arrangement is without a doubt one of the most challenging obstacles. There are two different methods of embedding that are readily apparent and considered to be the primary techniques: layered embedding, in which piezoelectric devices are positioned beneath the surface of the road and incorporated within the regular pavement layers; and modular embedding, in which slabs or modules that have sensors attached to them are introduced or retrofitted into the pavement. When it comes to the ease of maintenance, the longevity of the installation, and the manner in which they transfer loads, the techniques of surface-mounted installations (which are on top of the pavement) and sub-surface placements (which are beneath the asphalt or concrete) are fundamentally different from one another Yuan et al. (2022) reported that subsurface embedding required detailed pavement structural modelling to avoid introducing weak planes, whereas layered embedding risks delamination under traffic.

In addition to it, the mechanics of load transfer, the distribution of stress, and temperature impacts all impose additional constraints. The wheel of a moving vehicle imposes dynamic axle loads, which lead to the generation of peak stresses, bending moments, and shear within the structure of the pavement. In the course of their investigation, Guo et al. (2022) assessed a piezoelectric pavement system that was exposed to moving traffic loads by employing multi-physics modeling. Their findings indicated that in order to achieve the most favorable performance, it was essential to synchronize sensor placement with the strain fields of the pavement and to avoid subjecting the sensors to excessive stress in order to reduce sensor fatigue. A number of different elements have an effect on the long-term durability of implanted harvesters, including changes in temperature on a daily basis, humidity infiltration, thermal expansion, and deformation of the pavement surface. As a consequence of the fatigue that was caused by load cycles and pavement vibration shock waves, Heller and colleagues (2023) found that the practical lifespan of the harvesters was reduced when they implanted piezoelectric cantilevers into steel profiles that were placed below the pavement.

The appropriateness of the materials is just as crucial. When it comes to embedding harvesters in asphalt or concrete, it is essential to consider a number of different variables. These include, but are not limited to, modifications to the binder, methods for road building, waterproofing, and ensuring that the modulus of the sensor insert matches that of the host material. If a mismatch in stiffness is caused by the piezoelectric module, the pavement may experience uneven settling or cracking. Qabur & Alshammari (2018) underlined that a considerable majority of feasibility studies forgot to undertake a thorough examination of the structural stability of pavements when piezoelectric devices were added. There are practical limitations that are imposed by access for maintenance, vibration fatigue, and repair procedures.

It is imperative that preparations are made for the repair of sensors, the maintenance of skids, and the resurfacing of roads; scalability might be limited by modules that cannot be accessed without stopping the road to traffic. In addition, it is possible for the sensor to experience fatigue as a consequence of being exposed to vehicle passes that are repeated in nature. If this occurs, it may result in a drop in output and an increase in the amount of time that is spent inactive.

Helpful integration approaches may be identified by examining case studies from throughout the world. The Innowattech pilot program, which was carried out on Highway 4 in Israel, made the choice to include modular inserts inside the lanes of the roadway, as well as to design the project with the intention of accommodating heavy traffic conditions. In order to achieve a balance between structural health and energy harvesting, researchers from Japan and the United States used layered embedding under asphalt overlay and instrumented pavement with load monitoring. The original versions of expressways in China were equipped with integrated sensors and traffic monitoring systems in their design. This was done to decrease the amount of structural damage that was incurred. These integrations often required the coordination of the structural, electrical, and traffic engineering disciplines in order to maximize both location and performance (Zhou et al., 2023).

When it comes to the construction of roads in India, the characteristics of the soil, the variation of the traffic load, and the lifetime of the pavement are all factors that must be taken into consideration throughout the process of engineering optimization. The fact that Indian corridors usually contain a range of vehicle types, including trucks, buses, and two-wheelers, as well as varied speeds, means that they require design tolerances that are durable. The structure of the pavement has to be able to withstand the high levels of moisture that are typical of the monsoon season, in addition to huge vehicle loads and extreme heat. Because of this, it is necessary for sensor modules to be built in a manner that will allow them to be quickly swapped out, have the least amount of impact feasible on the structure, and interact seamlessly with the standard road maintenance procedures. In order to assure that the design is both robust and compatible with Indian smart-city corridors, design specifications may include sensor slabs with a low profile, waterproof encapsulation, and compliance with regular asphalt toppings.

4. INTEGRATION FRAMEWORK FOR SMART ROAD NETWORKS

The implementation of a digital and technological framework that is effectively developed, which incorporates material, structural, and information systems, is required for the integration of piezoelectric roads into the infrastructure of a smart city in order to achieve optimal performance. The goal is to transform traditional traffic lanes into intelligent systems that can generate energy and monitor themselves, which will help to promote sustainable urban growth and efficient energy management.

The integration framework is predicated on the assumption that three essential layers—the physical infrastructure, the data communication network, and the governance and operational layer—are working in concert with one another at the conceptual level, hence generating a synergistic effect. The piezoelectric modules that are embedded in the road pavements and function at the physical layer are capable of converting the mechanical stress that is caused by automotive traffic into electrical power.

The energy is stored in batteries that are physically situated near the device, or it is sent to a centralized grid through energy distribution nodes. The gateways that are based on the Internet of Things (IoT) transmit the data that were generated by the sensors to the digital monitoring system from the physical environment. The sensors are responsible for taking measurements of the physical environment, such as the pressure of a load, the output of voltage, and the change in temperature.

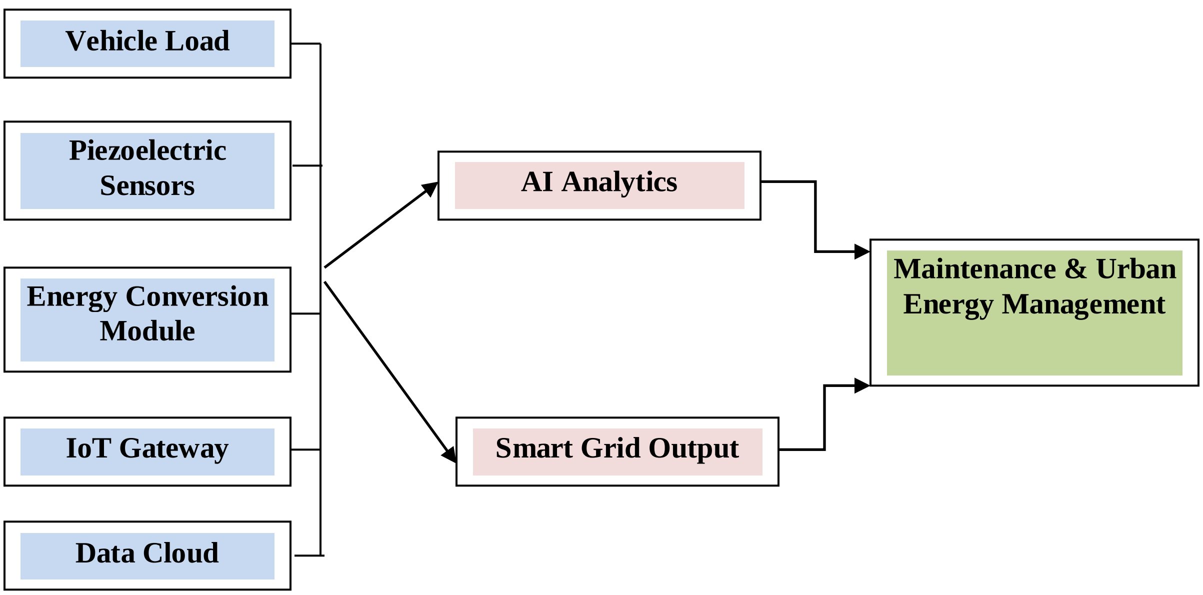

Figure 1: Conceptual Model for Smart Road Energy Integration

By displaying the movement of both information and energy that occurs inside an intelligent road ecosystem, the model is able to provide a clear demonstration. When vehicles are moving, power is created as a result of the piezoelectric sensors that have been implanted collecting mechanical stress. Once the sensors have collected the data, it is then sent to a cloud-based platform through the Internet of Things gateway. After that, artificial intelligence-driven analytics are applied to the data in order to analyze the functioning of the system and predict whether or not maintenance is required. Following the completion of the data analysis, the results are then forwarded to the urban energy management system. This system is in charge of determining how much electricity is distributed to streetlights, signs, and electric car charging

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stations. In a similar manner, feedback loops are able to supply information to urban planners and engineers, which allows them to make changes and updates to policies on a real-time basis that will be applied over the long term.

There are a wide variety of situations in which this integrated system may be applied. By utilizing the energy that is gathered to light lamps, traffic signs, environmental sensors, and localized electric vehicle (EV) charging stations, it is possible to lessen the reliance on external sources of electricity. As a consequence of this, the roads fulfill two functions: they make the journey easier, and they also produce renewable energy.

In addition, the information that is collected by Internet of Things (IoT) devices has the potential to contribute to the optimization of intelligent routes, as well as to detect regions of congestion and enhance traffic management.

The incorporation of monitoring that is based on artificial intelligence (AI) is an essential component of this design. Machine learning algorithms are able to examine data from sensors in order to predict system failures, identify modules that are not performing to specification, and arrange repairs in advance of any breakdowns. In addition, by taking into consideration the circumstances of the environment and the intensity of the traffic, predictive analytics may be used to optimize the distribution of load and the flow of energy. In addition to reducing the amount of energy that is lost, this will extend the lifespan of both the sensors and the pavement.

The establishment of links at both the institutional and policy levels is necessary for the successful implementation of the aforementioned. Public-private partnerships (PPPs) are one way to facilitate joint investments; these collaborations combine plans for government infrastructure with innovation from the private sector. National programs and city-level innovation financing can provide assistance to initiatives that attempt to scale up and implement experimental concepts.

The Smart Cities Mission in India is an example of a national program that can provide this type of help. Experimental projects will eventually grow into initiatives that will have enduring, sustainable infrastructure as a result of the partnership between academic institutions, technical firms, and municipal authorities.

As a consequence, the integrated framework that has been proposed incorporates precision in the technological design, data intelligence that is enabled by the Internet of Things, and coordination at the policy level. Intelligent highways are converted into energy-generating networks of intelligence as a consequence of this confluence, which then provide assistance to urban areas that are both robust and sustainable. By taking these actions, they provide a direct contribution to the objectives of India, which include urban development that takes climate change into consideration, energy efficiency, and the process of digital transformation.

5. CONCLUSION AND RECOMMENDATIONS

The outcomes of the research indicated that the use of piezoelectric pavement technology has great potential as a breakthrough in the field of energy harvesting. This innovation was sustainable and could be utilized to support metropolitan road networks. It was determined on a worldwide scale that systems of this nature were not only theoretically practicable but also structurally viable, as evidenced by initiatives that were executed in nations that were technologically competent. The findings of the engineering assessments indicate that certain materials possess the capacity to withstand stress that is attributable to traffic, temperature fluctuations, and fatigue that persists for an extended length of time when these materials are utilized in settings that are controlled.

Lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and zinc oxide (ZnO) composites are all examples of these materials. It has been determined that the ability of a material to be sustainable is significantly affected by a variety of factors, including its ability to adapt to diverse conditions, the protocols that are employed for its maintenance, and the modularity of the system in which it is employed. The outcomes of this study indicated that piezoelectric energy-harvesting highways are a legitimate and feasible choice for incorporating renewable energy generation into intelligent transportation systems.

The fact that these systems were able to maintain a high level of performance and safety on the road without compromising any of these factors was demonstrated by the application of techniques for modular and layered embedding, which showed that the systems were practicable from an engineering viewpoint. It was established that the energy conversion rates were able to be optimized by the use of an improved composite design and sensor architecture, which was evidenced by the material improvements that were observed in a range of prototypes from across the world. In addition, the integration of Internet of Things (IoT) and artificial intelligence (AI)-based monitoring systems has facilitated the transition of traditional infrastructure into smart energy networks that are capable of performing predictive maintenance and diagnostics in real time.

The proof that was supplied by the fact that these kinds of improvements were allowed to take place showed that piezoelectric pavements not only had a positive impact on the environment but also adhered to the notion of sustainable urban infrastructure that was held at the time.

The findings of the research that was conducted in the context of India showed that there were a number of criteria for readiness that would have an influence on the potential adoption of this technology. It was assessed that the level of infrastructure readiness was at a modest level.

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Among the shortlisted smart cities that were reviewed for their ability to undergo pilot testing, Jaipur, Pune, and Indore were considered to have acceptable traffic density and upgraded road networks. The process of developing governance preparation was now underway, as national and municipal authorities were gradually including frameworks for renewable energy into their strategies for urban development. Financial readiness remained to be an issue as a result of the exorbitant costs connected with the first investment, the limited amount of information available, and the absence of focused approaches to creative finance. The establishment of partnerships between the public and private sectors was thought to be required in order to resolve the difficulties that were present in the fields of both technology and finance. It would become feasible to provide collaborative investments in the areas of research, development, and deployment as a result of this.

In order to promote the development of a path that leads to the large-scale implementation of piezoelectric pavement systems in India, a number of suggestions were made as a result of these findings. First and foremost, it is important to demonstrate that the technology is capable of being deployed in the real world under genuine traffic and climatic conditions. In order to accomplish this, it is required to start pilot projects in a number of carefully selected smart cities. Second, the development of uniform engineering standards is of great importance since it ensures that every project will comply with identical processes related to design, material use, installation, and testing.

Third, the development of indigenous materials and sensor technologies that are capable of working effectively in India's various weather and traffic conditions necessitates the promotion of collaboration between academics and industry.

In addition, it was suggested that piezoelectric pavement systems be included into Smart City legislation that apply to energy and mobility. The goal of this proposal is to bring local innovation into sync with the sustainability objectives of the nation. When it comes to allocating funds for urban innovation, the focus should be given to experimental infrastructure that promotes energy efficiency and self-sufficiency. To sum up, it is necessary to establish criteria for long-term monitoring and assessment in order to evaluate the economic performance, durability, and consistency of output of the systems that have been implemented. In the end, the investigation brought to light the reality that India was about to go through a phase of technological transformation. The incorporation of piezoelectric pavements into the frameworks of smart cities will be crucial in the nation's achievement of its objectives for sustainable mobility and renewable energy, according to the findings of the research.

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