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Efficiency of automated road lighting in public spaces using piezoelectric generator

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Abstract

Reliable public street lighting supports safety, mobility, and nighttime activity in communities with unstable power supplies. This study evaluated the efficiency of an automated road lighting system powered by piezoelectric generators in public spaces in San Jose, Occidental Mindoro. The system converted mechanical energy from vehicular movement and human footsteps into electrical energy, powering light-emitting diode streetlights via a light-dependent resistor. The study applied a quantitative, experimental, and developmental evaluation research design. The researchers constructed a prototype and tested it under controlled conditions simulating pedestrian and vehicular pressure. The experiment measured voltage output, energy conversion rate, storage capacity, and lighting activation across repeated trials using different applied loads. Results showed consistent voltage generation from both vehicles and pedestrians. Increased applied weight produced higher voltage output. Motorized vehicles generated higher average voltage values than human footsteps. Human footsteps exhibited higher energy-conversion efficiency due to the concentrated pressure on the piezoelectric discs. The automated lighting system activated successfully under low-light conditions using stored electrical energy, confirming the system's automation and energy storage performance. The findings demonstrate the technical viability of piezoelectric generators as a supplementary energy source for automated road lighting in power-challenged communities. The study provides empirical data relevant to small-scale infrastructure applications. It supports the further development, optimization, and localized deployment of kinetic energy-based lighting systems on public roads and in pedestrian areas.

Keywords: piezoelectric generator, piezoelectric disc, automated road lighting system, energy conversion rate

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1. Introduction

Reliable public street lighting is one of the most visible indicators of progress within a community. Beyond its role in illuminating roads and public spaces, it contributes significantly to public safety, economic productivity, and overall community well-being. Without adequate lighting, communities may experience increased risks of accidents and criminal activity, as well as reduced nighttime mobility (Perkins et al., 2015). In the Philippines, many local governments continue to face challenges in maintaining efficient and cost-effective street lighting systems. According to the World Bank (2018), some Philippine cities spend as much as 65 percent of their total electricity consumption and about 5 percent of their municipal budget on street lighting alone. This situation underscores the need for innovative and sustainable energy solutions to support public infrastructure. In the province of Occidental Mindoro, persistent and long-duration power interruptions have made this issue even more pressing. GMA News (2023) reported that the province was placed under a state of calamity due to daily blackouts lasting up to 20 hours, severely affecting households, businesses, and essential public services, including street lighting.

As students and residents of San Jose, Occidental Mindoro, the researchers have personally experienced recurring power outages and their direct impact on safety, livelihood, and public convenience. Recognizing these challenges, these students and residents aim to explore sustainable, community-driven alternatives to street lighting, particularly those that use mechanical energy generated by daily human and vehicular movement to provide reliable illumination despite frequent power outages. The local government of San Jose has long struggled to maintain reliable street lighting due to frequent, prolonged power outages lasting up to 20 hours a day (Philippine News Agency, 2023). While electricity rates have been reduced from around PHP 20 to PHP 10.61 per kilowatt-hour (The Manila Times, 2024), sustaining conventional street lighting systems remains costly and dependent on an unreliable grid.

Several studies have explored alternative approaches to public lighting. Santos et al. (2019) demonstrated that piezoelectric transducers could generate voltages sufficient to power LED streetlights, ranging from 3.85 to 5.89 volts under different loads. Applied Energy (2016) confirmed the real-world feasibility of embedding piezoelectric harvesters beneath pavements, while Microsystem Technologies (2023) emphasized that placement under wheel contact areas significantly improves energy collection. More recently, Powering Lights with Piezoelectric Floors (2024) highlighted successful applications of energy-harvesting floors for LED lighting, and PV-Magazine International (2025) compared piezoelectric energy with solar and wind, noting its relative economic limitations but unique situational advantages. However, most existing studies focus on a single mechanical input for power generation, either the pressure from moving vehicles or the footsteps of pedestrians. Kyrillos et al. (2024) developed a piezoelectric floor tile that harvested electrical energy from human footsteps, while Ni et al. (2024) investigated road-embedded piezoelectric systems that relied solely on vehicular loads. Despite the success of these independent designs, very few research efforts have integrated both input sources in a single framework. This study bridges that gap by combining vehicular weight and pedestrian footsteps to generate electrical energy for automated road lighting. The dual-source approach aims to maximize energy capture and enhance the practical viability of piezoelectric systems in smaller municipalities like San Jose.

Despite these promising findings, most existing research has been conducted in controlled environments or urban centers with larger infrastructures. There is limited evidence on the efficiency and practical viability of piezoelectric-based automated road lighting systems in smaller municipalities such as San Jose, where power interruptions are frequent, and resources are limited. The purpose of this study is to evaluate the efficiency and feasibility of automated road lighting powered by piezoelectric generators in public spaces of San Jose, Occidental Mindoro. Specifically, it aims to measure the energy output, assess lighting performance, and its storage capacity, with the ultimate goal of determining whether kinetic energy harvesting can provide a sustainable and reliable alternative for public street lighting in power-challenged communities.

***Statement of the Problem* -** This study aimed to evaluate the efficiency of Automated Road Lights powered by piezoelectric generators as an innovative solution for public lighting in San Jose. Specifically, the researchers aimed to provide answers to the following problems: (1) What is the amount of voltage produced using the piezoelectric generator? (2) What is the level of efficiency of the Automated Road Lights using a piezoelectric generator in terms of the weight of the vehicle, and the pressure of human footsteps? (3) What is the level of efficiency of the Automated Road Lighting System based on its technical performance in terms of energy conversion rate, storage capacity, and lighting activation? (4) Is the amount of voltage generated by the piezoelectric disc in producing electricity significantly affected by the weight of the vehicle and the pressure of human footsteps? (5) Is the level of performance of the Automated Road Lighting System using a Piezoelectric Generator affected by the weight of the vehicle and the pressure of human footsteps?

***Statement of Hypothesis* -** This study aimed to test the following hypothesis: H01: The amount of voltage generated by the piezoelectric disc for electricity production is not significantly affected by vehicle weight or the pressure of human footsteps. H02: The level of performance of the automated road lighting system using a piezoelectric generator is not significantly affected by the weight of the vehicle and the pressure of human footsteps.

***Significance of the Study* -** This experimental research focused on using piezoelectric generators to power automated road lights in public spaces by harvesting mechanical energy from vehicles and pedestrians. The study emphasized improving nighttime road illumination in San Jose, where passing traffic provides the energy source. This innovation not only promoted road safety but also offered a sustainable lighting solution. The findings of this study were expected to provide practical benefits to the following sectors: First, for pedestrians, this study will improve nighttime visibility, enhance safety, and provide a sustainable lighting solution that supports safer, more accessible public spaces. Second, nighttime residence: this study will help nighttime residents of San Jose feel safer and more secure in well-lit neighborhoods, while also promoting energy efficiency and reducing the city’s dependence on traditional power sources. Third, this study offers a practical solution that could help city authorities lower public lighting costs, allocate budget savings to other community needs, and demonstrate leadership in adopting sustainable technologies that improve urban safety and efficiency. Fourth, the community: this study supports safer nighttime environments and lowered dependence on conventional energy sources. It will also help create more reliable, eco-friendly public spaces that improve the daily quality of life for people living and moving in the area. Fifth, the environment and sustainability: this would encourage the use of clean energy by harnessing everyday movement to power public lighting. It also helps reduce carbon emissions and supports greener, more sustainable urban development. Sixth, for business owners and market vendors, this study will help create safer, better-lit commercial areas at night, encouraging more customer visits and longer operating hours. It also supports sustainable lighting that benefits local businesses and markets. Lastly, to advance this work and provide more knowledge for current and future researchers, and to support anyone interested in improving the environment of public roads through innovative approaches, researchers may focus on making this work more widely known.

***Scope and Delimitation of the Study* -** This study focused on the design, construction, and evaluation of an automated road lighting system for pedestrian areas along Felix Y. Manalo Street in San Jose, Occidental Mindoro, powered by energy generated by piezoelectric transducers. The system used mechanical pressure from vehicular movement and human footsteps to generate electrical energy, which was stored and later used to automatically power LED streetlights during low-light conditions. The research covered the development, assembly, data gathering and testing of the automated road lighting system prototype using the specified components—piezoelectric transducer, storage battery, light dependent resistor (LDR), stranded wire, light-emitting diode (LED) lights, pole, cement, 100k receptor, BC547 transistor, multi tester, plain hard rubber sheet, and power inverter—within August 2, 2025 to February 2026. It primarily determined the system's efficiency in generating and storing energy, measured the brightness and functionality of LED lights powered by stored energy, and evaluated the lighting system's automation capability through the LDR mechanism. Due to safety and accessibility constraints, vehicle load testing was limited to motorcycles of varying types and weights, which served as representatives of vehicular pressure on the piezoelectric tiles. The study was limited to the prototype stage of an automated road lighting system and did not involve installing a full-scale system across San Jose's entire public road network. Testing was conducted in a controlled environment within the identified research site, where pedestrian and vehicular activity could be simulated. Efficiency was measured only in short-term trials under specific traffic conditions, excluding factors such as extreme weather, long-term material degradation, and large-scale cost-benefit analyses. While the study tests lighting activation based on ambient brightness, it does not account for extreme weather conditions, such as heavy rain, snow, or extreme heat, on the hardware’s durability. Furthermore, the study focused solely on the prototype's technical performance—energy conversion rate, storage capacity, and lighting activation—and did not delve into social, financial, economic, or policy feasibility and implementation beyond what was necessary to support technical recommendations.

2. Methodology

Research Design - The effectiveness of the variables in the studies was evaluated using a quantitative experimental design, specifically a developmental evaluative design. The importance of experimental design lies in its ability to systematically manipulate and control variables to accurately determine relationships among factors, ensuring that the analysis remains objective and unbiased (Brysbaert, 2024). This design was used to determine the cause-and-effect relationship between the independent variables, which are the vehicle weight and human footsteps, and the voltage generated as the dependent variable. Controlled experiments were conducted on a prototype model by applying varying pressures from simulated vehicle loads and human footsteps onto piezoelectric generators to measure the resulting voltage output. This method enabled an accurate evaluation of the conversion of mechanical energy into electrical energy, thereby determining the efficiency of the prototype piezoelectric-based automated road lighting system.

Data Gathering Procedure - The study was conducted in a controlled environment by the researchers, simulating the conditions of a public road in San Jose, Occidental Mindoro, where both vehicular and pedestrian activities typically occur. The automated road lighting system prototype was designed and tested to represent a road segment found in the area, specifically along Felix Y. Manalo Street, allowing the researchers to evaluate its performance under similar conditions. Since the research involves no human respondents, all data were obtained through experimental trials and instrument readings from the prototype model. The procedure spans three weeks, ensuring sufficient data is collected to evaluate the system’s performance under various conditions. To begin, the researchers prepared and assembled the automated road lighting prototype using the required materials, including a piezoelectric transducer, a storage battery, an LDR (Light Dependent Resistor), LED lights, a BC547 transistor, a multimeter, and other listed components. The system was installed on a small section of pavement where pressure from both vehicle weight and human footsteps can be applied—the data collection proceeds in three main stages. First, during the Mechanical Energy Production stage, the researchers tested the piezoelectric generator by allowing motorcycles and pedestrians to pass over or step on the system. Each event generated mechanical pressure, which was converted into electrical energy. Using a multimeter, the researchers recorded the voltage (V) and current (A) generated by both vehicle weight and human footsteps. Repeated trials were performed to ensure accuracy and consistency of results.

Next, during the Energy Storage and Conversion Efficiency stage, the generated electrical energy was stored in a storage battery or capacitor connected to the system. The researchers monitor and record the battery’s voltage before and after charging, enabling them to determine the energy conversion efficiency and storage capacity. The collected numerical data were used to determine the efficiency of mechanical-to-electrical energy conversion. Finally, in the Lighting Activation and Performance stage, the researchers tested the prototype's automated lighting feature using a Light Dependent Resistor (LDR) and measured brightness with a lux meter. The LDR automatically turns on the LED lights in low-light conditions. The researchers measure how long the stored energy can power the lights and how many bulbs it can support. All numerical data were recorded on a data sheet, organized, and statistically analyzed to determine the prototype's efficiency with respect to vehicle weight, human footsteps, energy conversion rate, storage capacity, and lighting activation. Any external factors were noted to ensure the validity of the results.

Research Process

Stage 1 Preparation and Gathering of Materials - The researchers focused on gathering and preparing all of the materials and components needed for the experiment. The researchers ordered the materials and components online and from local hardware stores after determining the best-suited components for the proposed product. The cost of the automated road lighting system prototype is Php. 3500. The materials and components used include a piezoelectric transducer, storage battery, light-dependent resistor (LDR), stranded wire, battery-powered light-emitting diode (LED) light bar, PVC Pipe and Elbow, cement, 100K resistor, BC547 transistor, digital multimeter, plain hard rubber sheet, and a lux meter. To ensure proper functionality, various materials and components were organized and evaluated before testing. This preparation aims to ensure that all materials and components are in good condition and ready for installation for the construction and development stage.

Stage 2: Building and Development of the Project - The researchers created a sketch of the automated road lighting system prototype model, showing its size, structure, and overall design. The sketch also included the prototype circuit, the dark-sensor diagram, and the road layout, serving as the basis for assembling the components and for visualizing how the piezoelectric-based automated road lighting system would function. After creating the initial sketch of the automated road lighting system prototype, the researchers proceeded to the construction and development phase, which lasted 2 weeks. The necessary materials were purchased and tested to ensure their functionality and compatibility with the design. For the physical structure, a sturdy base was constructed from plywood, and cement was applied on top to simulate the road surface and enhance the prototype's durability. For the automation system, the researchers utilized a Light Dependent Resistor (LDR), a transistor, and a receptor, which were properly connected to the 12 LED lights to enable automatic operation based on light intensity. The piezoelectric discs were carefully wired and connected to the battery to store the generated electrical energy. The LED lights were also connected to the same battery, allowing the stored energy to power the lighting system. All components were assembled according to the planned circuit design to ensure the efficient functioning of the piezoelectric-based automated road lighting system.

Figure 1. Actual Image of the Prototype Model

Stage 3: Experimental Stage, Observation and Data Recording - To evaluate whether the piezoelectric-based automated road lighting system is functional, the researchers begin by assembling the prototype using the prepared materials and components. The piezoelectric transducers were placed beneath a plain hard rubber sheet to simulate a road surface, while the LEDs, battery, and LDR were connected to complete the circuit. The researchers then apply simulated vehicle weight and human footsteps on the surface to generate pressure and measure the voltage output using a multimeter. Data on energy generation, storage, and lighting performance were collected to assess the prototype's efficiency and feasibility.

The researchers conducted systematic observation and data recording to gather accurate, consistent results during the testing phase of the piezoelectric-based automated road lighting system, which lasted 1 week. During the testing phase, the researchers observed and recorded the piezoelectric generator's voltage output under mechanical pressures induced by both vehicle weight and human footsteps. A digital multimeter is used to measure the voltage (V) and current (I) produced in each trial. In contrast, a weighing scale and recorded mass data are used to estimate the applied force (F) using the formula $F = m \times 9.81$. Each test was conducted in multiple trials to ensure accuracy and consistency. Observations were conducted under controlled conditions, and all readings were recorded in a prepared data table that included the trial number, applied weight or force, voltage output, current, time duration, and corresponding efficiency. All recorded data were entered into a spreadsheet to compute the mean, weighted mean, regression, and efficiency values. Observational notes regarding prototype performance, stability, and responsiveness were documented to support quantitative findings. Through this process, the researchers obtained reliable data that accurately represented the prototype’s energy conversion performance under varying conditions of human footsteps and vehicle pressure.

Statistical Treatment of the Data - The researchers used mean and efficiency computations, along with regression analysis, to statistically analyze data from prototype testing. These statistical tools helped determine the efficiency of the piezoelectric-based automated road lighting system in converting mechanical energy into electrical energy under varying pressure conditions caused by vehicle weight and human footsteps. The study used descriptive and inferential statistics. For descriptive statistics, a weighted mean was computed from the voltage measurements obtained with a digital multimeter to characterize the efficiency and performance of automated road lights powered by piezoelectric generators. Moreover, for inferential statistics, regression analysis was used to determine whether the voltage generated by the piezoelectric disc was significantly affected by vehicle type and human footsteps.

The computed regression equation was analyzed to determine if there is a statistically significant relationship between the independent and dependent variables. The decision rule was based on a 0.05 level of significance ($\alpha = 0.05$). A p-value less than 0.05 indicates a significant effect of vehicle weight or human footsteps on the voltage output of the piezoelectric generator. In contrast, a p-value greater than 0.05 indicates no significant effect. To determine the system's energy conversion efficiency, the researchers compared the electrical energy output and mechanical energy input using the efficiency formula. These measurements were recorded for each trial, and the average efficiency was computed for both vehicle weight and human footsteps. This allowed the researchers to determine which source provides higher energy conversion performance. A t-test was used to compare the mean efficiency between vehicle and footstep trials to determine if there is a statistically significant difference between the two sources. Using these statistical tools, the researchers quantitatively assessed the efficiency and performance of the automated road lighting prototype, specifically its ability to convert mechanical energy from both vehicles and pedestrians into usable electrical energy for lighting. Efficient computation ensured that the study not only measured the voltage output but also evaluated the system's effectiveness in converting applied pressure into usable energy.

Ethical Considerations - The researcher ensured that all experimental procedures were conducted safely within a controlled environment, adhering to proper protocols for handling electrical equipment and components to prevent accidents. All data obtained pertained solely to the prototype's performance and efficiency and was used exclusively for research purposes. Additionally, all written outputs and references adhered to the guidelines and standards set by the American Psychological Association (APA) 7th edition. Throughout the study, the researchers uphold the core values of being a Divinian: integrity, service, and competence, together with transparency in the collection, analysis, and reporting of results.

3. Results and Discussions

Table 1 presents results showing a direct correlation between the applied weight and the electrical output of the piezoelectric disc. In the vehicle category, the heaviest source, the N-MAX V2 (140 kg), produced the highest mean voltage of 2.0046 V (High Level). In contrast, the lightest source, the Bicycle (14 kg), produced the lowest mean of 0.5158 V (Low Level), demonstrating that increased mass significantly enhances voltage production. These findings were supported by Xiong and Zhang (2019), who evaluated vehicle axle loads and found that the voltage produced by the piezoelectric elements correlated closely with static loading. Similarly, in Table 2, the human footstep trials across various weights (37 kg to 90 kg) consistently yielded a Moderate Level of voltage, with an overall weighted mean of 1.3128 V, demonstrating that the system is responsive to mechanical stress from both vehicular and human pressure. These were supported by Wang et al. (2021), who reported that increased load consistently raised voltage and power output, reinforcing the direct relationship between mechanical stress and electrical generation.

The consistent variation in mean voltage across different weight classes indicates that the piezoelectric generator's ability to generate electricity depends on the pressure source's intensity. Higher weight loads consistently shifted the interpretation from Low to High levels, indicating that the automated road lighting system's performance is directly dependent on these external mechanical inputs. Thus, this study finds that vehicle weight and the pressure of human footsteps significantly influence the voltage output and system performance. These findings are supported by previous studies showing that heavier vehicles impose greater mechanical loads, leading to increased strain on piezoelectric materials and larger electrical outputs (Gaber & AbdelRaheem, 2025).

Table 1

Amount of Voltage Output Produced by Various Sources of Pressure Using a Piezoelectric Generator

VEHICLE								
SOURCE OF PRESSURE	WEIGHT (kg)	TRIAL 1	2	3	4	5	MEAN	INTER-PRETA-TION
N-MAX V2	140 kg	1.97	1.91	2.11	2.13	1.90	2.00	HL
MIO GEAR 5	96 kg	1.29	1.28	1.38	1.32	1.05	1.27	ML
CLICK V2	112 kg	1.28	1.26	1.29	1.38	1.38	1.32	ML
BICYCLE	14 kg	0.55	0.65	0.39	0.41	0.58	0.52	LL
HONDA XRM 125 DS	102 kg	0.99	0.95	0.97	1.02	1.07	1.00	ML
RUSI KR-Y150CC	115 kg	1.16	1.12	1.14	1.94	1.99	1.47	ML
YAMAHA YBR 125	124 kg	1.79	1.91	2.01	1.66	1.05	1.68	ML
SNIPER 155	119 kg	1.19	1.76	1.15	1.78	1.53	1.48	ML
N-MAX V1	127 kg	1.76	1.26	1.89	1.88	1.90	1.74	ML

Legend: Low level (LL) at 0.1-0.9, Moderate level (ML) at 1.0-1.9, High level (HL) at 2.0-2.9

Table 2

Amount of Voltage Output Produced by Various Sources of Pressure Using a Piezoelectric Generator

HUMAN FOOTSTEPS								
SOURCE OF PRESSURE	WEIGHT (kg)	TRIAL 1	2	3	4	5	MEAN	INTER-PRETA-TION
Participant 1	37 kg	0.96	0.70	1.42	0.95	1.29	1.06	ML
Participant 2	48 kg	0.23	1.09	1.57	1.59	1.54	1.20	ML
Participant 3	76 kg	1.59	1.16	1.56	1.56	0.57	1.29	ML
Participant 4	90 kg	1.11	1.37	1.10	1.33	1.90	1.36	ML
Participant 5	88 kg	1.71	1.48	1.27	1.68	0.39	1.30	ML
Participant 6	85 kg	1.10	1.49	1.20	1.34	0.99	1.23	ML
Participant 7	47 kg	1.09	1.59	1.09	0.89	1.75	1.28	ML
Participant 8	52 kg	0.55	1.29	1.87	1.34	0.54	1.19	ML
OVERALL WEIGHTED MEAN							1.32	ML

Legend: Low level (LL) at 0.1-0.9, Moderate level (ML) at 1.0-1.9, High level (HL) at 2.0-2.9

The data presented in Table 3, derived from the mean voltage outputs of the initial trials, demonstrate that the Level of Efficiency of the Automated Road Lights is significantly sustained by both pressure sources, with vehicle weight yielding a mean of 1.3591506 and human footsteps yielding a mean of 1.2306. Because both values fall within the established range of 1.0 to 1.9, the results indicate that the piezoelectric generator operates at a Moderate Level of efficiency, successfully converting mechanical stress into usable electrical energy. This consistent performance directly addresses Problem 2 by demonstrating that the system's efficiency is not stagnant or negligible but rather actively driven by the specific mechanical inputs from vehicular and pedestrian traffic. Thus, this study finds that voltage generation and the performance level of the automated road lighting system are significantly affected by these variables; these results reject the null hypotheses. This result is supported by Xiong & Zhang (2019), who affirmed that heavier vehicles impose greater mechanical loads, leading to increased strain on piezoelectric materials, and by Gaber & AbdelRaheem (2025), who noted that such mechanical loads generate larger electrical outputs.

Table 3

Mean Level of Efficiency of the Automated Road Lights using the piezoelectric pressure.

SOURCE OF PRESSURE	MEAN	INTERPRETATION
Weight of Vehicle	1.36	Moderate Level
Pressure of Human Footsteps	1.23	Moderate Level

Legend: Low level at 0.1-0.9, Moderate level at 1.0-1.9, High level at 2.0-2.9

Table 4

Mean level of efficiency of the Automated Road Light in terms of Energy Conversion Rate of the Piezoelectric Generator

VEHICLE DATA						
SOURCE OF PRESSURE	WEIGHT (kg)	MEAN VOLTAGE (V)	ELECTRI-CAL POWER (W)	MECHA-NICAL ENERGY (J)	EFFICIENCY (%)	INTER-PRETA-TION
N-MAX V2	140 kg	2.00	0.00004018	6.87	0.000585%	HE
N-MAX V1	127 kg	1.74	0.00003016	6.23	0.000484%	HE
YAMAHA YBR 125	124 kg	1.68	0.00002822	6.08	0.000464%	HE

SNIPER 155	119 kg	1.48	0.00002194	5.84	0.000376%	LE
RUSI KR-Y15OC	115 kg	1.47	0.00002158	5.64	0.000383%	LE
CLICK V2	112 kg	1.32	0.00001732	5.49	0.000315%	LE
HONDA XRM 125	102 kg	1.00	0.00001009	5.00	0.000202%	LE
MIO GEAR 5	96 kg	1.27	0.00001600	4.71	0.000340%	LE
BICYCLE	14 kg	0.52	0.00000266	0.69	0.000387%	LE

Legend: High Efficiency (HE) at ≥ 0.000393%, Low Efficiency (LE) at < 0.000393%

Table 5

Mean level of efficiency of the Automated Road Light in terms of Energy Conversion Rate of the Piezoelectric Generator

HUMAN DATA						
SOURCE OF PRESSURE	WEIGHT (kg)	MEAN VOLTAGE (V)	ELECTRICAL POWER (W)	MECHANICAL ENERGY (J)	EFFICIENCY (%)	INTER-PRETA-TION
Participant 1	90 kg	1.36	0.00001851	4.42	0.000419%	HE
Participant 2	88 kg	1.31	0.00001708	4.32	0.000396%	HE
Participant 3	76 kg	1.29	0.00001655	3.73	0.000444%	HE
Participant 4	37 kg	1.06	0.00001641	2.31	0.000712%	HE
Participant 5	85 kg	1.23	0.00001502	4.17	0.000360%	LE
Participant 6	48 kg	1.20	0.00001447	2.35	0.000615%	HE
Participant 7	52 kg	1.12	0.00001251	2.55	0.000490%	HE
Participant 8	47 kg	1.28	0.00001129	1.82	0.000622%	HE

Legend: High Efficiency (HE) at ≥ 0.000393%, Low Efficiency (LE) at < 0.000393%

Tables 4 and 5 show a specific trend in the technical performance of the piezoelectric generator: energy conversion is more efficient when triggered by human footsteps than by heavier vehicles. The highest efficiency recorded was 0.000712% from a 37kg human footstep, whereas the most powerful vehicle (140kg) resulted in a lower efficiency of 0.000585%. This difference is due to pressure concentration. The 35mm piezoelectric discs respond to localized force; the sharp impact of a human foot concentrates weight more effectively onto the ceramic material than the broad, rubberized surface of a vehicle tire, which cushions and spreads the force. These findings were supported by Wang et al. (2021), who reported that increased load consistently raised voltage and power, while embedment depth and tire contact placement also influenced performance. Similarly, Kolhatkar et al. (2024) emphasize that strategically placed piezoelectric sensors can leverage footstep-induced stress to increase electricity generation. Furthermore, the system exhibits a "saturation effect": as vehicle weight increases, the mechanical energy input rises significantly, whereas the electrical output does not increase at the same rate, leading to a decrease in overall efficiency for heavier loads. For an automated road lighting system, this is a highly favorable outcome, as it ensures the system remains responsive and functional even under lighter pedestrian traffic.

The results in Table 6 show that the 12V battery performed stably during both trials. In Trial 1, the voltage decreased by only 0.10 V after 12 hours of operation, whereas in Trial 2, it dropped by 0.12 V after 8 hours. In Trial 3, the battery exhibited a larger voltage drop of 1.10 V after 23 hours and 40 minutes of continuous operation; however, this value still falls within the study's defined stable range. The minimal voltage drop in both trials indicates that the battery sustained the LED load without significant discharge. This stability can be attributed to the LED system's low power consumption, which does not heavily strain the battery. Overall, the findings suggest that the battery has sufficient storage capacity to maintain consistent performance under the given load conditions. This finding is supported by the study of Wang et al. (2021), which confirmed the reliability of energy collection and storage under open-traffic conditions. Their results showed that a 3300 μF system can be fully charged within 2–6 minutes, with storage performance influenced by driving load and vehicle frequency. This supports the present study's observation that energy storage systems can maintain stable output when operating under controlled load conditions, further validating the reliability of the battery used in the automated road lighting system.

Table 6

Mean level of efficiency of the Automated Road Light in terms of the storage capacity of the battery

Trial	Initial Voltage	Final Voltage	Operating Time	Voltage Drop	Interpretation
1	12.53	12.40	12 hours	0.10	Stable
2	12.40	12.28	8 hours	0.12	Stable
3	12.29	11.8	23 hours and 40 mins	1.10	Stable

Legend: Stable—Voltage drops within 0.10–1.10 V and operating time ranging from 8 hours to more. Not Stable – Voltage drops exceeding 1.10 V and operating time below 8 hours

Table 7

Mean level of efficiency of the Automated Road Light in terms of Lightning Activation of the Battery

Trial	Ambient Condition	LED Status	LED Brightness (lux)	Interpretation
1	Bright	OFF	0	Deactivated
2	Dark	ON	3.1 lux	Activated
3	Dark	ON	2.0 lux	Activated
4	Bright	OFF	0	Deactivated
5	Dark	ON	2.4 lux	Activated

Legend: Deactivated at 0 lux; Activated at >1.0 lux

Table 7 presents the results of the lighting activation and performance test of the developed prototype integrated with a Light Dependent Resistor (LDR). The findings demonstrate that the system responds appropriately to varying ambient light conditions, with brightness measurements taken at a fixed distance of 30 cm to ensure consistency and accuracy. During bright ambient conditions (Trials 1 and 4), the LED remained OFF and recorded a brightness level of 0 lux at the specified measurement distance. This confirms that the system successfully deactivated the LED when sufficient environmental illumination was present, thereby preventing unnecessary energy consumption. Conversely, under dark ambient conditions (Trials 2, 3, and 5), the LED automatically activated and produced brightness levels of 3.1, 2.0, and 2.4 lux, respectively. These results indicate that the prototype effectively detects low-light conditions and triggers illumination accordingly. This observed performance aligns with the findings of Subhalakshmi and Jayalakshmi (2019), who developed a piezoelectric harvesting system integrated with LDR control that successfully activated lamps under low-ambient-light conditions. Their study emphasized the reliability of sensor-based activation in improving lighting efficiency. In relation to these studies, the present findings support that the developed prototype exhibits functional sensor responsiveness and automatic activation capability. The system's ability to distinguish between bright and dark conditions and respond accordingly verifies its operational reliability. Consequently, the findings provide scientific evidence that integrating LDR-based control improves automation and energy efficiency in pathway lighting applications.

Table 8

Linear Regression Analysis of the Weight of Vehicle and Pressure of Human Footsteps Affecting Voltage Generation in Piezoelectric Discs

Variable	Regression Coefficient (β)	R^2	t-value	p-value	Interpretation
Weight of Vehicle	0.01	0.78	4.99	0.0016	Significant
Human Footsteps	0.74	0.55	2.70	0.0356	Significant

Legend: Significant at $p \leq 0.05$; Not Significant at $p \geq 0.05$

Table 8 indicates that vehicle weight has a statistically significant effect on the voltage generated by the piezoelectric disc. This is confirmed by a p-value of 0.0016, which is well below the 0.05 significance threshold. The R-squared value of 0.7805 indicates a strong correlation, suggesting that approximately 78.05% of the variance in voltage output is directly attributable to the vehicle's weight. Furthermore, the positive regression coefficient of 0.0105 indicates that as vehicle weight increases, the voltage produced increases proportionally. This was supported by Wang et al. (2021), who reported that increased load consistently raises voltage and power. It also indicates that the pressure of human footsteps significantly affects the voltage generated by the piezoelectric disc. The analysis yielded a p-value of 0.0356, which falls within the conventional threshold for statistical significance. These findings were supported by Ruman et al. (2019), who demonstrated through prototype development that human footsteps can effectively generate electricity using piezoelectric tiles, showing promising results for small-scale applications. The R-squared value of 0.54688 indicates a moderate relationship, with 54.69% of the voltage variation explained by the pressure from human steps. With a positive regression coefficient of 0.7407, the data confirm that higher footstep pressure yields higher electrical output, although the relationship is slightly less consistent than that of vehicle weight. Thus, through this data, the null hypothesis was rejected.

Table 9

Linear Regression Analysis on the Level of Performance Affected by the Weight of Vehicle and Human Footstep Pressure

Source of Pressure	Regression Coefficient (β)	R^2	t-value	p-value	Interpretation
Weight of Vehicle	0.01	0.78	4.99	0.0016	Significant
Human Footsteps	0.74	0.56	2.70	0.0356	Significant

Legend: Significant at $p \leq 0.05$; Not Significant at $p \geq 0.05$

Table 9 provides a robust statistical foundation for the study, demonstrating that the performance of the Automated Road Lighting System is significantly influenced by mechanical input. The regression analysis for vehicle weight reveals a strong positive correlation, with weight accounting for 78.05% of the variance in system performance and a highly significant p-value of 0.0016. Similarly, human footstep pressure shows a significant effect (p-value = 0.0356), explaining approximately 54.69% of the performance variance. These results confirm that the system is highly sensitive and responsive to the specific pressure intensities applied by both vehicles and pedestrians. The observed data were supported by the findings of Gaber and AbdelRaheem (2025), who examined embedded piezoelectric generators under roadways and reported that power output is influenced by vehicle weight, speed, and embedment depth of the piezoelectric materials. Because the p-values for both variables are well below the 0.05 significance threshold, the data provide empirical evidence that the system's performance is not independent of the applied weight and pressure. This statistical significance directly contradicts the assumption of no effect; thus, the data support rejecting the null hypothesis.

4. Conclusions

Based on the study's findings, the researchers conclude that pedestrian activity, such as footsteps, and vehicle pressure both reliably generate electrical energy for the piezoelectric generator. This shows that the generator efficiently converts mechanical energy into usable electrical energy, ensuring consistent energy output. Vehicle pressure and pressure from human footsteps reliably generate electrical energy for the piezoelectric generator. This demonstrates that the system efficiently converts mechanical stress from passing vehicles and mechanical movements into usable electrical energy, ensuring consistent energy generation. The system performs stably and reliably under varying mechanical loads. It maintains consistent electrical output despite increasing loads and confirms the system's reliability in maintaining high-efficiency power generation across diverse pressure sources for the Automated Road Light. The battery performed steadily, with only small voltage drops during operation, making its storage capacity sufficient to power the LED for a long time. The LDR-based control accurately responds to ambient light, activating the LED under dark conditions and turning it off in bright conditions. The vehicle's weight and pressure from human footsteps significantly affect the voltage generated by the piezoelectric disc; therefore, the null hypothesis that the voltage is not significantly affected by these factors is rejected. The performance of the Automated Road Lighting System using a Piezoelectric Generator is significantly affected by vehicle weight and the pressure from human footsteps. The null hypothesis, that the performance of the automated road lighting system using a piezoelectric generator is not significantly affected by vehicle weight or the pressure of human footsteps, is rejected.

Recommendations - The study's results indicate that the proposed automated road lighting system powered by piezoelectric generators can serve as an alternative energy source for streetlights. The researchers propose the following recommendations to further the development of the product presented to concerned agencies, the community, future researchers, and system developers. For future developers, it is recommended that future implementations of the system use higher-capacity piezoelectric discs or multiple-disc configurations to increase the voltage output. This improvement may enhance the system’s ability to support automated road lighting applications. For future developers and the Department of Public Works and Highways (DPWH), it is recommended that future system implementations expand installation to roads with moderate to heavy vehicle traffic and to additional pedestrian-dense locations, such as school walkways, terminals, and public sidewalks. Using locations with repeated vehicle loads and continuous pedestrian foot traffic will help the system generate more energy and operate more efficiently. Future developments of the system may focus on generating energy from pedestrians, maintaining stable energy storage, ensuring reliable LED lighting activation, and incorporating a power inverter to regulate and stabilize the output voltage. Moreover, make sure any connected electrical loads, such as LED lights, match the inverter's output rating to avoid overloading or damage. Community members and residents are encouraged to use the pedestrian paths with the Automated Road Lighting System, because their footsteps help generate electricity and keep the lights working. For system developers and future researchers, it is recommended that the system's mechanical design and load-handling capabilities be enhanced to maintain consistent performance under varying loads. This may include making the piezoelectric discs more durable, adjusting the thickness of the rubber sheet and other force-distributing parts, and calibrating the system to respond more effectively. Future researchers are encouraged to conduct tests under various environmental conditions to ensure the product’s reliability, safety, and long-term effectiveness. Environmental factors such as weather conditions, temperature changes, and humidity levels must be carefully evaluated, as these may significantly affect the durability, efficiency, and overall performance of the system.

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