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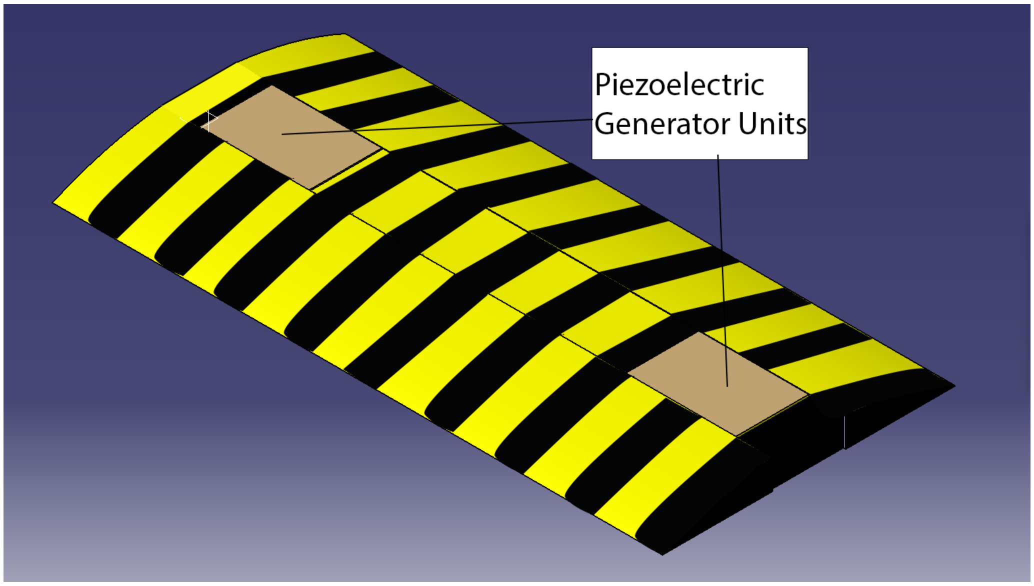
INTEGRATION OF PIEZOELECTRIC SPEED BUMPS INTO AIRPORT ROADWAYS

(January 2023 - April 2023)



Design Challenge: Airport Environmental Interactions Challenge: C

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INTEGRATION OF PIEZOELECTRIC SPEED BUMPS INTO AIRPORT ROADWAYS

Executive Summary

The proposal is a design for embedding piezoelectric speed bumps on airport traffic roadways, which can be a viable solution for generating clean and renewable energy. This proposal addresses the ACRP **Airport Environmental Interactions Challenge: C** to improve the energy efficiency of the airport terminal area and other ground facilities (ACRP, n.d.). Currently, airports are increasing the number of renewable energy sources to supply their energy demands. However, piezoelectric energy embedded in airport roadways has not been implemented yet. Piezoelectric speed bumps are expected to produce a substantial amount of energy with the potential to replace non-renewable energy usage. In exploring the proposed use of piezoelectric energy harvesting technology in high-traffic ground transportation systems, this study considers four factors: regulatory compliance, safety-risk assessment, benefit-cost analysis, and sustainability analysis of the proposed design.

To examine the implementation of the proposed design, the team selected Dallas Fort-Worth International Airport (DFW), Indianapolis International Airport (IND), and Akron-Canton Airport (CAK) as the case study airports in this study. The three airports are selected to showcase the feasibility of the proposed design across the different hub airport sizes in the United States. Based on the assumptions of ground traffic flow, the benefit-cost ratios for DFW, IND, and CAK are 1.12, 1.15, and 1.19, respectively. These results indicate that the proposed study could lead to a positive net present value and be economically viable while supporting the airports' efforts to achieve environmental sustainability.

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1. Problem Statement and Background

Airport electricity consumption contributes to 5% of the total greenhouse gas emissions by the air transport system, making it crucial to find sustainable solutions for the aviation industry (Janic, 2011). The Federal Aviation Administration introduced the Bipartisan Infrastructure Law in 2022, allocating $5 billion for airport terminal development projects that enhance sustainability (Federal Aviation Administration, 2019). Piezoelectric technology is proposed as a renewable energy source for airport terminals.

The ACRP challenge that this report aims to address is the Airport Environmental Interactions Challenge, specifically in increasing energy efficiency in managing the terminal area and airport buildings. The proposed solution is to introduce a system and a method for power harvesting comprising a plurality of piezoelectric devices embedded in a speedbump installed on parts of an airport road and configured to produce electrical power when vehicles pass through the location of these piezoelectric devices. A report claims that a 100-meter (328 feet) road embedded with 30,000 piezoelectric cymbals can produce 65 MWh of electricity annually (Correia & Ferreira, 2021). If this technology is applied to airport roads, such as in LAX, a 328 feet road paved with piezoelectric cymbals can contribute to 18.5% of the airport's energy source in 2019 (Los Angeles World Airport, 2021)

This is a significant contribution to the energy source of airports for a roadway. This report assesses the viability of this technology with the help of experts from the airport and piezoelectric technology, in the hopes of the proposed design becoming a real-life solution to increase the energy efficiency of airports.

The technology behind piezoelectric generators is founded on the concept of the piezoelectric effect. This effect pertains to the capability of certain materials to produce an electrical field when exposed to mechanical stress. (Berlincourt, 1971). Piezoelectric technology can generate electricity using the mechanical stress generated by natural vibrations and movements, such as footfall, vehicle movement, and wind. The generated electricity can power airport facilities, such as signs, lighting, air conditioning, and control systems.

Piezoelectric technology is a promising renewable energy source. Although it has been implemented in engineering, healthcare, and military applications, its use in airports is still experimental.

There are specific challenges unique to airport environments that must be addressed. One of the significant issues is the variability of energy output. The energy output of piezoelectric energy harvesting technology depends on the mechanical stress's amplitude, frequency, and duration (Correia & Ferreira, 2021). The energy output can also be affected by factors like the speed and weight of vehicles and the volume of pedestrian traffic (Correia & Ferreira, 2021). This variability can affect the reliability of the energy source, making it difficult to predict energy generation. Additionally, the constant movement and vibration in an airport environment may cause wear and tear, decreasing energy generation capacity. Furthermore, maintenance can be expensive and requires specialized skills and equipment.

Cost-effectiveness is also a significant consideration. The costs of installing and maintaining piezoelectric cymbals must be weighed against potential energy savings and environmental benefits. A thorough cost-benefit analysis should be conducted to determine the feasibility of this technology in the airport environment.

This study aims to examine the integration of piezoelectric energy generator technology in airport roadways as a self-sustained energy source. The design project will cover the energy-harvesting system, a safety risk assessment, a cost-benefit assessment, and an analysis of the potential impacts of the proposed intervention.

2. Summary of Literature Review

This section discusses literature related to piezoelectric harvesting speed bumps in the airport runway, addressing the current state of the art of energy harvesting methods and real-world application of piezoelectric harvesting technology. This summary reviews and summarizes multiple previous Airport Cooperative Research Program University Challenge Design projects based on piezoelectric technology.

2.1.The standard energy harvesting methods

A key component of sustainable energy production is energy harvesting, which involves capturing and converting energy from various natural sources, including the sun, wind, and water, as well as from waste materials (Rowlings, A.J.,2016).

In the past ten years, piezoelectric energy harvesting has gained significant interest among researchers, primarily because of its benefits, like high power density, straightforward design, and adaptability to various sizes. (Erturk, A., & Inman, D. J, 2011). It is a method of generating electrical energy from mechanical vibrations. This technology is based on the piezoelectric effect, which refers to the capability of generating an electric charge from mechanical stress (Toprak, A., & Tigli, O, 2014).

Piezoelectric materials can be used to create piezoelectric generators, which can transfer mechanical input into electrical energy output (Correia et al., 2021). These devices typically consist of a piezoelectric material, such as quartz or lead zirconate titanate (PZT), placed between two electrodes (Correia et al., 2021). When the material is subjected to mechanical stress, such as vibration or pressure, it generates an electric charge collected by the electrodes.

The Seebeck Effect refers to the occurrence in which a temperature disparity between two different metals or semiconductors produces a voltage, resulting in a potential difference that can be harnessed to generate electrical power. (Correia et.al, 2021). This effect is used in thermoelectric generators to convert the temperature difference between two surfaces into electrical energy. This is the principle of Thermal Energy Harvesting.

More recent energy harvesting methods include electromagnetic and pneumatic energy harvesting. Electromagnetic energy is processed by converting electromagnetic radiation into usable electrical energy. Radiation includes various forms of energy such as radio waves, microwaves, infrared radiation, and visible light. The energy harvesting process involves using an antenna to capture electromagnetic radiation and convert it into an electric current.

Pneumatic energy harvesting generates electrical energy from fluid flow, such as air or water, in a pipeline or duct. The technology is based on the principle of fluid dynamics. Pneumatic energy harvesting typically involves the use of a device known as a piezoelectric generator, which is designed to convert the energy from fluid flow into electrical energy.

Energy harvesting methods offer several benefits over traditional energy sources. They are renewable as they do not deplete natural resources, and they produce fewer emissions and pollutants, making them environmentally friendly. They also have the potential to be long-run cost-effective, as they often require less maintenance and can provide a reliable energy source. Overall, sustainable energy harvesting methods are critical to achieving a more sustainable future.

2.2. Real-World Application of Piezoelectric Harvesting Technology

Over recent years, there has been an increase in research interests in energy conversion and harvesting, with solutions for diverse locations addressing new forms of energy production options. Many countries have used piezoelectric energy harvesting technology in the real world to serve the public in an environmentally and sustainably beneficial manner since it can be a practical substitute for fossil fuels and other traditional energies, which have been generating pollution. For example, Israel inaugurated the first piezoelectric freeway in 2009, composed of a ten-meter strip of asphalt with piezoelectric generators beneath. Meanwhile, East Japan Railway Company in Japan implemented a piezoelectricity-driven walkway at the ticket gate in the railway station in 2009. This walkway is a power-generating floor embedded with piezoelectric parts as well as a loudspeaker. As the loudspeaker transforms electrical signals into sound vibrations, the floor subsequently generates electricity by capturing the vibrational energy created by the physical motion of train passengers.

The use of piezoelectric energy harvesting technology has become the interest of research over the last decade. Studies list several practical and potential uses of piezoelectric energy harvesting technology, such as powering streetlights and lighting dancing floors (Tandon & Kumar, 2014). Among all applications, roadway pavement is one commonly addressed subject for this harvesting technology. Abramovich et al. (2009) invented and registered a patent for harvesting power on roads and highways using a piezoelectric generator. Chen et al. (2016) designed a new approach by harvesting mechanical energy from the deformation of road pavements to supply electric power for highways. Their experimental analysis demonstrated the feasibility of applying piezoelectric elements to convert mechanical energy in road traffic. Jasim et al. (2017) developed the design of a piezoelectric energy harvester for recycling energy from roadways, which is estimated to yield approximately 0.73mJ of potential energy. Song et al. (2019) designed a roadway speed bump with a piezoelectric energy harvesting device. Their experiment indicated that a compact vehicle passing the bump at a speed of about 20mph could, at most, generate an output electric voltage of 144 V, an output current of 45.2 mA, and an output power of 4.08 W. As the bump is passed by nine compact or larger vehicles with about 20mph or even faster, the electricity output generated is sufficient to charge a cell phone—the results by Song et al. (2019) significantly demonstrated the feasibility of a piezoelectric energy harvesting system in actual practice.

Concerning the airport sector, several studies have suggested using piezoelectric energy devices in the airfield pavements, such as runways, to recycle unused or wasted energy. Agarwal and Sharma (2014) proposed a multimorphemic piezoelectric device that can harvest vibrational energy generated on the airport runways at London Heathrow International Airport. Through estimating the revenues and plantation costs, Agarwal and Sharma concluded that this energy harvesting technology could return a revenue of around 1.5 billion USD within the first decade of device plantation. The considerable financial returns and environmental benefits demonstrated that this project is economically viable and sustainable. Zhao and Wang (2020) conducted a mechanistic modeling and economic analysis using piezoelectric energy harvesting technology in airfield pavements. Their results showed that power output generated by piezoelectric energy harvesting technology is subject to several factors, including aircraft load, speed, and the depth of horizontal locations of energy harvesting devices embedded in the pavements. As Zhao and Wang Field (2020) suggested, the piezoelectric energy harvesting system can be used as a distributed energy source in the airfield for other microgrid applications.

In addition to these publications, three studies awarded by Airport Cooperative Research Programs proposed using piezoelectric energy harvesting technology at airports. Falcon and his undergraduate team (2009) proposed the piezoelectric energy harvesting technology application into ice detecting systems for runway and taxiway uses, which was concluded to be not practical. Instead, they referred to some real-world use of piezoelectric energy harvesting technology and proposed the application of sustainable floor tiles into the terminal of San Jose International Airport (SJC). These tiles are designed to serve as power-generating floors to help SJC reduce the amount of electricity. Nixon, Ziegler, and their undergraduate teams (2018) suggested harvesting kinetic energy from landing aircraft by embedding a piezoelectric system on the runway center. The system is designed to convert the harvested energy to batteries and the primary airport power grid source for the airfield equipment, such as runway lights. Riley and her undergraduate teams (2014) focused on illuminating overhead LED lights installed on a jet bridge with self-sustainable energy generated by piezoelectric energy harvesting technology. They illustrated the feasibility of their design by completing an engineering analysis, which consisted of fatigue and failure studies, material integrity analysis, and motion analysis.

3. Problem-Solving Approach to the Design Challenge

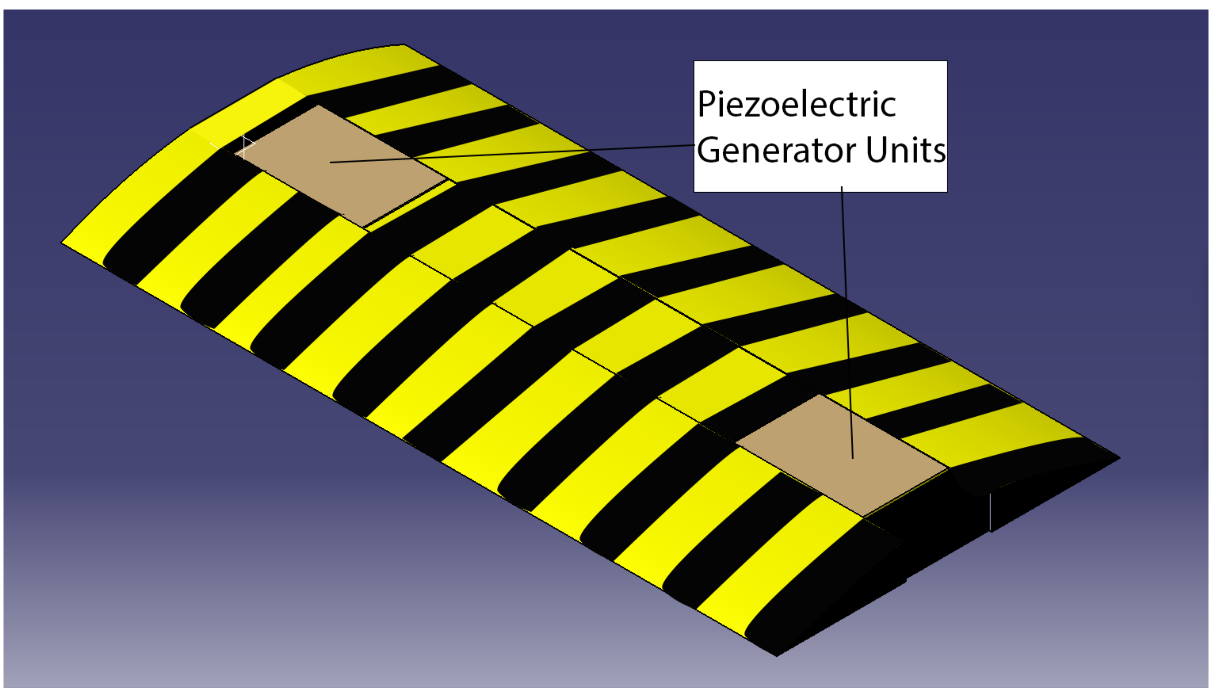
In this section, the team's approach to problem-solving is described, encompassing four key components: mechanical design, optimal usage location, circuit design, and regulatory compliance. These four areas were prioritized to ensure that the proposed design would be effective, safe, and compliant with relevant regulations.

3.1. Proposed Mechanical Design

Figure 2 shows the design of the piezoelectric speedbump generator. The piezoelectric generators will be placed where the wheel of a car is located to optimize the utilization of the mechanical pressure from the passing cars.

Figure 1

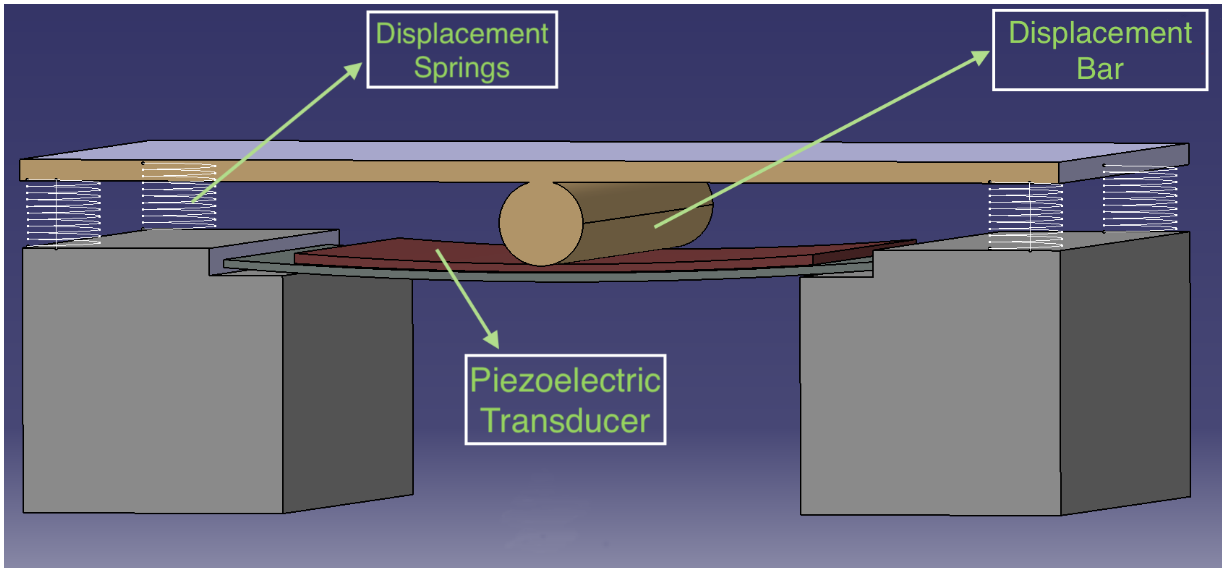
Piezoelectric Speed Bump Design



Two piezoelectric generators will be installed in the speed bump design. These piezoelectric generators consist of a series of piezoelectric discs laid out in layers. The piezoelectric discs will have a bar that will create the displacement of the piezoelectric discs, which will then be converted into electricity. The illustration of the mechanism can be seen in Figure 2. Meanwhile, the project team has considered using industrial rubber tiles to ensure the proper functioning of the piezoelectric speed bumps to prevent erosion caused by vehicle exhaust and other wastes. These tiles are designed to withstand harsh environmental conditions and provide a durable, non-slip surface for speed bumps. Additionally, regular maintenance of the speed bumps and surrounding area would be necessary to prevent the build-up of debris or damage to the equipment. By implementing these measures, we can ensure that the piezoelectric speed bumps will keep functional effectively and safely over the long term.

Figure 2

Demonstrates the mechanism of the Piezoelectric Generator.



3.2.Proposed Circuit Design

The system setup involved harnessing energy from a speed bump through an energy harvester. As shown in Figure. 4, the frame includes a receiving circuit, a rectifier module, and a regulator module. On the receiving circuit, the piezo-electricity generators produce AC voltage, which is fed through a full-bridge inverter. The rectifier module, which follows the receiving circuit, rectified the AC voltage, and the resultant energy was stored in a 10 mF super-capacitor. This capacitor served as a storage device for the rectified energy. Then the regulator module is regulated by a linear regulator to provide a steady DC voltage. The regulator module then regulated the stored energy using a linear regulator to supply a steady DC voltage. The load could power various loads such as parking meters, lighting systems, and battery charging.

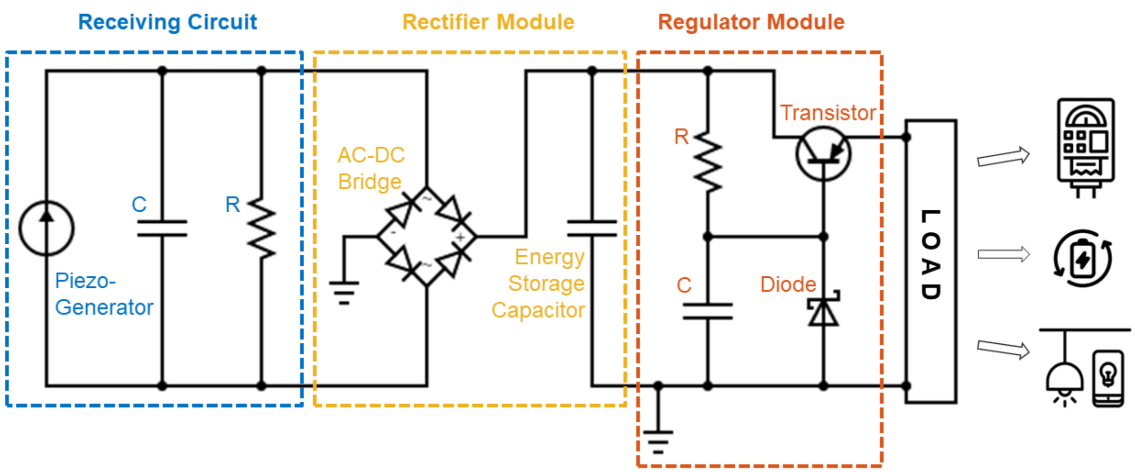
a) parking meter (Further details on the implementation plan for the parking meter load could be provided).

b) battery charging (integrating the energy harvester with existing sustainable battery design in Indianapolis Airport for battery charging)

c) the harvested energy could be utilized to power lighting systems like lighting-based road signals and emergency lighting.

Figure 4

The schematic frame of the energy harvesting control

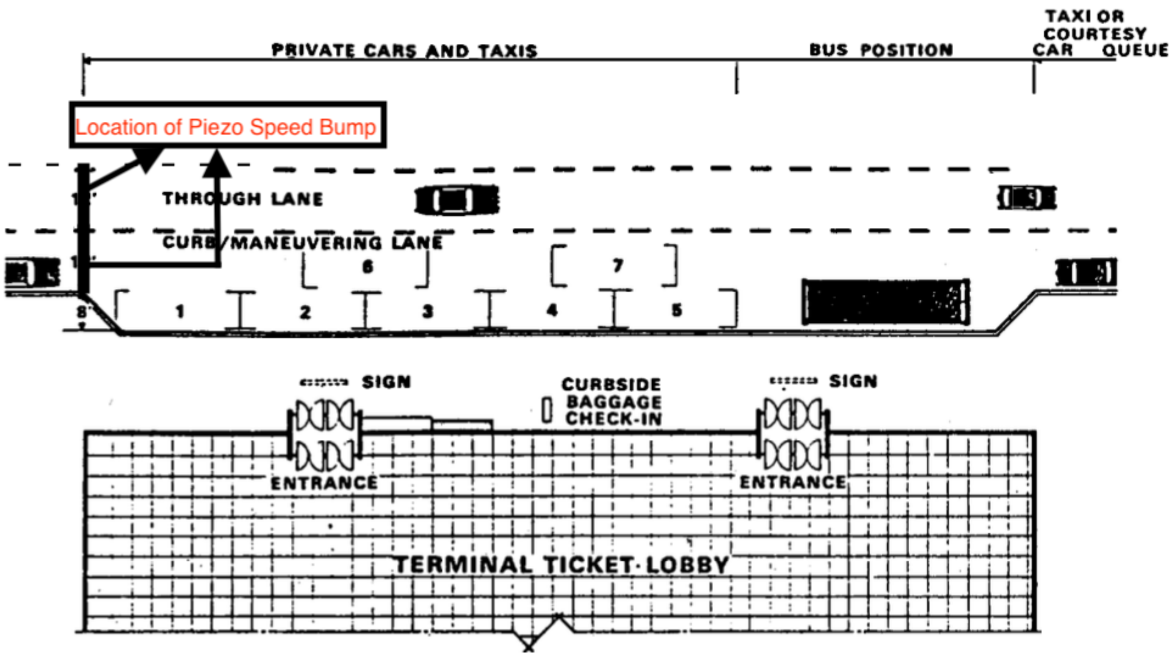


3.3.Optimal Usage Location

After interacting with the airport experts, the team learned about the ideal places for piezoelectric speed bumps. These piezoelectric speed bumps are ideally placed at the main entrance/exit of an arrival/departure roadway. In other words, this project proposed a point with the most ground traffic volume at the airport as the optimal location for installing the proposed speed bump. Figure 3 shows the proposed location of piezoelectric speed bumps.

Figure 3

Proposed location of the Piezoelectric Speed Bump at the enplaning area (Federal Aviation Administration, 1988, p.119)



3.4.Regulatory Compliance

According to the standard addressed by Federal Highway Administration in the Manual on Uniform Traffic Control Devices, there is no standard requirement for the height, width, length, or spacing of actual speed bumps (Federal Highway Administration, 2023). Instead, it is recommended to refer to the technical guidance on criteria, dimensions, and spacing, which is published by The Institute of Transportation Engineers. Many cities and counties in the US apply this guidance in developing the design and use of speed bumps.

Meanwhile, based on the Updated Guidelines for the Design and Application of Speed Humps by Parkhill et al. (2007), the length of the speed bump is recommended to be 12 to 14 feet long, and the height should range from 3 to 6 inches with a travel length of 1 to 3 feet. It is noted that a speed bump should be equipped with a road sign or a marking to warn road users of the physical features of the road.

4. Projected Impacts of the Proposed Design and Findings

The airports are expected to increase their usage of clean, renewable energy sources through this proposal. The piezoelectric speed bumps will harness energy from vehicles passing over the speed bumps. The proposed design may increase the utility of general speed bumps placed around the airport.

In terms of commercial potential, airports will be saving on costs and expenses related to non-renewable sources of energy. The harnessed energy from the piezoelectric speed bumps will be stored in batteries which will eventually be used to power various appliances around the airport. Through this technology, not only will the piezoelectric speed bumps make the airports "greener" in terms of power consumption, but also add to the sustainability of airports for years to come.

As discussed in the previous section of the proposed design, the design of the piezoelectric speed bump is quite simple and flexible. The layout and structure ensure the maintenance and repairability of such devices. Generally, the speed bumps will require frequent maintenance due to the sensitivity of the piezoelectric generator units. Overall, the benefits are worth the effort, which is discussed further in the cost-benefit analysis.

5. Benefit-Cost Analysis

This section aims to evaluate the potential benefits and drawbacks associated with the proposed design. Given that benefits and costs rely on utilizing the proposed speed bump, three primary hub airports were selected as the case study airports for a benefit-cost analysis. The project team has referred to the experimental results presented by Song et al. (2019) for conducting a benefit-cost analysis of implementing piezoelectric speed bumps at commercial airports. The objective is to determine the feasibility of implementing the proposed design by weighing the potential benefits against the expected costs and then help to inform decision-making regarding its implementation.

5.1. Benefits

The proposed design of a piezoelectric speed bump can bring multiple advantages to airports. Concerning potential tangible benefits, the electricity produced by the piezoelectric speed bump can serve as a renewable energy source for several utility purposes at a lower cost, including backup power and LED lighting. This design can contribute to airports' environmental sustainability goals by generating clean energy and reducing their carbon footprint. Additionally, the use of piezoelectric speed bumps can bring intangible benefits. For example, airports can enhance their public image as "Green airports." Also, the adoption of backup power can help airports improve resilience to electricity outages.

5.2. Costs

This study considers three types of costs: research and development (R&D), device-related, and labor-related costs. This project considers all initial development and expert review expenses as alpha costs, as detailed in Table 1. During the 12-week R&D stage, four-graduate students invested 10 hours of work per week in the ACRP university design competition, and the cost of faculty advisor review was also considered. In addition, an overhead cost of 5% of total R&D costs, including travel and utilities, was also estimated. The estimated total one-time R&D cost is expected to be $15,120.

Table 1

Research & Development Cost Breakdown

Item	Rate	Quantity	Subtotal	Notes
Research & Development (R&D)				
Student Efforts	$20 per hour	480	$9,600	4 graduate students*10 hours/week* 12 weeks* student rate ($20)
Faculty Efforts	$100	48	$4,800	4 hours/week*1 advisor*12 weeks*advisor rate ($100)
Overhead Cost			$720	5% of total R&D cost (travel, utilities, tax, etc.)
Total			**$15,120**	**One-time costs**

Note: Suggested by ACRP Cost-Benefit Analysis (Byers, 2016)

The costs associated with equipment include the price of piezoelectric disc transducers, rubber speed bumps, and circuits. According to the product provider Physik Instrumente USA, each piezoelectric disc transducer is priced at $20 and can withstand up to ten million uses (Physik Instrumente, 2023). The cost of a rubber speed bump, which has a two to three years lifespan, is estimated to be around $200. The researchers will spend approximately $150 purchasing the wire for circuit connections. Labor costs will be involved for device installation and regular maintenance, which are subject to the life cycle and utilization of the device.

5.3. Case Study

As aforementioned, to avoid ground traffic separation and maximize the energy harvesting performance of piezoelectric speed bumps, the team conducted case studies on airports with one primary lane for ground traffic entrance and exit. The present study considers Orlando International Airport (MCO), Indianapolis International Airport (IND), and Akron-Canton Airport (CAK) as the case study airports to conduct the benefit-cost analysis of the proposed design. These three airports are selected to represent large, medium, and small hub airports in the United States based on their annual enplanements. The researchers have established and considered the following assumptions while conducting the case studies.

- This study assumes that the peak hours of ground traffic occur between 6 AM to 11 PM, with the remaining hours considered off-peak.
- The results presented in this study are based on one traffic lane at each case study airport.
- The team referred to the experiment and findings by Song et al. (2019) for the results of electricity output generated by piezoelectric speed bumps. The experiment results by Song et al. (2019) showed that at least 4.08 W could be produced when a medium-sized passenger vehicle passes over the piezoelectric speed bump at a speed of 20 miles per hour.
- The vehicles passing through the speed bump travel above 20 miles per hour but below the designated speed limit.
- This statement indicates that the piezoelectric speed bump is functioning correctly and is not experiencing any issues or malfunctions.

Based on the above-stated assumptions, the team estimated the electricity generation potential of the piezoelectric speed bump for one lane of ground traffic at each of the studied airports. Based on the electricity output suggested by Song et al. (2019), the results indicated that the maximum annual electricity generation capacity of the proposed speed bump is approximately 18,254 KWH for MCO or other equivalent large-hub airports, 15,212 KWH for IND or other equivalent medium-hub airports, and 10,022 KWH for CAK or other equivalent small-hub airports. Table 2 presents the benefits of the piezoelectric speed bump, which includes annual savings in energy costs.

Table 2

Annual cost savings of electricity energy

	Hub	Periods	Hourly traffic flow	Daily crossings	Daily energy output (KHW)	Annual energy output (KHW)	Annual energy cost savings	Total
MCO	Large	Off peak	150	2,100	8.58	3,131.92	$393.06	$2,684.01
		Peak	360	12,240	50.01	18,254.61	$2,290.95	
IND	Medium	Off peak	100	1,400	5.72	2,087.95	$262.04	$1,980.26
		Peak	270	9,180	37.51	13,690.96	$1,718.22	
CAK	Small	Off peak	50	700	2.86	1,043.97	$131.02	$1,276.50
		Peak	180	6,120	25.01	9,127.31	$1,145.48	

To quantify the cost savings associated with the carbon footprint reduction benefit of the proposed design, the researchers converted the amount of electricity generated by the piezoelectric speed bump into the equivalent volume of carbon emissions that would be produced by generating the same amount of electricity using conventional means. The project then applies a social cost of $185 per additional ton of carbon dioxide emitted into the atmosphere to estimate the total cost savings. This cost coefficient is suggested by Rennert et al. (2022).

Table 3

Annual cost savings of carbon emission

	Hub	Periods	Energy generated per year	Carbon emission (kg)	Cost per ton carbon emission	Carbon emission cost savings	Total
MCO	Large	Off peak	3,131.92	1161.94	$185	$214.96	$1,467.86
		Peak	18,254.61	6772.46		$1,252.91	
IND	Medium	Off peak	2,087.95	774.63		$143.31	$1,082.99
		Peak	13,690.96	5079.35		$939.68	
CAK	Small	Off peak	1,043.97	387.31		$71.65	$698.11
		Peak	9,127.31	3386.23		$626.45	

Table 4 summarizes the total cost savings achieved by using piezoelectric speed bumps to generate electricity based on the information provided in Tables 2 and 3. Additionally, it presents a ten-year cost savings estimate for the three studied airports.

Table 4

Potential benefits of using piezoelectric speed bump

	Hub	Cost savings of electricity energy	Cost savings of carbon emission	Total one-year cost savings	Total ten-year cost savings
MCO	Large	$2,684.01	$1,467.86	$4,151,87	$41,518.70
IND	Medium	$1,980.26	$1,082.99	$3,063.25	$30,632.50
CAK	Small	$1,980.26	$698.11	$2,678.37	$26,783.70

The researchers also considered equipment-related and labor costs in addition to the benefits of the proposed design. Equipment-related costs include the piezoelectric disc transducers, circuit wires, and rubber speed bumps, estimated at $1,000. Labor costs are associated with installing and replacing the entire piezoelectric speed bump and vary depending on the lifespan of the speed bump, which is subject to utilization. The researchers assume the installation or replacement work can be finished within five hours by a team of four licensed electricians, whose hourly wage is $150. Hence, the total expected labor cost is about $3,000.

Table 5 provides estimated costs, expected life cycle, and maintenance costs for ten years of utilization for the proposed design at different hub airports.

Table 5

Potential Costs of using piezoelectric speed bump

<table>
<tr><th></th><th>Hub</th><th>Device</th><th>Labor</th><th>Expected replacement</th><th>Ten-year maintenance cost</th><th>R&D cost</th><th>Total cost for ten-year</th></tr>
<tr><td>MCO</td><td>Large</td><td rowspan="3">$1,000</td><td rowspan="3">$3,000</td><td>1.9 years</td><td>$18,947.37</td><td rowspan="3">$15,120</td><td>$34,067.37</td></tr>
<tr><td>IND</td><td>Medium</td><td>2.6 years</td><td>$11,553.36</td><td>$26,673.36</td></tr>
<tr><td>CAK</td><td>Small</td><td>4 years</td><td>$7,447.44</td><td>$22,567.44</td></tr>
</table>

Table 6

Benefit-cost analysis for subject airports

	Hub	Ten-year benefits	Ten-year costs	Benefit-Cost ratio
MCO	Large	$41,518.70	$34,067.37	1.22
IND	Medium	$30,632.50	$26,673.36	1.15
CAK	Small	$26,783.70	$22,567.44	1.19

Using the data provided in Tables 4 and 5, the researchers calculated the benefit-cost ratio for the selected airports and presented the findings in Table 6. The study found that the benefit-cost ratios for MCO, IND, and CAK are above one, indicating that the proposed design can produce a favorable net present value and be financially feasible for focused large, medium, and small hub airports. This will aid the primary hub airports in their pursuit of environmental sustainability by facilitating the implementation of eco-friendly practices.

6. Safety Risk Assessment

This section discusses the safety risk assessment of the piezoelectric speed bump. As part of the Safety Management Systems (SMS) for airport operations, Safety Risk Management (SRM) needs to be conducted before implementing a new design. As part of the safety risk assessment, this chapter will discuss safety risk identification and use the appropriate FAA Advisory Circular and order to create the safety risk matrix.

6.1. Safety Risk Identification

When considering the implementation of piezoelectric speed bumps at airports, it is essential to thoroughly examine multiple layers of risk. The top priority must be to ensure human safety. Therefore, before replacing the original speed bumps with the proposed piezoelectric ones, thoroughly reviewing the airport ground transportation layout is crucial. Any potential issues that may interfere with emergency vehicles or cause unnecessary speed reductions at specific locations must be identified and addressed.

Furthermore, properly installing the piezoelectric cymbals is essential to minimize the risk of accidents. Improper installation could lead to uneven road surfaces or loose cymbals, posing a significant risk to vehicles, pedestrians, and airport equipment. Therefore, paying close attention to the installation process and ensuring that all safety measures are followed is necessary. Additionally, ongoing maintenance and inspection must be conducted to ensure that the speed bumps remain in good condition and continue to operate effectively without posing any safety hazards.

Another important layer of risk that must be considered when implementing piezoelectric speed bumps at airports is the impact of weather-related factors. Since these speed bumps will be externally exposed on the road, they will be sensitive to fluctuations in weather and temperature conditions. In addressing the impact of extreme weather conditions, this study considers the following elements for the proper and safe installation of proposed piezoelectric speed bumps at airports.

a) The selection of piezoelectric cymbals and materials should prioritize those with proven durability and resistance to extreme weather phenomena such as storms, snow, and heavy rain. The materials should also be able to withstand both high and low temperatures.

b) The electrical system should be designed to accommodate potential weather-induced impacts, including providing proper drainage to avert water accumulation around the cymbals. Extreme weather conditions may influence their connections to the airport's electrical grid.

c) Persistent monitoring of the piezoelectric energy harvesting system's performance during extreme weather events is crucial, enabling necessary adjustments to ensure ongoing safe operation.

Lastly, the production and disposal of piezoelectric materials must adhere to eco-friendly practices. Careful consideration of environmental consequences is essential, and efforts should be made to avoid materials with high pollution potential as much as possible. By ensuring the sustainable production and disposal of these materials, implementing the piezoelectric speed bump system can contribute to the overall environmental goals of the airport while minimizing potential negative impacts.

6.2. FAA Advisory Circular and FAA Safety Management System Manual

When implementing a new system at an airport, Safety Risk Management (SRM) is a crucial step in the Safety Management System (SMS) (Federal Aviation Administration, 2023). A thorough and organized SRM process is carried out under Advisory Circular (AC) 150/5200-

37 and FAA Order 5200.11A to identify, mitigate, and prevent hazards within the airport. AC 150/5200-37 outlines the five phases of SRM: identifying the system, hazard, and risk, determining the level of risk, analyzing the risk, and controlling it. (Federal Aviation Administration, 2023).

The FAA Order 5200.11A provides airports with a safety risk matrix that will help airports identify the risk level of each potential risk that was identified. The risk level is divided into three categories. These categories are:

1. High Risk: If a hazard has a significant initial risk, the plan cannot proceed unless the dangers are reduced further, so the risk level becomes moderate or low. It is necessary to monitor and manage high-risk hazards and their corresponding measures. (Federal Aviation Administration, 2021)
2. Medium Risk: The least amount of risk deemed safe is at a moderate level, which serves as the lowest acceptable safety goal. It is essential to monitor and control the level of risk. (Federal Aviation Administration, 2021).
3. Low Risk: Attaining a low level of risk is the desired outcome. Although it does not require active management, it must be recorded in the Safety Risk Management documentation. (Federal Aviation Administration, 2021).

Table 7

Risk Matrix by FAA Order 5200.11A (Federal Aviation Administration, 2021)

Likelihood \ Severity	Minimal (1)	Minor (2)	Major (3)	Hazardous (4)	Catastrophic (5)
Frequent (5)	5	10	15	20	25
Probable (4)	4	8	12	16	20
Remote (3)	3	6	9	12	15
Extremely Remote (2)	2	4	6	8	10
Extremely Probable (1)	1	2	3	4	5*

* High Risk with Single Point and/or Common Cause Failures

Key:
High Risk (Red)
Medium Risk (Yellow)
Low Risk (Green)

Table 7 shows the format for the safety risk matrix by the FAA. Each hazard is evaluated in severity and likelihood of the hazard. The severity refers to the degree of harmful impacts caused by the hazards. The likelihood is the proportion of a particular hazard to occur (Federal Aviation Administration, 2021). Finally, the risk level is assessed by the multiplication of the points of the likelihood and severity of each hazard.

6.3. Safety matrix

The team produced a safety risk matrix by applying the same principles from the FAA Order 5200.11A in Table 7. The point system of the likelihood is modified into a numeric system instead of using the alphabet system. Eventually, the risk matrix shown in Table 8 was created.

As shown in Table 7, five low-risk potential hazards and three high-risk potential hazards were identified. Low-risk hazards are permissible but need to be documented. The potential high-risk hazards are unacceptable. However, the design proposal can still be implemented if the risk is mitigated beforehand. Table 8 shows how the potential high-risk hazards will be mitigated before and after implementing the proposed solutions.

Table 8

Potential Hazard Risk Matrix

	Potential Risks	Likelihood	Severity	Risk Level	Potential Solutions	Residual Risk
1	Reduced emergency braking distance can increase the risk of collision.	4	5	20	Put a sign "slow down" to alert drivers.	10
2	Slippery surfaces due to snow and ice buildup can cause accidents.	3	5	15	Installing rubber speed bumps with anti-slip patterns are used. Spread de-icing salt during icy and snowy days.	6
3	The speed bump can distract drivers and cause accidents	3	5	15	Paint the speed bump yellow and black to alert the drivers. Put a sign "speed bump ahead"	8
4	Piezoelectric elements are brittle and can wear after certain pressure cycles	1	1	1	Conduct regular maintenance checks to collect output voltage to see if the device is still working optimally	1
5	Vehicles passing causing parts of the speed bump to be chipped	1	2	2	Perform correct installation of the speed bump and perform regular inspection of the structure of the speed bump	1
6	Piezoelectric speed bumps can cause damage to vehicle suspension	1	2	2	Put a speed limit sign of 20mph before the speed bump. Speed bumps are placed in areas that do not exceed 20 mph.	1
7	Delay emergency response of emergency response vehicles	2	1	2	Put a sign "speed bump ahead" to alert emergency response drivers. Alert emergency response personnel of the airport vicinity of the piezoelectric speedbump.	1
8	Snow and ice buildup causing the speed bump to not generate electricity optimally	2	1	2	Spread De-icing salt during icy and snowy days	1

7. Sustainability Analysis

Sustainability is an integrated approach that focuses on addressing current requirements without jeopardizing the capacity of upcoming generations to satisfy their necessities. This section introduces the sustainability analysis for using piezoelectric speed bumps on airport roadways. The analysis here has been performed with the help of the EONS model, which was found on the Sustainability Aviation Guidance Association (SAGA) website. This model provides a way to assess sustainability holistically for airport operators (SAGA, n.d.). Each section of the EONS model has been analyzed with its effects on Airport sustainability. The following table gives a summary of the sustainability analysis.

Table 9

Sustainability characteristics of the Piezoelectric Speed Bump (EONS model)

Elements of EONS	Sustainability Impact	Positive (+) Or Negative (-) Effects on Airport Sustainability
Economic Vitality	Savings on non-renewable source of energy costs	+
	Electricity cost savings	+
	Long-term savings outweigh the costs for construction (10 years)	+
Operational Efficiency	Reduction in outage impacts from improved resilience	+
	Advantageous over a conventional speed bump	+
Natural Resources	Addition to renewable sources of energy	+
	Reduced carbon footprint	+
	Implementing recycling and waste management programs for piezoelectric materials	+
Social Responsibility	Establishing the public image of "Green Airport"	+
	Draws attention, increasing the level of traffic and airport operations	-
	Further promotion of sustainability in aviation	+

7.1. Economic Vitality

By implementing piezoelectric speed bumps, airports can reduce their reliance on conventional energy sources and achieve energy cost savings associated with electricity. Based on the benefit-cost analysis, it can be inferred that the proposed design has the potential to generate positive economic value for airports. Although there are upfront expenses associated with constructing the piezoelectric speed bumps, long-term savings over ten years can cover the initial construction costs. This aspect can significantly impact airport sustainability, resulting in greater economic viability and a reduced environmental footprint.

7.2. Operational efficiency

The proposed speed bumps offer the additional benefit of serving as backup power sources that can help address the issue of energy outages at airports. This can result in a decrease in the negative impacts of power outages on airport operations. Furthermore, piezoelectric speed bumps are advantageous over traditional speed bumps in terms of efficiency and practicality. This alternative solution offers improved utility and operational effectiveness, making it a compelling option for airport operators seeking to enhance their sustainability efforts.

7.3. Natural resources

While providing a backup power source and reducing energy costs, piezoelectric speed bumps can contribute to a cleaner and more sustainable airport energy supply. This will assist in reducing the airport's carbon footprint, a critical component of environmental sustainability efforts. Furthermore, by establishing recycling and waste management programs for piezoelectric materials, the airports can maximize the use of available materials, avoiding dependence on new materials or resources. This approach aligns with the circular economy principles, promoting resource reuse, recycling efficiency, and minimizing waste impact.

7.4. Social Responsibility

Implementing the proposed design will bolster the airport's image as a "green airport" that prioritizes aviation sustainability, which is becoming increasingly important in the aviation industry. By promoting eco-friendly practices and utilizing innovative piezoelectric speed bumps, airports can attract more environmentally conscious visitors and passengers. This could increase usage and traffic as individuals become more interested in supporting sustainable initiatives. The increased utilization of sustainable and renewable energy supply practices can promote the importance of environmental sustainability in the aviation industry, encouraging other airports to follow suit and adopt similar practices.

7.5. United Nations Sustainable Development Goals (SDGs)

The United Nations Sustainable Development Goals (SDGs) represent a universal and transformative agenda designed to address humanity's most pressing global challenges. Adopted by all 193 UN member states in September 2015, the SDGs provide a shared blueprint for peace, prosperity, and environmental sustainability by 2030. The following table gives SDGs addressed by the proposed design of Piezoelectric speed bumps.

Table 10

Sustainable development goals addressed through Piezoelectric Speed Bumps

Note. UN SDGs and the logos have been taken from the United Nations website.

SDG	Relevance To the Design
7 AFFORDABLE AND CLEAN ENERGY	• Provide a renewable and sustainable energy source. • Reduce the dependence on non-renewable energy source. • Mitigate the negative environmental impact associated with conventional energy sources
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	• Motivate the creation of new industries and the development of new infrastructure. • Encourage the innovative practices of renewable and sustainable energy
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	• Promotion of circular economy by converting existing vibrations into electricity generating • Reduce the need of new materials

8. Conclusions

Previous research has illustrated the potential of piezoelectric effects in generating electricity. However, limited research efforts have been made on the practical application of piezoelectric devices for harvesting energy in the ground transportation of airports, leading to a significant environmental challenge of energy recycling and reuse. In response, this study proposes the design of a piezoelectric speed bump to help airports overcome this challenge and achieve the goal of sustainability in aviation.

To evaluate the practicality and benefits of implementing the proposed piezoelectric speed bump design in various types of airports, this study conducted case studies at Dallas Fort-Worth International Airport, Indianapolis International Airport, and Akron Canton Airport. The findings indicate that the proposed design is economically feasible for airports and offers multiple benefits. The benefit-cost ratios of all three primary hub airports exceeded one, indicating that this design is financially viable for primary large, medium, and small hub airports, and has the potential for significant cost savings.

Furthermore, this research highlights that the electricity generated by the proposed piezoelectric speed bump design can significantly enhance the resilience of airports during energy outages, ensuring that operational efficiency is not impacted during emergencies. Implementing this proposed design is expected to promote aviation sustainability, providing a sustainable solution to energy harvesting and waste reduction. By doing so, airports can reduce their carbon footprint, enhance energy efficiency, and establish themselves as leaders in sustainable aviation practices.

Appendix A. Contact Information

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Appendix B. University Description

Purdue University, located in West Lafayette, Indiana, is a top public research institution founded in 1869. Known for its strong emphasis on STEM fields (Science, Technology, Engineering, and Mathematics), the university offers a variety of undergraduate, graduate, and professional programs across its ten academic colleges. With over 40,000 students and a vibrant campus life, Purdue attracts a diverse community of learners from across the United States and worldwide.

The university is renowned for its engineering and aviation programs, including the prestigious School of Aeronautics and Astronautics. Purdue has a rich history of producing accomplished graduates, including 25 astronauts like Neil Armstrong and Eugene Cernan. The university is also known for its cutting-edge research facilities, such as the Purdue Research Park and the Discovery Park, where faculty, students, and researchers collaborate on groundbreaking projects.

Besides its strong academic reputation, Purdue boasts a robust athletics program with its team, the Boilermakers, participating in the Big Ten Conference. The university offers various extracurricular activities and student organizations, creating a well-rounded and engaging student experience. Purdue's commitment to research, innovation, and excellence has made it a highly respected institution in the United States and around the globe.

Appendix C. Interaction with Industry Experts

Dr. Stewart W. Schreckengast – Dr. Schreckengast serves on the Graduate Faculty at Purdue University, where he leads undergraduate and graduate aviation safety and security classes. His applied research focuses on airport growth, safety management, and comprehensive security initiatives. With a deep understanding of FAA rules regarding airport development and safety management, Dr. Schreckengast has also contributed to the creation and execution of ICAO Annexes 1, 6, 8, 11, 13, 14, 17, and 19.

Mr. Alan Gonzalez - Mr. Gonzalez holds the position of Landside Manager at Dallas/Fort Worth International Airport (DFW). His past roles include Guest Transportation Assistant Manager and Ground Transportation Supervisor. He earned a Bachelor of Business Administration from The University of Texas at El Paso and a Master of Science in Aviation & Aerospace Management from Purdue University. Additionally, he has AAAE certification in Safety Management Systems. With his vast experience and education, Mr. Gonzalez is an excellent fit to oversee DFW's landside operations.

Mr. Guangshuai Huang – Mr. Huang is a graduate researcher in Civil Engineering at Purdue University. His research interest is the development of piezoelectric materials and sensors for civil engineering applications.

Mr. Yichen Zheng – Mr. Zheng is a consultant at Ricondo & Associates, Inc, now after receiving his master’s degree in science from Cornell University. He has a Bachelor of Science in aviation technology degree from Purdue University. His current focus is on the ground transportation of airports.

Mr. Jarod Klaas – Mr. Klaas is a Professional Engineer with nearly 30 years of engineering experience in the private and public sectors. He has been with the Indianapolis Airport Authority for 12 years and is the Senior Director of Planning and Development. Jarod leads the infrastructure rehabilitation and asset life-cycle planning initiatives and is responsible for implementing a $1 billion capital budget planning process. He oversees managing, designing, and delivering complex projects for the Indianapolis International Airport and five regional aviation facilities. Jarod is also a mentor and lecturer for local STEM students and a member of the Minority Engineering Program of Indianapolis (MEPI) Advisory Board.

Appendix E. Evaluation of the Educational Experience

Students' Questions and Responses

1. Did the Airport Cooperative Research Program (ACRP) University Design Competition for Addressing Airport Needs provide a meaningful learning experience for you? Why or why not?

The competition has been a significant learning experience for the team. There are three reasons why it was valuable for us. First, as team members, we were able to hold weekly meetings, which made us closer, and we got to know each other's personalities and strengths. Second, after coming up with an idea we agreed upon, we discovered that the concept does not have to be fixed and can change very differently from our initial hypothesis. This process resulted from discussions with the advisor, people from other participating teams, and experts in the airport industry. Third, we knew that it is essential to conduct research to make airports more sustainable. However, implementing these alternative energies has a rigorous research and development process. This did not stop us from curating this proposal, as we believe in the potential of piezoelectric technology.

2. What challenges did you and your team encounter in undertaking the competition? How did you overcome them?

We changed our ideas three times before finally coming up with our final design. At first, we were looking to find alternative usage of airport road traffic during less busy times. Still, then after discussions with several professors, the idea was changed entirely into proposing a device that can provide alternative energy for the airport building. At first, we wanted to design a "hamster wheel" that could produce electricity by using kinetic energy conversion and install them in the boarding areas of the terminals; however, after several discussions, we realized that the safety hazards were too high. We finally changed our idea into making a piezoelectric speed bump that will be installed on airport roads.

3. Describe the process you or your team used for developing your hypothesis.

First, we conducted background research on what kind of challenges the airport faces so it can perform better. After completing the study, each team member came up with their ideas. We discussed these ideas and finally came up with one idea we agreed upon. We then identified what questions we should answer before proceeding with that idea. For instance, does our vision address any of the competition challenges? Then, to answer these questions, we did background research on our assigned questions. Then we formulated a tentative explanation for these answers and refined our hypothesis by changing our ideas. Finally, after we came up with the final view, we tested it by conducting the benefit-cost, sustainability, and safety analyses. Once our belief satisfied the study, we revised it and finalized the hypothesis.

4. Was participation by the industry in the project appropriate, meaningful, and valuable? Why or why not?

Contacting industry experts was very appropriate, meaningful, and valuable. Our interviews allowed us to consider airport needs, the design of our piezoelectric speed bump, and places where the speed bump can be installed. During our interview with Mr. Alan Gonzalez from DFW airport, we received many considerations we did not anticipate before talking with him. Our interview with the Indianapolis Airport team was also very insightful because they gave us the car traffic flow at the airport. We also interviewed a piezoelectric specialist, giving us initial insight into how exactly a piezoelectric transducer can produce electricity.

5. What did you learn? Did this project help you with the skills and knowledge you need to be successful in entering the workforce or pursuing further study? Why or why not?

We learned many things from this project. The industry interactions with the experts trained us on how to communicate in a professional setting, giving us insight into how we should conduct ourselves in the workforce. It also gave us an insight into an airport's priorities and needs. Since airports will always find ways to improve safety, sustainability, and operations efficiency, pitching our idea to them was welcomed with positive reviews. This project can potentially be a dissertation topic for further research.

Faculty Questions and Responses

1. Describe the value of the educational experience for your student(s) participating in this competition submission.

Because the teams choose their challenge areas, they are more invested in the outcome and dedicate much time to the projects. Many of these students make contacts that will be a resource throughout their careers. The students gain more value by applying newly learned design and sustainability skills to a project based on real airport needs. While they know theoretical information, the learning that occurs through team and expert interactions cannot be easily replaced.

2. Was the learning experience appropriate to the course level or context in which the competition was undertaken?

This competition package is one of the choices for a project in a graduate-level Aviation and Aerospace Sustainability course. The course level and context are appropriate and famous for project types.

3. What challenges did the students face and overcome?

The team formed quickly and began searching for experts to contact. While the team changed design concepts as they learned more about airports and piezo-electric technology, they never gave up on themselves and showed remarkable resilience. Previous coursework had yet to prepare them for this project. They began working with each other and contacting airport experts. This design is in a spring semester course. I am proud of how this team met challenges and developed new solutions.

4. Would you use this competition as an educational vehicle in the future? Why or why not?

I definitely will continue to use this competition as an educational vehicle. The knowledge the team gains in 12 weeks is irreplaceable through readings and shorter projects.

5. Are there changes to the competition that you would suggest for future years?

I would add sustainability as an aspect of the project that should be addressed because this issue is challenging and is becoming requested by more communities and other stakeholders.

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