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Investigation on the Selection of Piezoelectric Materials for the Design of an Energy Harvester System to Generate Energy from Traffic

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***Abstract*— This article investigates various existing piezoelectric materials and the structures of the piezoelectric transducers. Then the article explores the idea of using the electricity generated using piezoelectric elements and compares the energy requirement of this era of power electronics. Then, the most compatible piezoelectric transducer for producing sustainable energy from the road traffic was analyzed using the finite element analysis. This included the various structural designs of the piezoelectric harvester designs to determine the performance of the piezoelectric material. The structures focused on this article are namely the Pile type, Multilayered, Thunder, Bridge, Cymbal and Moonie piezoelectric generators. The finite element analysis was also used to categorize the chemical behavior of various piezoelectric elements. After which, the article focuses on the two main types of implementation of the piezoelectric generators on the road to produce the sustainable form of energy. This energy is captured by harnessing the wasted vibration and kinetic energy due to the moving vehicles on the surface of the road. These two main types of implementation include the cantilever beam type implementation such as the bimorph with a tip mass, which requires a fixed support. The other implementation was based on embedding the piezoelectric transducers into the road to harvest the strain and kinetic energy due to the vehicles directly.**

***Index Terms*— Energy, Piezoelectric, Performance, Sustainability, Transducers**

I. INTRODUCTION

The piezoelectric effect was initially found by Curie. The word 'piezo' on its own implies pressure which was derived from the Greek, while electric alludes to electricity or power. This form of electricity is produced when the precious stones such as the crystals with a piezoelectric nature are pressurized, an electric field is produced. Curie found that voltage can be seen when the crystals are squeezed, this is known as the piezoelectric effect. These electric fields were produced in entirely small quantities and were not exceptionally helpful until the *LiTiBa* ceramic was found. After the presentation of the *LiTiBa* ceramic, the performance of piezoelectricity was enhanced and was generally utilized as electric devices such as sensors and actuators. A standout amongst the most well-known zones is resonators.

Piezoelectric material works both ways. The electric power can be utilized to produce mechanical force or deflection and can create electric power due to the mechanical force or deflection. With a typical piezoelectric ceramic, the deflection with an electrical energy input is almost invisible to the naked eye. To expand the diversion of deflection, a stacked device, or bender device, is utilized. In the sensor application, conventional diaphragm designs or sometimes spring mass damper designs are utilized.

Hence, this article presents the various analyses of the existing piezoelectric elements to qualify the most suitable element required for the generation of energy from traffic considering various factors such as the spring mass damper, mass of the load, Curie temperature and the environmental conditions. This article reflects the reason to why *PZT*-5H is the most adaptable material in structuring of the road energy harvesters. Then the article presents two main types of implementation include the cantilever beam type implementation such as the bimorph with a tip mass, which requires a fixed support. The other implementation was based on embedding the piezoelectric transducers into the road to harvest the strain and kinetic energy due to the vehicles directly.

II. FUTURE OF PIEZOELECTRICITY

Before the invention of piezoelectric energy harvester devices, the piezoelectric material were purely used to measure the voltage generation and used in the application of sensors and actuators.

Until recently, the piezoelectric generator (PEG) was not used as a source of power generation because of its small power generation. Modern and advanced electrical devices are becoming compact in structure and require smaller amounts of electrical energy. In this era, individuals are wearing electronic devices similar to a PC such as the iWatch from apple and their mini portable iPads. In the near future, these wearable computers will not require much power. Fig. 1 addresses the energy requirements of electronic devices.

With current innovation, the power necessity for low power microprocessors is just around 1mW [1], and is conceivable with piezoelectric energy generators known as the PEGs. Hypothetically, humans can produce adequate electrical power with ordinary movements using viable methods of utilizing energy harvesting devices, individuals won't require batteries to operate portable electrical devices.

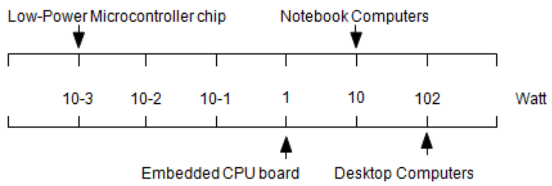

Fig. 1: Energy Requirements of Electronic Devices

This technology will serve in favor for patients who require an operation for a battery transplant. For instance, walking can generate 5.0-8.3 W, while breathing creates 0.2 W of

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power [1]. Power generation demonstrates the gathering of electrons at a useful electric potential. Free electrons, which can be gathered, are discovered all over within conductive material. There are almost infinite numbers of free electrons in even small sizes of conductive material. In common power generation, power is not actually generated, but rather converted in to electrical energy from other sources of energy.

III. Materials

Piezoelectric materials are classified into two main types; namely the natural occurring elements and the synthetic elements such as crystals, polymers, and ceramics. These materials are further classified into their structural types such as the thin film, ceramic plates, piles and so on. Piezoelectric effect is observed in various materials such as the quartz, tourmaline and Rochelle salt which are naturally occurring piezoelectric elements. The man-made chemically obtained polycrystalline ferroelectric materials tend to produce more electricity than naturally occurring monocrystalline (quartz, tourmaline and Rochelle salt).

Polycrystalline ferroelectric ceramics such as *barium titanate* (BaTiO3) and *lead zirconate titanate* (*PZT*) exhibit larger displacements when deformed or induce larger electric voltages when compressed. *PZT* piezo ceramic materials are available in many variations and are most widely used for actuator or sensor applications. Special doping of the *PZT* ceramics with *Ni, Bi, La, Nd* or *Nb* ions make it possible to specifically optimize piezoelectric and dielectric parameters. *PZT* is a type of piezoelectric material commonly known as lead zirconium titrates. These piezoelectric ceramics convert kinetic energy to electrical energy and they have an advantage over the other means of energy harvester system that converts kinetic energy to electrical such as turbines. The PEGs doesn't have a complex system in comparison to the turbine and the structure of the piezoelectric generator will be discussed in the next subsection. It is noteworthy to consider that the PEGs can be packages in a closed form and it requires no fuel or rotating shafts in terms of powering the generator to convert energy.

In previous studies, the researches have conducted research on various loading conditions, such as impact and response for the piezoelectric generator and they claim that the generators lose their performance under the resonance forcing condition [2]or the impact forcing condition[3,4,5] .

For numerical counts, an incredible measure of examination and research was carried out. The constitutive mathematical statements set up the electrical and mechanical coupling in the *PZT* ceramics [6] and multiple layered cantilever beams equations for actuators [7, 9, 10] and sensors [8].

It ought to be called attention to that while there are numerous piezoelectric materials from which a piezoelectric generator (PEG) can be configured, but for the proposed application, the *lead zirconate titanate* (*PZT*) piezoelectric material is considered due to the following reasons addressed in the following subsections.

A. Characteristic properties of Synthetic Piezoelectric Elements

The *lead zirconate titanate* (*PZT*) material was the most robust commercially produced crystal amongst the other naturally occurring crystals. The piezoelectric materials evaluated in this work are *PZT-4*, *PZT-5A* and *PZT-5H* ceramics. These materials were all commercially produced. The properties of these materials were analyzed and measured between -150 and 250°C. Table 1 presents the definition of symbols used in the determination of piezoelectric coefficients.

B. Characteristic properties of Synthetic Piezoelectric Elements

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Table 1: Definition of Symbols

Symbol	Definition	Units
d_{31}	Transverse Strain Constant	m/V
d_{33}	Extensional Strain Constant	m/V
D	At constant electric displacement	superscript
E	At constant electric field	superscript
f_m	Frequency of minimum impedance	Hz
f_n	Frequency of maximum impedance	Hz
g_{31}	Transverse voltage constant	V m/N
g_{33}	Extensional voltage constant	V m/N
k_{31}	Transverse coupling coefficient	
k_{33}	Extensional coupling coefficient	
k_{eff}	Effective electro-mechanical coupling coefficient	
k_p	Planar coupling coefficient	
K_3	Dielectric constant	
L	Length	m
S_{11} ,S_{33}	Elastic compliance constants	m/N
ε_0	Permittivity of free space, 8.85 x 10	F/m
ρ	Density	kg/m

Fig. 2 depicts the dielectric constant versus temperature curve. The materials exhibited the lowest dielectric constant values at -150°C, and the dielectric constant value increased with the increase in the temperature as observed. The dielectric constants of the *PZT*-4 and *PZT*-5A ceramics were linearly proportional to the temperature. The characteristic curve neither possessed Curie point in the temperature range between -150 to 250°C. However the *PZT*-5H material exhibited Curie points within the range. The *PZT*-5H ceramics possessed a T value of 180°C at each frequency. At that instance, the temperature of the maximum dielectric constant was observed to increase from 72 to 91°C while the frequency ranges from 100 Hz to 100 kHz.

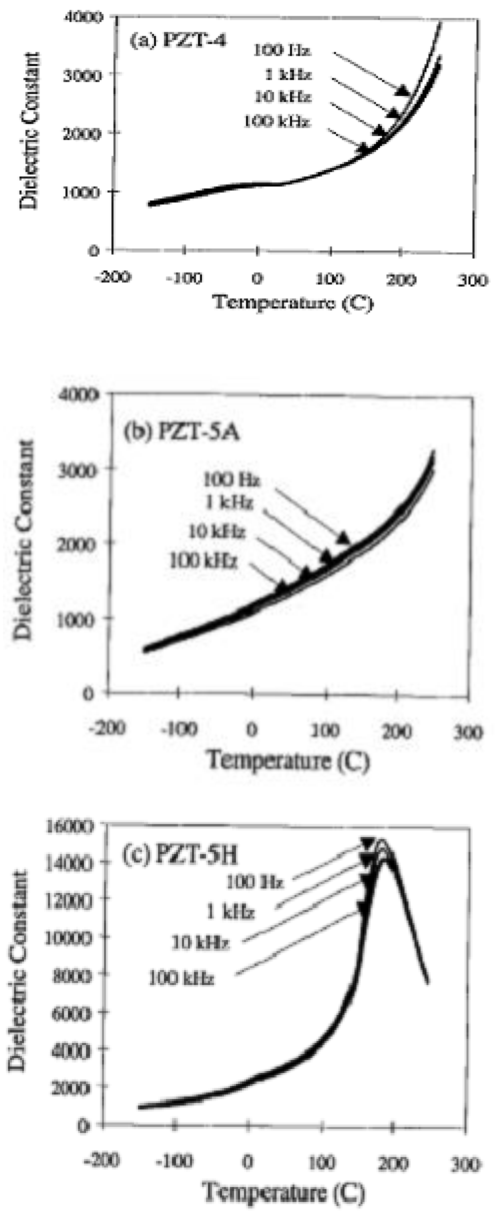

Fig. 2: Dielectric Versus Temperature curve for: (a) *PZT*-4 (b) *PZT*-5A (c) *PZT*-5H

Moreover, the dissipation factors for each material were also found to be dependent upon both the temperature and measurement frequency. It is noteworthy to note that *PZT*-5H piezoelectric ceramics exhibited maximum tan δ (dissipation factor) values at each measurement frequency which correspond to their respective Curie points. *PZT*-5H ceramics exhibited the highest piezoelectric properties (i.e., k_{eff}, k_p, $|d_{31}|$, and d_{33}) at room temperature, followed by the *PZT*-5A and *PZT*-4 materials, respectively. When cooled to -150°C, the k_{eff} and k_p values of each composition remained relatively constant. The$|d_{31}|$ and d_{33} values for *PZT*-4 also remained relatively stable over this temperature range. The d constants for the *PZT*-5A and *PZT*-5H ceramics, however, decreased to approximately 50% of their room temperature values when cooled to -150°C. When heated to 250°C, the electro-mechanical coupling coefficients of *PZT*-4 and *PZT*-5A decreased from their room temperature values, whereas the d constants for these materials increased over this temperature interval. The properties of the *PZT*-5H specimens exhibited similar trends when heated above room temperature. However, in this instance the specimens no longer exhibited measurable resonances above 170°C, thereby indicating that the specimens had been thermally de-poled.

Due to these advantages over other piezoelectric elements, *PZT*-5H material was the most appropriate element to use in designing of the piezoelectric energy harvester.

IV. Method

A. Structure of Piezoelectric transducers using PZT piles

From the study given in [12] where the finite element analysis was performed to determine the structure and the material to be used to design a piezoelectric transducer. It was found that the man made *PZT*-5H element was appropriate as it exhibits highest piezoelectric property from 25° to 170° which is well within the curie temperature and it was practically proved that the design of piezoelectric transducers from the study given in [12] can yield up to 150kW/h per lane per kilometer. The analysis performed in [12] for seven typical transducers were examined by the means of finite element analysis.

On performing FEM, the number, shape and the $V_{potential}$ of the *PZT* piles were determined to structure the efficient piezoelectric transducer and the their results confirmed that the *PZT* piles and multilayer, concave plates of brasses that makes up the transducer to bridge the piles together has the potential of working under the asphalt pavement environment for certain. In [11], it was recommend to use about 8-16 *PZT* piles for 0.04 m^2 (A_c) pavement area where these *PZT* piles were arranged between the circular steel plates as seen in Fig. 3. The round shape of the *PZT* piles was to ensure the reduction of stress concentrated in an area where as the multi-layering was recommended to decrease the electric potential of the generator. Moreover, for future references, these generators can be improvised as sensors that are within the pavement to monitor the traffic, pavement stress and the temperature.

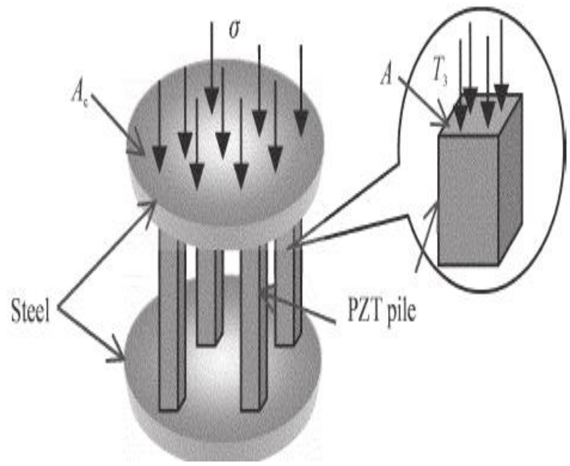

Fig. 3: Piezoelectric Transducer Structure

The number of *PZT* piles required was deduced from the following relationship curve from [11] which is dependent on the vertical displacement of the pavement.

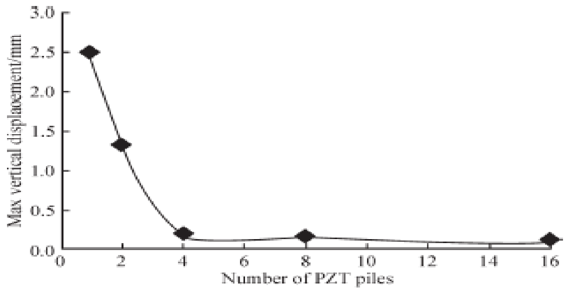

Fig. 4: Displacement versus Number of *PZT* piles

Moreover, the shape of the *PZT* piles were analyzed using FEM and the three main shapes such as the square shaped *PZT*, circular shaped *PZT* and the hexagonal shaped *PZT* were considered and produced the following results.

Table 2: Stress for Various *PZT* shape

Maximum stress/MPa	Square	Circle	Hexagon
Compressive stress	2 635	1 002	1 406
Shear stress	675	440	556

Since, the round shaped *PZT* pile produced the least concentrated stress, it was recommended in structuring the piezoelectric generator.

Further analysis based on multi layering of the *PZT* material was conducted in [12] and from the piezoelectric equation. It was delivered that the electric potential between two polarization surfaces increases linearly with the thickness of *PZT* and external stress. The electric potentials of *PZT* with different thickness at various T are listed in Table 3.

Table 3: Electric Potential for Various *PZT*'s

External Stress T/MPa	Electric potential/V			
	t= 0.1 mm	t= 1 mm	t= 10 mm	t= 100 mm
10	20	197	1 971	19 708
20	39	394	3 942	39 415
50	99	985	9 854	98 538
70	138	1 380	13 795	137 953
100	197	1 971	19 708	197 075

It was concluded that, huge electric potential will be produced for the thicker *PZT* under larger external stress. However, it was difficult to deal with large electric potential for pavement energy harvesting and outputting. So the external stress and thickness of *PZT* was restricted to have a balance. A multilayer structure was suggested for pavement energy harvesting, as shown in Fig. 5, which has reasonable size and very thin single layer. (< 0.1 mm).

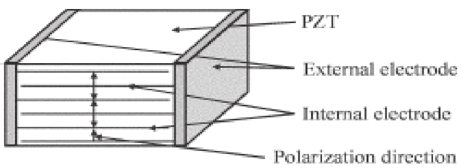

Fig. 5: Multilayer Structure of *PZT*

The multilayer structure has the same performance as normal *PZT* pile, and low electric potential (< 200 V) given by equation (1).

$$V = g_{33} T_3 t \tag{1}$$

However, in the pavement, the stress is mainly from the vertical vehicle load. So the vertical stress is considered as the major external stress for the *PZT*. Assuming the 3rd axle for *PZT* is in vertical direction, then for pavement energy harvesting is given by Equation (2).

$$U_E = \frac{1}{2} d_{33} g_{33} T_3^2 At \tag{2}$$

Where U_E is the energy harvested from the pavement for single *PZT*; T_3 is the stress on the top of *PZT*; A is the area of *PZT*, t is the thickness of *PZT*. From Equation (2), we know that larger U_E will be obtained from larger stress. In order to magnify the stress on the *PZT*, a structure shown as Figure 5 was designed in [12]. The stress on those *PZT* piles can be calculated by Equation (3) and Equation (4).

$$T_3 = \frac{\sigma A_C}{nA} \tag{3}$$

$$A_c = \frac{\pi (h+d)^2}{4} \tag{4}$$

Where A_c is the effective load area for calculation as shown in Fig. 6; σ is the vertical stress in the pavement; n is the number of *PZT* piles used in one generator; h is the embedding depth of generator; d is the diameter of one tire print.

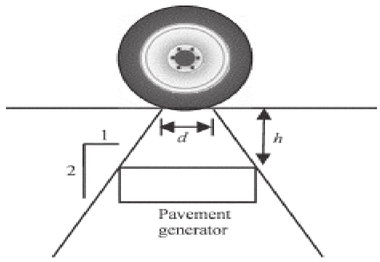

Figure 6: Effective Load Area

Moreover, it was concluded that the energy increases with the decrease of *PZT* area that is depicted by Fig. 7. However, the stability and strength of the generator decreases with the area.

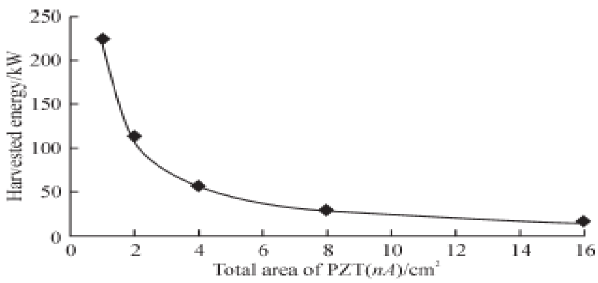

Fig. 7: Harvested Energy versus *PZT* area

B. Comparison of Various Structures of the Piezoelectric Transducer

In addition to the structure of the piezoelectric generators, the study from [18] was assumed that the road structure was elastic as it was necessary to determine the stress and deformation caused by the vehicle load to the surface using softwares such as BISAR, Openpave or finite element analysis. It was found that a truck of 6 tires in total (1+1 type) and one rear axle produced a contact stress between the tire and the asphalt pavement of 0.7 Mpa when the load was considered to be uniformly distributed in a circular area. Fig. (8) demonstrates the surface displacement under the center of the tire for a typical pavement structure with the following parameters tabulated in Table 4.

Table 4: Parameter Structure for Load conditions

Truck type	Truck sketch	Tire load/kN	
		Front	Rear
1+1		30	25
1+2		30	22.5

Layer	Thickness /m	Elastic Modulus /MPa	Poison ratio
Surface layer	0.04	1 800	0.35
Binder layer	0.11	1 500	0.35
Base	0.4	600-3 000	0.3
Sub-base	0.15	300	0.4
Subgrade	-	40	0.4

In Fig. (8), it can be clearly seen that vertical displacement of the *PZT* decreases with the increased strenght of the the road structure represented using the modulus of the material used as the base that forms the road structure. Moreover, the structural layers of the road can be observed in Fig. (9).

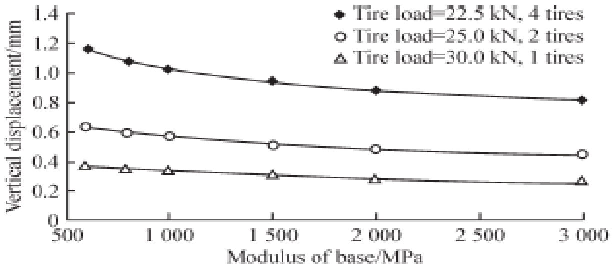

Fig. 8: Surface Displacement under the centre of the tire with various base Modulus

However, the measure of potential mechanical energy in the asphalt road is equivalent to the work done by the vehicle tires, which can be estimated using the equation given by,

$$W = \sum_{i=1}^{n} F_i D_i \tag{5}$$

Where W is the potential energy in asphalt road (J); F_i is the load for each tire (N); D_i is the maximum displacement under each tire (m); n is the number of tires of the vehicle. The placement of the transducers that were directly placed into to the pavement is shown in Fig. 9.

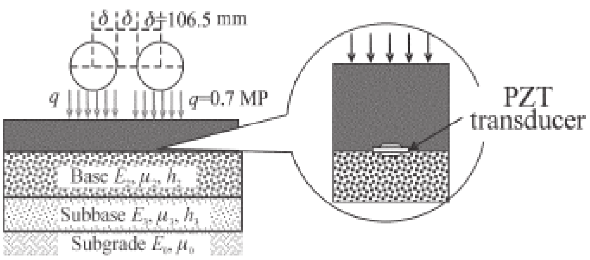

Fig. 9: Placement of the transducer on to the road

The performance of transducers was evaluated by finite element analysis as evaluated in the previous sections. However, when the tires are under uniform stress of a value that approaches 0.7 MPa, the efficiencies of the transducers are assessed by the electromechanical coupling factor k and the energy transmission coefficient λ_{max} In the meantime, the coupling performance with asphalt pavement was likewise considered. The comparing results of existing transducers such the Multilayer [13], Moonie [14], Cymbal [14], RAINBOW (Reduced and Internally Biased Oxide Wafer) [15], THUNDER (Thin Layer Unimorph Ferroelectric Driver and Sensor) [16], Bimorph, MFC (Macro-Fiber Composite) [17] etc. as are listed in Table 5. However, none of them were specifically designed to accommodate the asphalt road structure.

Table 5: Results Comparing Transducers

Transducer	k	λ_{max}	U_e/mJ	Stiffness
PZT pile	0.75	0.282	0.03	High
Multilayer	0.75	0.282	0.03	High
THUNDER	0.74	0.237	43.38	Low
Bridge	0.29	0.057	1.13	Medium
Cymbal	0.25	0.043	0.49	Medium
MFC	0.24	0.029	0.000 1	Very low
Moonie	0.23	0.012	0.012	Medium

They demonstrate that *PZT* pile and Multilayer have the most noteworthy factor, *k* and λ_{max}, which indicates that they have high ability to convert stress to electric energy and output the energy. Cymbal and Bridge are also suitable for their reasonable *k*, λ_{max} and medium stiffness. However, the energy level of those transducers is very low. They should be improved for further application.

Moreover, while considering single lane road of one kilometer highway and the number of truck volume in an hour to be 600, the potential energy in each lane produced by the truck reaches up to 150 kW in one hour as appears in Fig. 10 [11].

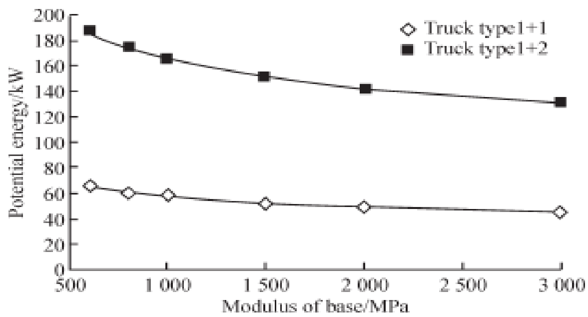

Fig. 10: Potential Energy at various Load conditions

In Fig. (10), it can be clearly observed that the truck with more area of contact with respect to the piezoelectric transducer, i.e truck type (1+2) which has a pair of tires in the front and 2 pairs for the rest of the vehicle length produces almost double the amount of potential energy per kilowatt.

However, the total energy harvested by the means of piezoelectric generator embedded directly on to the pavement was only able to produce a small amount of energy output as the generators produce significant amount of voltage and very minimal amount of current that limits the output energy harvested. Therefore, these transducers were recommended to be placed beneath the surface of the pavement as seen in Fig. 11 at a position level of 5 cm below the road surface; as the placement of the piezoelectric transducer also affects the energy production. In [11] a prototype pavement was designed and developed using the *PZT* piles that essential increased the production of the harvested energy where the generator can harvest more than 50kW/h energy from the pavement under heavy traffic conditions.

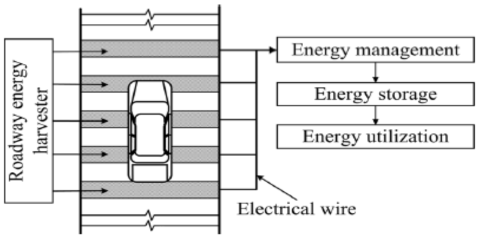

Fig. 11: Overall View of Laying out piezoelectric Energy Harvester

As seen from Fig. 11, these transducers are linked together which is then passed through the full bridge rectifier, boost converter and then an inverter. This was done to amplify the power produced for transmission purposes to ensure minimum power losses.

C. Formulation of Pavement Structure:

However, in this study these transducers comprise of piezoelectric elements. In order to study how the piezoelectric transducer was designed, first the analysis of what type of piezoelectric material is suitable for this form of implementation was considered and discussed in the earlier section. It was justified that the *PZT*-5H was the most appropriate material on designing an energy harvest design system for the application of generating energy from the moving traffic and the road after considering the various piezoelectric elements that exists.

This form of implementation was achieved by altering the foundation structure of the pavement such that it behaved like a plate resting on the Winkler foundation. This methodology was discussed in [18] that deals with the classic plate theory based on Kirchhoff's love plate theory and navies solution in conjunction with Fourier analysis, Cauchy's residue theorem and so on. In order to deduce the deformation of the pavement, the governing differential equation of the pavement is denoted by Equation (6) that was obtained according to the Kirchhoff's love plate theory [19] or commonly known as the classic plate theory.

$$D\,\nabla^4\omega(x,y,t) + \rho h\frac{\partial\,\omega(x,y,t)}{\partial\,t^2} + K\omega(x,y,t) = F(x,y,t) \tag{6}$$

Where K is the modulus of the subgrade, ρ is the density, and t is the time. The flexural rigidity of the pavement D is given by

$$D = \frac{E\,h^3}{12(1-\mu)} \tag{7}$$

Where E is Young's modulus, μ is the Poisson's ratio, and h is the thickness of the pavement and the fourth order displacement gradient is addressed by the following equation with the Winkler foundation is represented by the second and the third term of Equation 8.

$$\nabla^4\omega(x,y,t) = \left[\frac{\partial^4 w(x,y,t)}{\partial x^4} + 2\frac{\partial^4 w(x,y,t)}{\partial x^2\partial y^2} + \frac{\partial^4 w(x,y,t)}{\partial y^4}\right] \tag{8}$$

Incorporating Equation (6) and (8) in the piezoelectric equation given by Equation (9) [12] estimates the power produced in one particular piezoelectric transducer unit.

$$C_0\frac{dV(t)}{dt} + \frac{V(t)}{R} = \frac{dQ(t)}{dt} \tag{9}$$

Moreover, this form of implementation is better than the bimorph structural implementation for the following reasons:

- The output power increases with the decrease in
    - The condition of the road structure, and
    - Smaller bridges span length.

Since, this form of implementation requires fixed support with a tip mass, the power produced is exponential related to the load impact. As the system oscillates to produce displacement within the piezoelectric material, the settling time of the oscillating system will have an impact on the power generation. The following graph represented using Fig. 12 and 13 , provides the nature of power generation in a bimorph cantilever beam structured piezoelectric energy harvester.

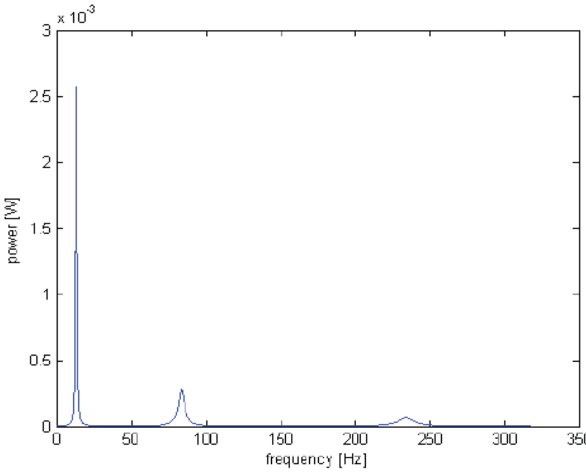

Fig. 12: Power versus frequency

Then the following graph shown in Fig. 13 represents the power generated using various resistance values after incorporating the design structural displacement value into the piezoelectric equation represented using Equation (9).

The graph obtained depicts various power generation curves at various load conditions. The graph represented in green was computed at 10 kΩ, similarly the blue and the red curve was obtained at 149 kΩ and 150 kΩ respectively.

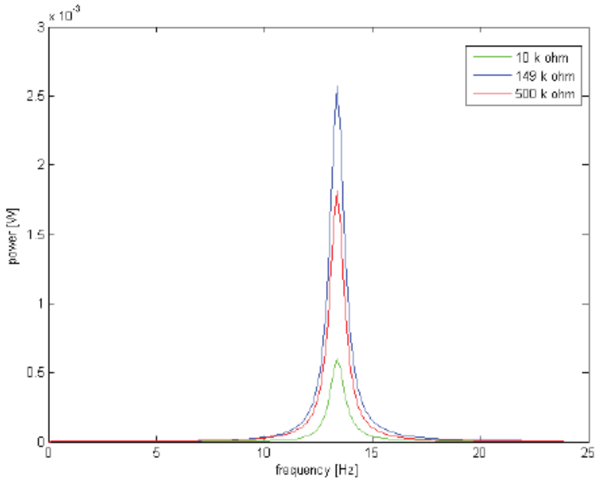

Fig. 13: Power generation at various resistance values

V. Conclusion

After analyzing various piezoelectric materials for the purpose of designing the appropriate piezoelectric transducers for harnessing the wasted energy from traffic; it was found that *PZT*-5H (*lead zirconate titanate*) was the most robust material amongst the other synthesized elements with a curie temperature relatable to the outside temperature. *PZT*-5H also exhibited high tolerance to the heavy load (tons) applied on them with amicable piezoelectric properties. Moreover, the piezoelectric transducer design was found to have 8-16 *PZT* pile structure placed between two steel plates having 0.04 m2 in area after performing the finite element analysis on the *PZT*-5H material. Furthermore, it was concluded that the dynamic response of the road with piezoelectric transducers embedded directly beneath the surface of the road was better than the bimorph structure as the bimorph structures require some settling time before transitioning (oscillating) the next vibration. Finally, the method to obtain the power produced was described using the piezoelectric equation.

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