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Power generation potential of piezoelectric harvesters and its application in auto estimation of traffic parameters

Abdullah Al Zahid[a], Shahriar Rifat[b], MD. Shamsul Hoque[a,b,*]

[a]Department of Civil Engineeging, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh
bDeparetment of Eleectrical & Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

Abstract

As a very prospectus emerging economy of the world and with is current excellent growth wave the need for sustainable supply of energy for Bangladesh is second to none. The pressure exerted by numerous running vehicles of the pavements are dynamic and nature and that can effectively be harnessed by using energy harvesters like piezo elements.

Considering the typical vehicle wheel width and the depth of pavement, we designed energy harvester of piezo elements with a volume of 44*31*3 cm3 contained 44 piezoelectric elements. To optimize the harvester, the circuit was rectified to the output current from each piezoelectric element and connected the elements in parallel to avoid phase difference interruptions. Analyzing the road vertical stresses below the pavement depth of 5 centimeters (considering depth of surface course of 2 inch), under vehicle speeds of 70 km/h & considering the relevant frequency of the national highway N-1 of Bangladesh, we applied the similar compressive load on the energy harvester device and calculated the output of electrical power of the elements for one-kilometer length of the roadway. This the first time we have tried to show the possible outcome of it and how the outcomes can be used for auto estimation of traffic parameters, such as, vehicular load estimation, vehicle counting & vehicular speed metering.. Side by side, attempt has been made to study on effectiveness of different geometric patterns for exerting pressure on piezoelectric elements for harvesting maximum amount of energy. Along with these issues, finally, the cost benefit analysis and financial prospect of this unique device (for next 10 years) in the current scenario of Bangladesh is discussed.

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Keywords: Piezoelectric roads; Piezoelectric technology; Energy harvesting roads; Renewable energy; Auto estimation of traffic parameters

1. Introduction

Energy harvesting, or energy scavenging, is a process that captures unused ambient energy that would otherwise be lost as heat, light, sound, vibration, stress or movement. The transportation system of Bangladesh consists of about 3,790.861 kilometers of national highways [1]. These roadways are exposed to energy in the form of vehicle vibrations,

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traffic loading strains or stresses, and thermal gradients that can be harnessed. These resources can be potentially converted into usable energy such as electric power. The concept of energy conservation and development of alternative energy resources becomes urgently needed due to the high cost and environmental impact associated with fossil fuels.

This energy can be harvested by multiple ways but the most prominent way is by using piezoelectric disks. The piezoelectric materials are capable of generating electric voltage due to the application of loading stresses and vibrations. The piezoelectric is activated if the load application oscillates with time. As the magnitude of load changes with time, the piezoelectric will polarize to form two distinct surface charges. These charges are the source of the electric voltage [2].

The piezoelectric materials are extensively available in several shapes and forms. Accordingly, they could be widely used to harvest vibration and stress energy caused by vehicles on roadways. The Bangladesh government has developed a policy to meet 10% of the country's electricity demand by 2020 [3]. To meet this increasing demand of electricity more work needs to be done for Bangladesh.

Also, so far, the research in such field was focused on only developing the piezoelectric device and how the energy can be maximized, but not on finding the use of it for different purposes as well as showing the informative values that can be added through it in research sector. So, this is the first time we have tried to show the possible outcome of it and how the outcomes can be used for auto estimation of traffic parameters, such as, vehicular load estimation, vehicle counting & vehicular speed recognition.

1.1. Objectives of the Present Study

The overall objective of the research work is to develop a stress induced piezoelectric energy harvesting device for flexible pavement and explore the potential of that device in terms of feasibly, financial sustainability and use in vehicle counting & vehicular load estimation. So, the precise objectives of the present study are expounded upon as below –

1) To explore the potential of self-made piezoelectric device designed with locally available materials and piezo elements.

2) To calculate the amount of harnessed electrical power from the invented device with proficiently and capture the loss of energy as much as possible.

3) To compare the result of the harnessed energy cost (fixed cost & maintenance cost) with conventional cost of electricity.

4) To determine the feasibility and financial prospect of the device by comparing the results & finding the ways of improvements.

5) To analyze the result and finding a relationship with the applied load and generated electricity by the device by quantitive analysis of the results.

6) To compare the results with vehicular load on the roadways and forming a relationship of Load-Electricity co-relation of the device. Thus developing a method to predict load associated with the vehicles moving on the roadway by analyzing the amount of electrical energy produced by the device using (Weigh-In-Motion) principle.

7) To develop a way of vehicle counting by analyzing the test results found from the generated electricity data and load relationship and showing the interpolating relation with mathematical equation.

8) To find out the overall prospect of this unique device of locally made materials by considering the National Highway lengths and loads implied on them in the perspective of Bangladesh. Also to help the government to achieve

the target goal of reducing the dependency of fossil fuel and increase the use of renewable and green energy sources by harvesting lost energy from roadways.

Besides of those major objectives some minor objectives of the thesis work are also compounded as below –

1) To analyze the different patterns of piezo-element setting on the device and finding the most efficient geometric design.

2) Understanding the potential of 4-5-4-5-4 design of piezo elements perpendicular to the roadway in harnessing energy.

3) To contribute green energy from the environment and reduce the dependency over fossil fuels and other non-renewable energy sources.

4) To use the Lost energy on the roadway surface and utilize the best out of it. Thus finding a way to support the government in reducing electricity generation cost.

The possible outcome of this research is to explore the uses of piezo-electric energy harvesting device and the overall feasibility analysis. This could be a very helpful research for future improvements and pathway to the implementation of this device in Bangladesh. It can help us to reduce the scarcity of electrical energy globally and reduction of CO2 as electric energy is one of the cleanest energy.

2. The device setup

Considering the typical vehicle wheel width and the depth of pavement, we designed energy harvester with a volume of 44*31*3 cm3 contained 44 piezoelectric elements. To optimize the harvester, the circuit was rectified to the output current from each piezoelectric element and connected the elements in parallel to avoid phase difference interruptions. Analyzing the road vertical stresses below the pavement depth of 5 centimeter (considering depth of surface course 2 inch), under vehicle speeds of 70 km/h & considering the relevant frequency of the national highway N-1 of Bangladesh, we applied the similar compressive load on the energy harvester device in laboratory and calculated the output of electrical power of the elements.

Figure 1 : Setting the device in the laboratory

3. Data Collection & Results

Analyzing the road vertical stresses below the pavement depth of 5 centimeters (considering depth of surface course 2 inch), under vehicle speeds of 70 km/h & considering the relevant frequency of the national highway N-1 of Bangladesh, we applied the similar compressive load (0-80KN) on the energy harvester device in laboratory and calculated the output of electrical power of the elements. Data collection was the primary part of the experiment and

was collected by applying pressure on the device under laboratory with a range of 0, 1, 2, 3, 4, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80 KN load on 9 different positions.

By applying such load on the device, the following are the results found –

Table 1 : The values of voltage and current

LOAD	Average Values of Voltage (V)	Average Values of Current (mA)	Power Values (mW)
80	14.04	3.28	46.11
75	13.99	3.22	45.14
70	13.94	3.15	44.02
65	13.89	2.88	40.11
60	13.70	2.70	37.09
55	13.44	2.48	33.46
50	13.12	2.41	31.69
45	12.69	2.27	28.87
40	12.63	2.11	26.70
35	12.10	1.84	22.35

LOAD	Average Values of Voltage (V)	Average Values of Current (mA)	Power Values (mW)
30	11.65	1.67	19.52
25	11.12	1.55	17.28
20	10.47	1.33	13.98
15	10.08	1.16	11.72
10	9.741	1.09	10.68
5	9.04	0.90	8.18
4	7.90	0.82	6.53
3	6.76	0.65	4.44
2	5.67	0.53	3.01
1	3.33	0.30	1.03

4. Relationships Of Load – Current – Voltage Values

The data interpolation for the overall averaged data is done by Bessel Spline interpolation as it has better fitting quality than cubic spline and linear interpolation. The interpolating equations are generalized from trend line tool of excel using polynomial of order 6.

4.1 Using Current value

When the load applied in larger scale, the value of the current generated increases accordingly and when the applied load is decreased, the value of generated power also decreases. From the data setting we found the equation –

$y = 0.1826x^6 - 3.5197x^5 + 25.132x^4 - 80.952x^3 + 123.55x^2 - 58.332x + 5.437$

The regression value is : $R^2 = 0.9992$

4.2 Using Voltage Value

The same procedure can be followed to show the relationship between loading and the voltage data –

$y = 0.0008x^6 - 0.034x^5 + 0.5241x^4 - 3.7412x^3 + 12.274x^2 - 15.307x + 4.3224$

The regression value is : $R^2 = 0.9922$

4.3 Using Power Value

The same procedure can be followed to show the relationship between loading and the power data –

$y = 2E\text{-}07x^6 - 3E\text{-}05x^5 + 0.0016x^4 - 0.0447x^3 + 0.6538x^2 - 2.6643x + 3.5351$
The regression value is : $R^2 = 0.9976$

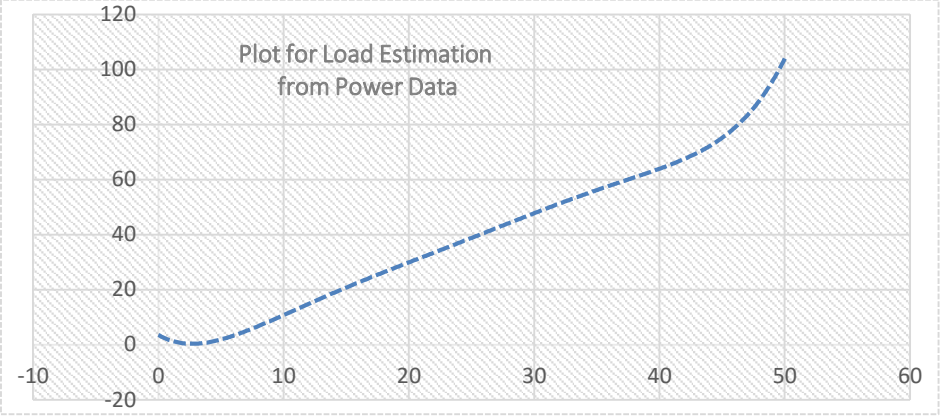

Figure 2 : The relationship between Applied Load(KN) and Power (mW)

5 . Yearly assumed generation of data from 2018 to 2028

Yearly estimated generation for 2018 to 2028 was determined along Dhaka-Chittagong National Highway of one kilometer of strip of road . Details calculations are given below –

Table 2 - The amount of generated power per single movement

Vehicle Type	*Load applied for single passing*	*Expected generation per single Movement (mW)*	*Total Amount (mW)*
Motor Cycle	0.882+0.882	.882*.8888+.882*.88888	1.56
Scooter	0.735+0.735	0.735*0.722+0.735*0.722	1.06
Car	3.675+3.675	3.675*5.86+3.675*5.86	43.07
Micro Bus	3.0625+3.0625	3.0625*4.55+3.0625*4.55	27.86
Minibus	3.675+3.675	3.675*5.86+3.675*5.86	43.07
Bus	32.7+2*32.7	32.7*20.94+2*32.7*40.43	3328.86
Truck	24.5+2*24.5+2*24.5	24.5*17.016+2*24.5*31.2323+2*24.5*31.2323	3477.65
Trailer	21.7+2*21.7+2*21.7+2*21.7+2*21.7	21.7*15.038+2*21.7*28.17576*3	3994.80
Toll Free	0.49+0.49	0.49*0.463327+0.49*0.463327	0.45

Table 3 : Approximate yearly generation for one km of roadway

Vehicle Type	Total Amount per single movement (mW)	Impact Time Factor(s)	Frequency in Year	Yearly Annual Generation (J)/ 1km of roadway
Motor Cycle	1.56	0.127	244844.21	48754.61
Scooter	1.06	0.127	1519651.69	204834.12
Car	43.07	0.127	3946918.08	21589709.03
Micro Bus	27.86	0.127	5190991.37	18372637.99
Minibus	43.07	0.127	2808723.37	15363764.63
Bus	3328.86	0.127	4114559.16	1739492512
Truck	3477.65	0.127	9802591.64	4329437031
Trailer	3994.80	0.127	602919.67	305885683.1
Toll Free	0.454	0.127	1188192.92	68517.95
Total				6430463445

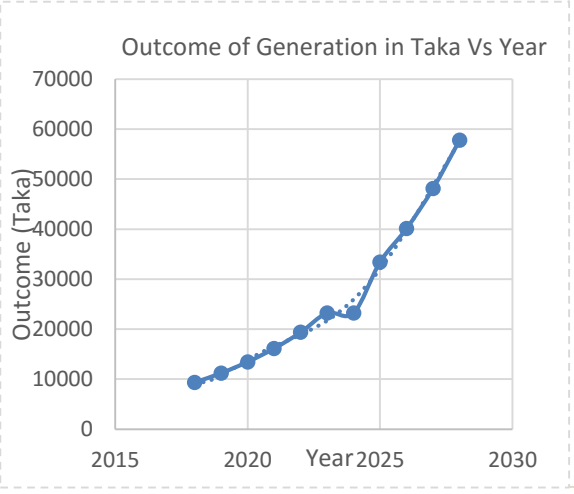

Figure 3 : Showing the Outcome in Taka

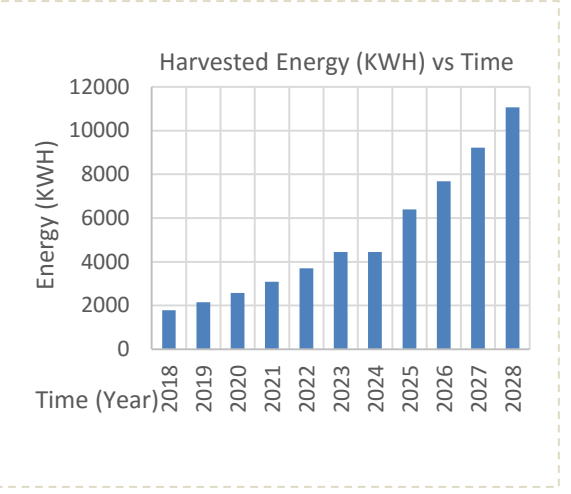

Figure 4 : Showing the Outcome in Energy

The whole process is done with a couple of steps. These are explained below –

- Firstly, the load of single wheel of every type of vehicle for moving along the roadway is determined and then corresponding total maximum load of vehicle per single movement is calculated.

- Then, Corresponding power values are determined through interpolation and power values are multiplied by corresponding loading.

- Then the total power values were summed up and the value found was for As we know , the generated electricity will be proportional to the amount of vehicles running on the roadways, it was essential to determine the frequency of different vehicle along side their subsequent loading characteristics of a specific highway in order to predict the possible outcome of generated power from the device. For this purpose Dhaka-Chittagong National Highway was chosen (N-1) for calculating the data. The percentage of vehicles running on this roadway was collected first and then growth rate was considered. The growth rate showed the increment per year and subsequent value of frequencies.

Table 4 : The total energy can be harvested from 2018 to 2028 is shown in the following table

Year	**Energy can be harvested/km (KWH)**
2018	6430463445
2019	7716556134
2020	9259867361
2021	11111840833
2022	13334208999
2023	16001050799
2024	16001050799
2025	23041513151
2026	27649815781
2027	33179778937
2028	39815734725
Total in ten years	**2.03542e+11 j**
	56539.41 kwh

As any recent data of growth rate of vehicles in Bangladesh 2018 was not available, the value from a theoretical analysis work of Mohammad Ahad Ullah, Hamid Nikraz and Professor Dr. Md. Shamsul Hoque in 2009 was interpolated.

The growth rate of Dhaka-Chittagong Highway from the table (20% used here) was used to estimate the road traffic volume for arrange of 10 years of 2018-2028. The Road traffic volume was found as 29,410,716 in 2018 by extrapolating the value of 5,700,000 of 2009 at a growth rate of 20%. Similar extrapolation was done for every single year of 2018-2018 .

- Then finally by multiplying the frequency and generated electricity per single vehicle, total amount of energy that can be harvested for a single year was determined for 2018-2028.

7. Cost analysis

Table 5 : Cost of single device

Component name	Cost of single unit (taka)	Number of components	Cost per unit device (taka)
Piezo Element	5	44	220
Wire	10	1	10
Soldering	3	1	3
plate	30	2	60
Scotch tape	10	1	10
Plastic Cap & Sitter	3	22	66
Circuits & Others	21	1	21
Toatl cost			390

As the cost of each device is about 420 Taka (With maintenance cost) , We can conclude that the break-even point of the project can be achieved within = (420*1000/295135.7274) = **14.23 year**
The reason behind such a long period of break even point is the piezo elements used for developing the device was poor in quality as only the locally available materials were considered during designing the device.
Using improved version of these piezo elements, efficiency can be achieved higher and thus the break even point can be achieved with much less time.

8. Data interpolation for vehicle counting

As we know piezo elements will give discrete electric signal, we can simply get the number of vehicles by dividing the number of impulse signals received by 2. The reason is, as we know that the number of impulse load applied by a single vehicle for complete movement is 2 as because one from the frontal wheel and the other from rear end wheel. So , we can conclude –

The number of vehicles passed over the device = Number of impulse signals received/2

Figure 5 : Frontal and rear wheels providing 2 times impact on roadway

9. Conclusions

The entire research was designed as to explore the potential of the designed piezo electric energy harvesting device with locally available piezo elements. Thus, after designing the design and performing experiment , based on the results obtained, the following conclusions can be drawn:

- If the piezo electric device developed in this experiment is embedded under the pavement of Dhaka-Chittagong Highway for a length of one km (1000 devices) is going to produce 56539.41 KHW in the next 10 years

- The total cost associated with design and development of one single piezo electric device(44*31*3 cm3 with 44 piezo elements) is about 390 Taka, where as maintenance cost associated with it can be taken as 30 Taka more. So total cost of installment of the device within one kilometer roadway is about 420,000 Taka with 0.5 spacing.
- The generated electricity can efficiently be used for supplying electricity to street lamps and traffic signals.
- From proper analysis using Bessel spline interpolating function and 6th order polynomial trend line , the equation for weighting the moving vehicle (Load estimation) is y = 2E-07x6 - 3E-05x5 + 0.0016x4 - 0.0447x3 + 0.6538x2 - 2.6643x + 3.5351And the Regression value is -R^2 = 0.9976, which can be a very handy tool for government to monitoring and stopping overloading of vehicles.
- As the number of impulse load applied by a single vehicle for complete movement is 2 as because one from the frontal wheel and the other from rear end wheel, the number of vehicles passed over the device = Number of impulse signal received / 2 , which can be a handy tool for traffic volume survey.
- It's a form of clean energy. The power generation plant in our country does not take into consideration to the huge environmental burden it inherently bears. The piezoelectric harvester doesn't have any negative impact on environment. Considering this, its value cannot be judged by mere cost calculation alone. It is a harvesting agent of lost energy and source of green energy, it's an environmentally friendly solution for renewable source of energy as the stock of fossil fuel is diminishing quickly.
- As the demand of fossil fuel is enormously increasing over time, the future of generating power using non-renewable energy will come to a halt. This overconsumption and risks associated is pressuring the environment and economy as well. It can be considered as a pseudo form of renewable energy. So, it is a more sustainable form of energy than the typical coal or gas-based power plants in our country. Sustainability is simply a shortcut to a long-term profit earnings.
- As the design approach was to use the locally available piezo elements which are poor in performance, using of more efficient piezo elements can improve the efficiency of design upto 150%.
- Once installed properly there are a lot of scopes for collecting many tremendously useful data from this device. Like vehicular load count, speed estimation, road condition degradation etc. This creates a new horizon and more and more scopes for further research and development opportunities to improve our transport system. Which can be said as a step forward for practically implementing Intelligent Transportation System in Bangladesh. The value of this data can not be judged currently by just estimating an amount of money.

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