Waste to Energy: Piezoelectric Energy Harvesting from Vehicular Movements

Amanjot Singh, Naveet Kaur, and Suresh Bhalla

Abstract Wireless sensor technology used for continuous structural health monitoring (SHM) of the road infrastructure has increased the usability as well as the capability of data collection. However, electrochemical batteries are the main power source for these wireless sensors but they have to be replaced or charged regularly. For efficient usability of this, wireless health monitoring systems can efficiently self-sustain via an energy source. The solution lies in piezoelectric energy harvesting from road pavement itself using the mechanical energy generated by moving traffic. In this paper, a prototype for piezoelectric energy harvesting (PEH) has been developed utilizing the d_{33} mode of piezosensors, which converts the vehicular motion energy into electrical energy. Testing of prototype PEH has been conducted by fixing it on road surface to carry out a comprehensive parametric study with varying pavement surface, weight of vehicle, and speed of vehicle on the voltage and power output. It is found that power generated from PEH surface bonded on concrete surface is approximately **10%** higher as compared to bitumen pavement, and it is also increasing with the increase in speed and weight of vehicle. Maximum open-circuit voltage of **82 V** and peak power output of approximately **2.8 mW,** whereas maximum average power output of **0.25 mW** is generated with a truck weighing 7 Ton at speed of 40 km/h on concrete surface using the 1 MΩ load resistance circuit. Maximum energy of **0.72 µJ** was stored in a **10 µF** capacitor with single pass of a vehicle.

Keywords Piezoelectric energy harvesting · Pavements · Vehicular motion · Peak power · Average power · Traffic

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1 Introduction

In today’s world, automobiles are one of the most often used means of conveyance. India being a developing nation, hence, both the number of vehicles and the road network are increasing at an astonishing scale. Though this can act as a problem for the environmentalists, this can also act as boon in other ways. It results in a great potential for piezoelectric energy harvesting from the mechanical energy generated by vehicular motion. The external mechanical stress from the vehicular motion can be converted into the electrical voltage with the help of piezoelectric material, and hence, energy can be harvested in this way. Lead zirconate titanate (PZT) is one of the most robust commercially available artificial piezomaterials.

Vehicle load through the tyres will be transferred on to the road surface. The stress produced by this load will be converted into the electrical voltage using the stack actuator or d_{33}-mode of piezomaterial, thus resulting in an energy harvester. However, the vehicular load will be imparting an impact force on the road; hence, the d_{33} mode of piezo is being used in the piezoelectric energy harvesting.

Lee and Choi (2014) developed a piezoelectric energy harvester utilizing d_{33} mode of piezo which can be mounted inside a tyre for self-powering a wireless sensor system to monitor the health of tyre for increasing the vehicular safety. An output power of **1.37 μW/mm^3** was achieved. Behera (2015) also conceptualized piezoelectric energy harvesting by fixing of piezo materials inside the circumference of the tyre. By fixing 32 modules of PZT-5 A material, an estimated power output of **1.2 mW** per rotation of tyre was numerically achieved. Hiba and Muthukumaraswamy (2016) adjudged that higher electromechanical coupling factor (k) makes the PZT pile and multilayer type of piezoelectric transducers most suitable for energy harvesting from road pavements. It was also concluded that there exists a linear relation between the applied external stress and the electric potential generated by the transducer. A numerical study is done by the authors claimed to produce an energy output of **150 kW** from a surface bonded harvester in one hour from one-lane road of one km highway using truck volume of 600 per hour. Innowattech Energy Harvesting Systems, a private company in Tel Aviv, Israel, has claimed an output power of **200 kWh/h** from one km single lane of a road using embedded harvesters along two-wheel footprints with about 600 heavy vehicles per hour, moving at a speed of 72 km/h on average (Fig. 1).

2 Experimental Work Done and Analysis

Two prototypes energy harvesters were fabricated in the SSDL laboratory (SSDL 2018) using 04 Nos of 3-mm-thick aluminium plates of size 20 cm × 5 cm (Fig. 2). Prototype-I was prepared using CEL (Central Electronics Ltd. 2018) circular disc type piezo PZT-5A sensors of 25 mm diameter and prototype-II with 20 mm diameter sensors. Thickness of sensors used was 1.83 mm.

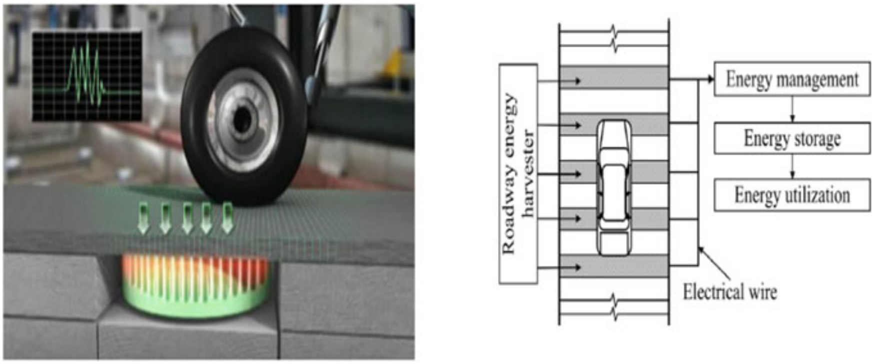


Fig. 1 Mechanism of piezoelectric energy harvesting by vehicular motion (Hiba and Muthukumaraswamy 2016)

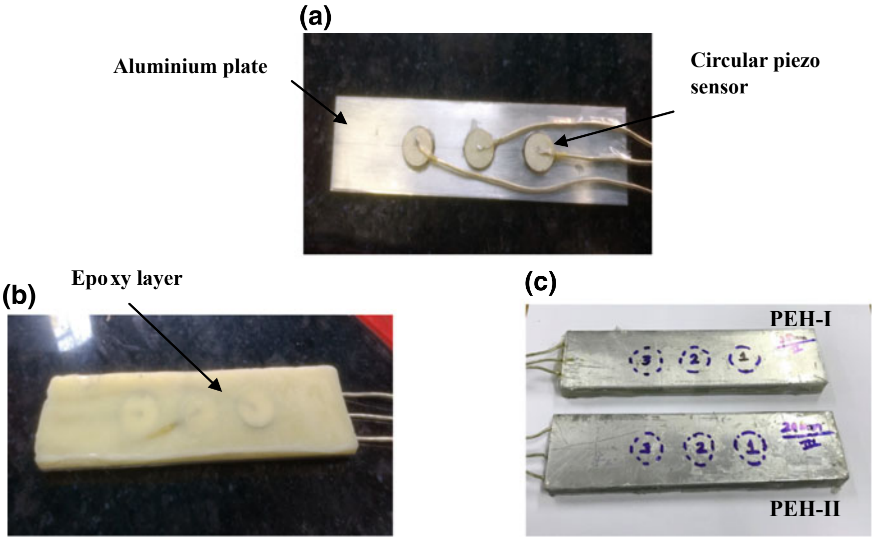
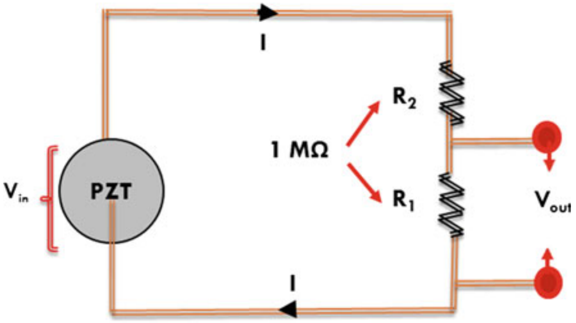


Fig. 2 Different stages of fabrication of prototype-I & II. **a** Different piezo sensors fixed on the plate. **b** Epoxy layer applied. **c** Top plate fixed

An indirect approach for measuring current and thus power was adopted in this study. A current measuring circuit as shown in Fig. 3 was fabricated and used for the same. As per the maximum power transfer theorem, the maximum amount of power will be dissipated when the load impedance matches with the impedance of the network supplying the power. The load resistances in the current measuring circuit were chosen on the basis of maximum power transfer theorem. The high electrical impedance of PZT patch results in a very small (in the range of micro Amperes) current flowing through the circuit, which is challenging to be measured directly

Fig. 3 Line diagram of current measuring circuit



(Kaur 2015). Therefore, the voltage (V_o) across the R_1 was measured, and further, the current and power output generated by PZT patch was determined using formula

$$I(\text{Current}) = V_o/R_1 \tag{2.1}$$

$$P(\text{Power}) = I^2(R_1 + R_2) \tag{2.2}$$

To achieve maximum power output, the resistances R_1 and R_2 were selected such that total load resistance ($R_1 + R_2$) has similar order of impedance magnitude as the PZT patch. Therefore, $R_1 = R_2 = 1$ MΩ was chosen as the impedance value of PZT patch was approximately 2 MΩ.

2.1 Comparison of Power Output from Different Size Sensors

PEH prototype-I and II were fixed on concrete pavement surface for comparison of power output by different sizes of piezosensors under d_{33} mode. SUV (INNOVA) weighing 2200 kg was used for inducing external stress on the prototype during the field experiment. Figure 4 shows the complete set-up of testing. Current measuring circuit as shown in Fig. 3 was used. Vehicle tyre was made to run over the prototype at varying speed (Fig. 4c) and using oscilloscope open-circuit voltage and voltage output across R_1 (Fig. 3) was recorded for sensors of both the specimens. Current (I) and peak power (P) were calculated using Eq. 2.2.

Table 1 shows that maximum open-circuit (OC) voltage of **80 V** was generated by PEH-I (25 mm dia sensor) when vehicle speed was 55–60 km/h, whereas maximum OC voltage of **76 V** was generated by PEH-II (20 mm dia sensor) at same vehicle speed. Peak power generated by PEH-I is **450 μW,** whereas PEH-II generated peak power of **359.12 μW**. Figure 5 shows the comparison of peak power generated by PEH-I & PEH-II at various speeds. It shows that power generation is increasing with the increase in speed of vehicle and also power output of CEL 25 mm dia sensor is

Fig. 4 Photographs showing different stages of testing of prototype. **a** Fixing of prototype on pavement surface. **b** Experiment set-up using oscilloscope, current measuring circuit and Innova. **c** Vehicle tyre passing over the prototype

Table 1 Open-circuit (OC) voltage, peak voltage and power across circuit generated by sensors

Vehicle speed (km/h)	Max OC voltage (V)		Peak voltage (V) across R_1		$R_1 + R_2$ (MΩ)	Peak power $P = I^2 (R_1 + R_2)$ (μW)	
	PEH-II	PEH-I	PEH-II	PEH-I		PEH-II	PEH-I
0–5	60	68	4.6	12	2	42.32	288.00
15–20	66	70	7.6	12.6	2	115.52	317.00
35–40	70	78	11.2	13.4	2	250.88	359.00
55–60	76	80	13.4	15	2	359.12	450

better than CEL 20 mm dia sensors as the surface area of 25 mm dia sensor is more than the surface area of 20 mm dia sensor.

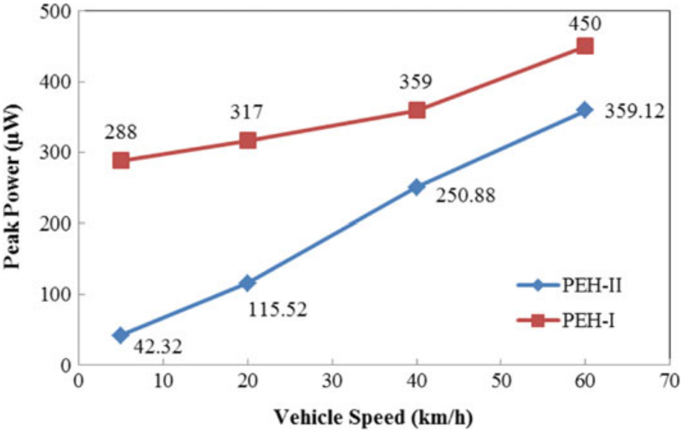


Fig. 5 Comparison of peak power generated by PEH-I & PEH-II at varying speeds

2.2 Comparison of Power Output with Different Pavement Types

PEH-I was fixed firstly on concrete surface and then on bituminous surface as shown in Fig. 6 for analysing the difference in output generation. SUV (Innova) was used for inducing external stress on the prototype. Vehicle tyre was made to run over the PEH at varying speeds for inducing external stress by the impact. Open-circuit voltage and voltage output across R_1 were recorded using oscilloscope. Further, peak power was calculated from the voltage output.

Maximum open-circuit voltage of **78 V** and **54 V** was generated by PEH-I (25 mm dia sensor) at concrete and bitumen surface, respectively (Refer Table 2). Peak power of **359 µW** and **327.68 µW** was generated by PEH-I when surface bonded on

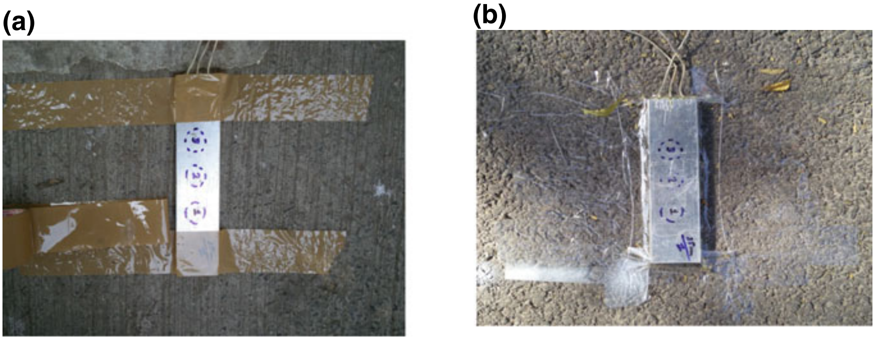


Fig. 6 Photographs showing fixing of PEH-I on different surfaces. **a** Fixing of prototype on concrete pavement surface. **b** Fixing of prototype on bituminous pavement surface

Table 2 Peak voltage and peak power generated by PEH-I (25 mm dia sensor) at bitumen and concrete pavement across R_1

Vehicle Speed (km/h)	Max OC Voltage (V)		Peak voltage (V) across R_1		$R_1 + R_2$ (MΩ)	Peak power $P = I^2 (R_1 + R_2)$ (μW)	
	Bitumen	Concrete	Bitumen	Concrete		Bitumen	Concrete
0–5	44	68	11	12	2	242.00	288.00
15–20	52	70	11.8	12.6	2	278.48	317.00
35–40	54	78	12.8	13.4	2	327.68	359.00

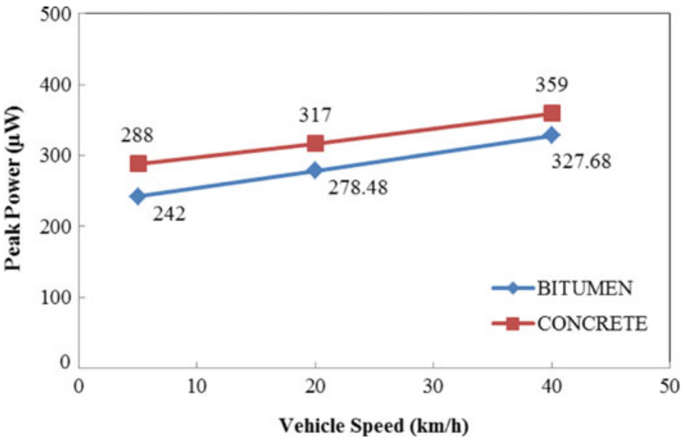


Fig. 7 Comparison of peak power generated by PEH-I at varying vehicle speeds on bitumen and concrete surfaces

concrete and bituminous surface, respectively (refer Table 2 and Fig. 7). Power output generated by PEH-I bonded on concrete surface was approximately **10% higher** than bitumen surface. This is due to the fact that concrete pavement is more rigid as compared to bitumen pavement. Power generation also increases with the increase in speed of the vehicle as the impact force on the sensor increases with the increase in speed of tyre hitting the PEH.

2.3 Comparison of Power Output Using Different Vehicle Type

Three vehicles with different weight were used for inducing external stress on the prototype. Vehicle No. 1—Fiat Punto (Car) with weight 1.1 Ton and tyre width 19 cm, Vehicle No. 2—Toyota Innova (SUV) with weight 2.2 Ton and tyre width 20.5 cm and Vehicle No. 3—Truck Eicher with weight 7 Ton and tyre width 19 cm were used


(a) (b)

(c)

Fig. 8 Photographs showing different vehicles used for testing. **a** Fiat Punto (Car). **b** Toyota Innova (SUV). **c** Eicher (Truck)

for the study (Fig. 8). The current measuring circuit used was same as used earlier. PEH-I was fixed on surface of concrete pavement, and vehicle tyre was made to run over the PEH at varying speeds for inducing external stress by impact. Open-circuit voltage and voltage output across R_1 were recorded using oscilloscope. Further, peak power and average power were calculated from the voltage output. Average power was calculated by determining area under the curve of power and time for the contact period for excitation. Maximum open-circuit voltage of **82 V** (Refer Table 3), peak power of **2.8 mW** (Refer Table 4 and Fig. 9) and Max average power of **0.25 mW**

Table 3 Maximum open-circuit voltage generated by PEH-I with different vehicles

Vehicle speed (Km/h)	Max open-circuit voltage (V)		
	Fiat Punto (Car) (1.2 Ton)	Toyota Innova (SUV) (2.2 Ton)	Eicher (Truck) (7 Ton)
0–5	58	68	58
15–20	64	70	80
35–40	68	78	82

Table 4 Peak voltage, peak power and average power generated across R_1 with Car, SUV and Truck

Vehicle Speed (km/h)	Peak voltage (V) across R_1			Peak power $P = I^2 (R_1 + R_2)$ (μW)			Average power (μW)		
	Car	SUV	Truck	Car	SUV	Truck	Car	SUV	Truck
0-5	10.4	12	19.2	216.32	288	737.28	40.57	53.2	71.8
15-20	12	12.6	27.2	288	317	1479.68	52.9	58.44	200.56
35-40	12.8	13.4	37.6	327.68	359	2827.52	58.88	70.55	253.1

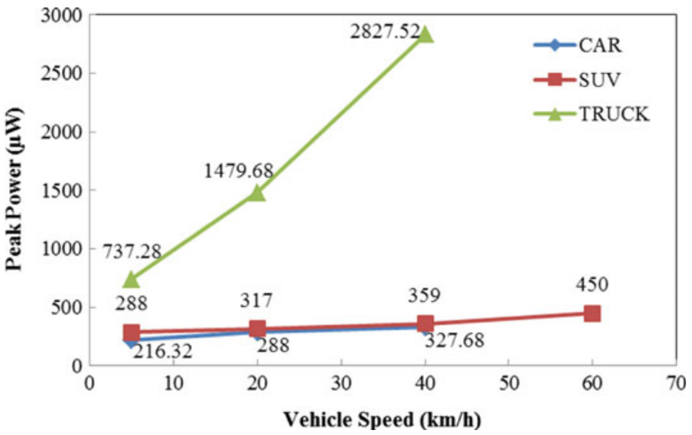


Fig. 9 Comparison of peak power generated at varying speeds with Car, SUV and Truck

(Refer Table 4 and Fig. 10) were generated by PEH-I with truck weighing 7 Ton. The power output increases with the increase in weight of vehicle used as the stress on the prototype is also increasing. Exceptionally higher power output of truck as compared to SUV may be because of lesser width of its tyre. Lesser contact area and with 1 Ton increase in weight, stress induced on the PEH also increases to a large extent which results in higher power output.

2.4 Energy Harvesting Using Different Vehicle Types

An energy harvesting circuit (Fig. 11) was fabricated in SSDL laboratory for storage of generated power from prototype in a capacitor. This circuit consists of a full wave bridge rectifier which converts AC input into DC output and a 10 μF capacitor for storage of DC output. Sensors in the prototype were connected to bridge rectifier for providing input voltage as generated with the passage of vehicle tyre over the prototype PEH to analyse the storage of output voltage and energy using different vehicles.

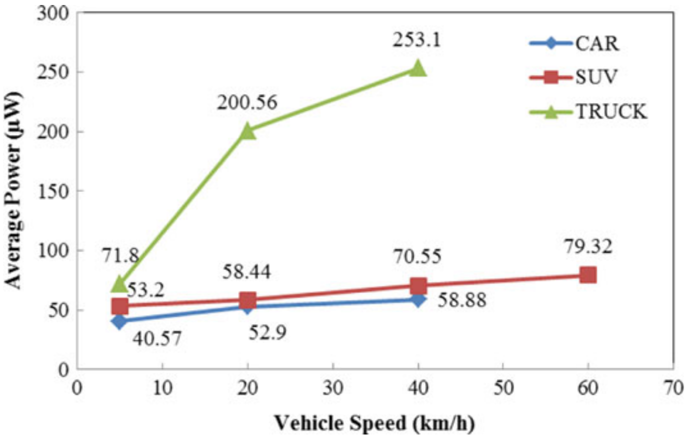


Fig. 10 Comparison of maximum average power generated at varying speeds with Car, SUV and Truck

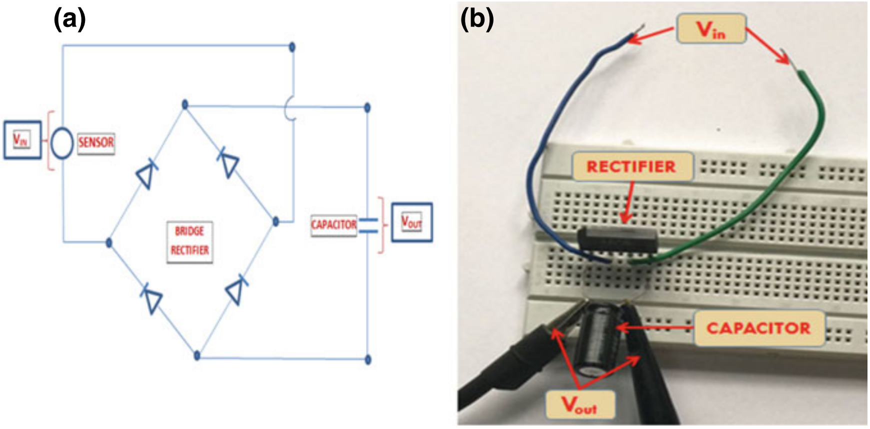


Fig. 11 Circuit for energy storage in capacitor. **a** Line diagram of circuit. **b** Actual circuit used for storing energy in capacitor

$$E = 1/2CV^2 \tag{2.3}$$

Using Eq. (2.3), the energy stored in the capacitor can be calculated. Here, C is the capacitance of capacitor and V is the voltage across the capacitor which was calculated with oscilloscope. Piezoelectric energy generated was calculated, and maximum energy of **0.34 µJ, 0.45 µJ and 0.72 µJ** was stored in 10 µF capacitor with Car, SUV and Truck, respectively (As per Table 5). Power and Energy output generated and stored increases with the increase in weight of vehicle used to induce external stress. Energy stored in capacitor is 6–24 times lesser than the energy being

Table 5 Comparison of maximum energy and power stored in 10 μF capacitor with single pass of Car, SUV and Truck

Type of vehicle	Voltage across Capacitor (V)	Energy generated (μJ)	Energy stored (μJ)	Power stored (μW)
Car	0.26	2.12	0.34	0.85
SUV	0.30	3.95	0.45	1.13
Truck	0.38	17.21	0.72	1.80

Table 6 Vehicle passes required for operation of various sensors

Type of sensor	Power required (μW)	No. of vehicle passes	Applications
TMP112 (Texas Instrument 2018)	36	20	Temperature sensor
PCT2202UK (NXP Semiconductors 2018)	54	30	Temperature sensor
MSP430FR4133 (Texas Instrument 2018)	453.6	252	Air quality index sensor
Colibry's VS1000 (Safran Colibrys 2018)	4170	2317	Vibration sensor (SHM)

generated by PEH which may be due to various losses in transmission and storage circuit.

3 Practical Applications

Energy harvested by the prototype can be utilized for powering various low power sensors such as temperature/heat detection sensors, air quality sensors and structural health monitoring sensors. Power requirement of one such sensor, TMP112 used as digital temperature sensor, is **36 μW,** whereas a maximum power of **1.8 μW** was stored experimentally in a capacitor with a single pass of truck (weight = 7 Ton). Therefore, a total of 20 such passes can store sufficient power in a capacitor for one-time operation of TMP112. Similar sensors (as shown in Fig. 4.16) which can operate with the power generated by PEH are summarized in Table 6.

4 Conclusions

This study resulted in the following conclusions:

1. Successful fabrication of a prototype piezoelectric energy harvester which converts impact energy from vehicular motion into electrical energy has been done and experimentally validated.
2. The power output from CEL 25 mm dia ceramic sensors is more as compared to the CEL 20 mm dia sensor which is due to larger surface area of sensor. Peak power output of approx. **2.8 mW,** whereas maximum average power output of **0.25 mW** is achieved by CEL 25 mm dia sensor.
3. Power generated from PEH surface bonded on concrete surface is approximately **10%** higher as compared to bitumen pavement as the rigidity of concrete surface is more than the bitumen surface.
4. Power generated increases with the increase in weight of vehicle used to induce external stress. Average power generated by Car (weighing 1.1 Ton) is **58 μW**, SUV (weighing 2.2 Ton) is **79 μW,** whereas Truck (weighing 7 Ton) is **0.25 mW**.
5. Power generated also increases with the increase in speed of vehicle as impact force increases with increasing speed.
6. Energy stored in capacitor also increases with the increase in weight of vehicle used to induce external stress. Energy stored in capacitor with single pass of Car (weighing 1.1 Ton) is **0.34 μJ**, SUV (weighing 2.2 Ton) is **0.45 μJ,** whereas Truck (weighing 7 Ton) is **0.72 mJ**.
7. Energy stored in capacitor is **6–24** times lesser than the energy being generated by PEH which may be due to various losses in transmission and storage circuit.

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