Future roads and mobility

Prediction Model of Electric Energy output of Energy Harvesting Element for Traffic Monitoring

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Abstract

To perceive traffic conditions, an energy harvesting element was developed and the electric energy output by energy harvesting element to simulated traffic conditions are calculated based on mechanical models, electrical model, and electromechanical coupling model. Results showed that a simpler mechanical-electrical coupling model of piezoelectric transducer for road can be derived by simplifying the vehicle load to half sinusoidal load. The modelling indicates that the energy output of the developed energy harvesting element is only related to parameters of piezoelectric material, loads, and speeds. The mechanical-electrical coupling model was supported by experimental results of piezoelectric transducer's electrical performance. The connection between piezoelectric ceramics also affects the energy output of energy harvesting element. Based on a daily traffic volume of highway, the daily energy output of piezoelectric energy harvesting element embedded in the surface of pavement can reach 950.6J. The six-axles truck contributes the most to the energy output who occupies as much as 52.3% if total energy output.

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1. INTRODUCTION

With the continuous development of modern transportation, people are more and more not satisfied with the single traffic function of the pavement. In order to facilitate urban drainage and improve driving safety, people put forward drainage pavement [1]. In order to improve driving comfort and reduce noise, people designed noise reduction road [2]. In order to alleviate the effect of urban heat island, the low heat absorption pavement was developed [3]. Nowadays, non-renewable energy is in short supply, so it is imperative to find alternative energy. As a large-scale infrastructure, the potential energy storage function of the road is gradually explored, so people put forward energy harvesting pavement [4]. The purpose of energy harvesting pavement is to collect the potential energy in the road environment in order to realize the multi-level utilization of resources. Road materials have strong heat absorption capacity, which contains rich thermal energy resources. The Seebeck effect of materials can be used to convert the heat energy on the road into electric energy [5]. In addition, there are also abundant mechanical energy generated by tire rolling in the road. If this part of mechanical energy can be excavated and utilized, the road is expected to become a huge energy reservoir. Piezoelectric materials can transform mechanical energy in the environment into electrical energy. The application of piezoelectric materials in the road has become a research hotspot.

Piezoelectric materials are not directly buried in the road, but first encapsulated as piezoelectric transducer. Piezoelectric transducer is the core component of piezoelectric pavement. I n 2008, Innowattech Company of Israel embedded several piezoelectric transducer into pavement structure and developed an system named IPEG (Innowattech Piezo Elecreic Generator) for energy harvester in road, however, no follow-up study has been reported [6]. In 2010, Zhao optimized the size of cymbal piezoelectric transducer by finite element modeling. The open circuit voltage of cymbal piezoelectric transducer under standard load (0.7 Mpa) was 97.33 V [7]. In 2015, Wang proposed a new type of rectangle-cymbal piezoelectric transducer based on cymbal piezoelectric transducer. The transducer was placed 4 cm below the road surface, and under the standard load, its open circuit voltage was about 21.36 V [8]. In 2015, Li analyzed the piezoelectric characteristics of the arch piezoelectric transducer. The maximum output voltage of the arch piezoelectric transducer was 130 V [9]. Huang in 2016 studied the energy output law of multi-layer piezoelectric transducer, but they didn't make further research on its energy output [10]. In 2016, Xiong placed the piezoelectric transducer in the weighing station to test its piezoelectric response under real wheel load. When a 5-axle truck passed, the maximum instantaneous power of the transducer was 0.116W, and the average power was 3.106 mW [11]. Song assembled 48 piezoelectric cantilever elements into a large energy acquisition device. Under the excitation force, the maximum output power of the device can reach 736 μW [12]. Yang laid 20 piezoelectric transducers in the piezoelectric pavement demonstration project. The open circuit voltage of a single piezoelectric transducer was 250~400 V under the wheel load of SUV [13].

The open-circuit voltage of piezoelectric transducer can not reflect its real energy output, especially the road load is discontinuous, and the power can not reflect the energy output during the whole loading process. Traffic load condition affects piezoelectric energy output. Establishing a mechanical-electrical coupling model of piezoelectric transducer related to traffic load can not only study its energy conversion law, but also measure the energy output of piezoelectric transducer, which is of great significance for energy conversion prediction of piezoelectric pavement.

2. ELECTROMECHANICAL COUPLING MODEL

2.1. Mechanical model of piezoelectric transducer

The piezoelectric transducer is embedded in the pavement structure and bears the vehicle load together with the pavement structure. When the vehicle passes over the piezoelectric transducer, there are two equivalent modes for the force model of the piezoelectric device, one is equivalent to trapezoidal load, the peak value is continuous, the other is equivalent to half sinusoidal load, and the peak value is instantaneous.

(1) Trapezoidal load

Assuming that the tire grounding shape is rectangular, the grounding length is l_1, and the length of piezoelectric transducer along the driving direction is l_2, and the vehicle speed is v. When the time is 0~t_1, the contact area between wheel load and piezoelectric device increases gradually, and the force of piezoelectric device increases gradually. When the time is t_1~t_2, the contact area between wheel load and piezoelectric device reaches the maximum, and the force of piezoelectric device remains unchanged. When the time is t_2~t_3, the contact area between wheel load and piezoelectric device decreases gradually, and the force of piezoelectric device decreases gradually. The load $F(t)$ undertaked by the piezoelectric device is given by formula (1), and the trapezoidal loading curve is shown in Figure 1.

$$F(t)=\begin{cases}\dfrac{vt}{l_1}F_{\max} & (0\le t\le t_1)\\ F_{\max} & (t_1<t\le t_2)\\ \dfrac{l_1+l_2-vt}{l_1}F_{\max} & (t_2<t\le t_3)\end{cases} \tag{1}$$

In the formula (1), F_{max} is the maximum load on the piezoelectric device under traffic load, t_1=min(l_1,l_2)/v, t_2=max(l_1,l_2)/v, t_3=(l_1+l_2)/v.

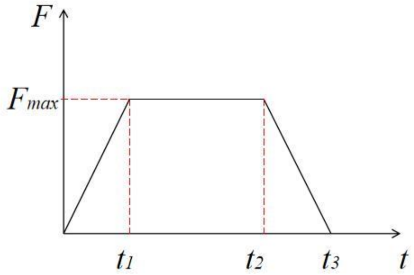


Figure 1: Trapezoidal loading curve

(2) Semi-sinusoidal loading

The trapezoidal loading model is more ideal. Even if the tire grounding shape and the shape of piezoelectric transducer are rectangular, the vehicles don't completely drive over the piezoelectric transducer. Therefore, there are many additional conditions to simplify the vehicle load into trapezoidal loading. Usually, the time of vehicle load acting on pavement is very short, only about 0.01-0.1s. The response time of piezoelectric transducer is only 0.072s when the length of piezoelectric transducer along the driving direction is 30 cm, the length of wheel-loaded grounding is 30 cm and the speed is 30 km/h. Generally, the length of piezoelectric transducer is less than the length of tire grounding and the vehicle speed is greater than 30 km/h, so the response time of piezoelectric transducer is shorter, but the only constant is that the top load of piezoelectric transducer always increases first and then decreases. Therefore, the load on the top surface of piezoelectric transducer can be simplified as half-wave sinusoidal loading. The sinusoidal amplitude is the maximum static pressure on the top of piezoelectric transducer. The loading time is the ratio of the sum of the length of tire grounding length and piezoelectric transducer to driving speed. When the length of piezoelectric transducer is small enough and it is not considered, the loading time is conservatively estimated, and the loading time is the time when the vehicle passes through the tire grounding length. The half-wave sinusoidal loading is shown in Figure 2. The load of piezoelectric transducer is given by formula (2)~(3).

$$F(t) = F_{max} \sin(\omega t) = F_{max} \sin(\frac{\pi}{T} t) \quad (2)$$

$$T = \frac{2r}{v} \quad (3)$$

In the formula: F_{max} is the maximum static load withstanding by piezoelectric transducer, ω is the equivalent angular velocity, T is the loading time, r is the equivalent circle radius (r=106.62 mm), v is the driving speed.

It is noteworthy that the piezoelectric material is a pre-compressed component. Under the half-sinusoidal load, although the load F has only half-wave sinusoidal, the piezoelectric response of piezoelectric ceramics is sinusoidal, and the piezoelectric response period is $2T$. That is to say, the piezoelectric material still generates electric energy after unloading [14].

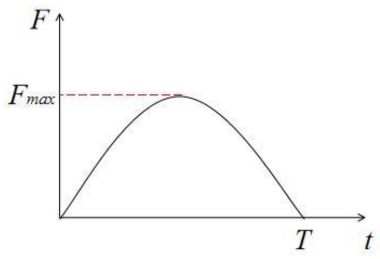


Figure 2: Half-wave sinusoidal loading model

2.2. Electrical model of piezoelectric transducer

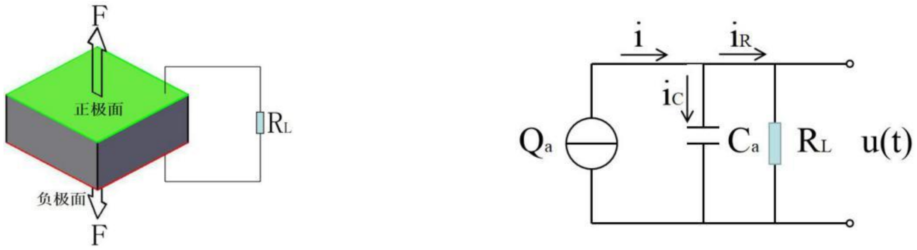
The core component of piezoelectric transducer is piezoelectric ceramics. The piezoelectric ceramics can be equivalent to active capacitor model because the surface of the electrodes collects charges under external loads and the piezoelectric ceramics are dielectric materials. There are two kinds of capacitor electrical models, one is the charge source equivalent model, as shown in Figure 3 (a), in which the charge source Q is connected in parallel with the equivalent capacitor C_a, and the other is the voltage source equivalent, as shown in Figure 3 (b), in which the voltage source U is connected in series with the equivalent capacitor C_a.

（a）Charge source equivalent model （2）Voltage source equivalent model

Figure 3: Equivalent circuit of piezoelectric ceramics

2.3. Electromechanical coupling model

The semi-sinusoidal model is used as the load model of piezoelectric transducer under traffic load, and the charge source model is used as the electrical model of piezoelectric ceramics to establish the mechanical-electrical coupling model of piezoelectric ceramics under traffic load. The external loads at both ends of piezoelectric ceramics are used as energy consuming elements. The mechanical and electrical models of piezoelectric ceramics are shown in Figures 4 (a) and 4 (b), respectively. In Figure 4 (a), the polarization direction of piezoelectric ceramics is Z axis and R_L is external load. In Figure 4 (b), Q_a is the charge generated by piezoelectric ceramics under external force, i is the total current of the circuit, i_R and i_C are the current flowing through the load and piezoelectric ceramics, C_a is the equivalent capacitor, and $u(t)$ is the output voltage of piezoelectric ceramics.



(a)Mechanical model of piezoelectric ceramics (b)Electrical model of piezoelectric ceramics

Figure 4: Electromechanical coupling model of piezoelectric ceramics

Under vehicle loads, the piezoelectric ceramics are subjected to force $F = F_{max}\, sin(\omega t)$, and the thickness direction of the piezoelectric ceramics produces stretching deformation. Under this mode, the piezoelectric ceramics are subjected to a single force and only polarization stress exists in the interior. The total current of the circuit is the derivative of polarization direction charge to time.

$$i(t) = \frac{dQ_3(t)}{dt} \quad (4)$$

In the formula (4), $Q_3(t)$ is the polarization direction charge, i. e. the circuit charge source; $i(t)$ is the total current of the circuit.

The polarization direction charge is the integral of the polarization direction charge density to the polar surface.

$$Q_3 = \iint D_3(t)dA \quad (5)$$

In formula (5), $D_3(t)$ is the charge density in polarization direction and A is the area of the polar surface of piezoelectric ceramics.

The charge density of polarized surface can be calculated by formula (6).

$$D_3(t) = \frac{d_{33}F}{A} = \frac{d_{33}F_{max}\, sin(\omega t)}{A} \quad (6)$$

The current flowing through both ends of the load R is:

$$i_0(t) = \frac{i(t)|Z|}{R} \quad (7)$$

Where |Z| is the internal impedance of the circuit, its value can be calculated from the following formula (8).

$$|Z| = \frac{R}{\sqrt{\omega^2 C^2 R^2 + 1}} \quad (8)$$

The current flowing through the load R can be obtained by taking |Z| into forluma (7)

$$i_0(t) = \frac{d_{33}F_{\max}\,\omega\cos(\omega t)}{\sqrt{\omega^2 C^2 R^2 + 1}} \quad (9)$$

Furthermore, the voltage of load R can be calculated by formula (10).

$$u_0(t) = \frac{d_{33}F_{\max}\,\omega\cos(\omega t)R}{\sqrt{\omega^2 C^2 R^2 + 1}} \quad (10)$$

3. VERIFICATION OF ELECTRICAL PERFORMANCE

3.1 Test materials and test methods

In order to verify the correctness of the above theory, piezoelectric material PZT-5H is used to fabricate the column piezoelectric transducer for pavement as shown in Figure 5. The other materials are nylon except the electrode sheet is copper.

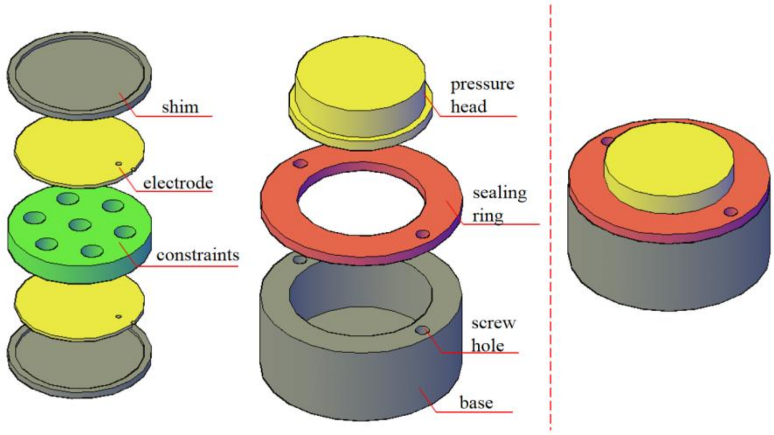


Figure 5: Column piezoelectric transducer

The cyclic loading test of the piezoelectric transducer was carried out by MTS (Landmark 370) to verify its electrical properties. The external load of piezoelectric transducer is ZX1G high resistance box. The adjustable range of resistance box is 0~1111.110 MΩ. The output voltage of external load is measured by an oscilloscope (UTD2102CEX). The oscilloscope bandwidth is 100 MHz, the sampling rate is 1 GS/s.

In electrical performance test, the load resistance was changed, and the load voltage of piezoelectric ceramics under different connection modes was measured. Finally, the load power was calculated as the output power of piezoelectric transducer. In order to ensure the stability of piezoelectric transducer, the number of piezoelectric ceramics in piezoelectric transducer is 3~5, and the electrical connection modes were series and parallel in turn. Loading frequency was 20 Hz and load amplitude was 0.9 kN.

3.2 Test result

The output power of piezoelectric transducer in parallel and in series is shown in Figure 6 and 7 respectively. The calculated load power variation is basically in accordance with the theoretical analysis. When piezoelectric ceramics are connected in parallel, the load power first increases and then decreases with the load resistance. The more the number of parallel connections, the lower the maximum load power, and the optimal load corresponding to the maximum power decreases with the increase of the number of parallel connections. When piezoelectric ceramics are connected in series, the maximum load power also decreases with the increase of the number of series connections, but the optimal load is positively correlated with the number of series connections.

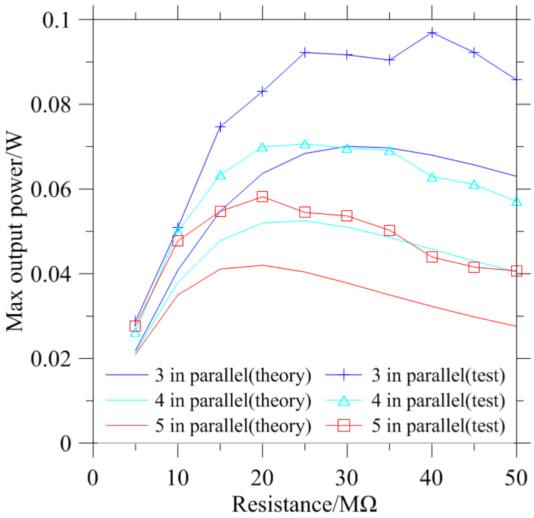


Figure 6: Output power of piezoelectric ceramics in parallel

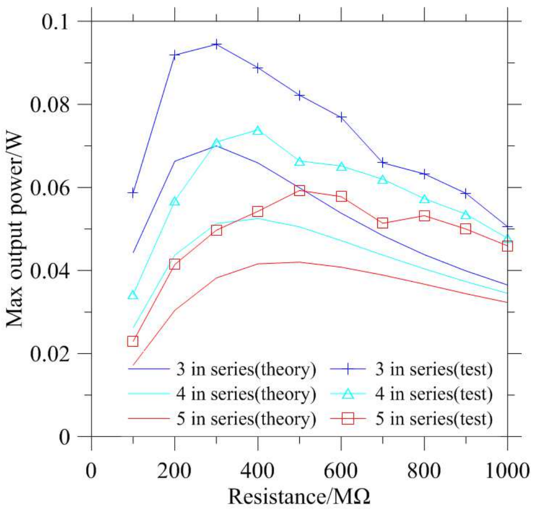


Figure 7: Output power of piezoelectric ceramics in series

4. ENERGY CONVERSION ESTIMATION

The energy output of piezoelectric transducer is related to the traffic load condition. Therefore, an actual traffic information of a highway is investigated and the output energy of piezoelectric transducer is estimated based on it. The daily traffic volume of a highway is 15,100. The specific survey data are shown in Tables 1 and 2.

Table 1. Daily traffic volume information of a highway

Vehicle type	Traffic volume（veh/d）	Proportion（%）	Speed Modulus（km/h）	Average speed（km/h）	Load action time（ms）	ω（rad/s）
Minibus	9758	64.6	110~125	117	6.561	478.811
Bus	691	4.6	110~125	117	6.561	478.811
2-axles truck	2023	13.4	65~70	69	11.126	282.376
3-axles truck	248	1.6	65~70	66	11.631	270.099
4-axles truck	340	2.3	60~65	65	11.810	266.006
5-axles truck	248	1.6	75~80	56	13.708	229.175
6-axles truck	1792	11.9	55~60	58	13.236	237.360

Table 2. Axle load statistics of various vehicle types

Vehicle type	Axle type	Axle load（kN）						Proportion（%）
		axle1	axle2	axle3	axle4	axle5	axle6	
Minibus	11	15	35					64.6
Bus	11	50	100					4.6
2-axles truck	11	30	50					1.7
	12	50	130					11.7
3-axles truck	112	50	60	150				1.4
	14	50	110	110				0.2
4-axles truck	114	55	55	140	140			1.6
	124	40	120	110	110			0.7
5-axles truck	127	50	130	100	100	100		1.5
	144	50	100	100	100	100		0.1
6-axles truck	1127	50	50	135	110	110	110	6.1
	147	50	100	100	100	100	100	5.8

Taking the piezoelectric transducer embedded on the road surface as an example, the piezoelectric transducer is equipped with a single cylindrical piezoelectric ceramics of Φ6 mm x 10 mm. Under the above traffic volume, the input energy of the piezoelectric transducer is the sum of the transformed energy of each vehicle type.

$$E_c = \sum \frac{1}{2} C \Delta U^2 \tag{11}$$

$$\Delta U = 2U_{\max} \tag{12}$$

Where, E_c is converts electrical energy of piezoelectric transducers, $\triangle U$ is peak voltage and U_{max} is peak open-circuit voltage.

When the piezoelectric transducer is connected with external load R, the voltage at both ends of the load is as the formula (10). Ideally, when the external load R tends to be infinite, the u_0 value is approximately equal to the open circuit voltage U of the piezoelectric transducer.

$$U = \underset{R\to\infty}{u_0} = \lim_{R\to\infty} \frac{d_{33} F_{\max} \omega \cos(\omega t)}{\sqrt{\omega^2 C^2 + \frac{1}{R^2}}} = \frac{d_{33} F_{\max} \cos(\omega t)}{C} \tag{13}$$

$$U_{\max} = \frac{d_{33} F_{\max}}{C} \tag{14}$$

Under different axle loads, the tire grounding pressure is different and the grounding area is different. In order to simplify the calculation, the tire grounding area remains unchanged (diameter=213.24 mm), and the load on the piezoelectric transducer (diameter=36 mm) is 2.85% of the axle load. Under each vehicle type, the loads of the piezoelectric transducer are shown in Table 3.

Table 3. Each axle load on piezoelectric transducer

Vehicle type	Axle type	Load (kN)					
		Axle1	Axle2	Axle3	Axle4	Axle5	Axle6
Minibus	11	0.43	1.00				
Bus	11	1.43	2.85				
2-axles truck	11	0.86	1.43				
	12	1.43	3.71				
3-axles truck	112	1.43	1.71	4.28			
	14	1.43	3.14	3.14			
4-axles truck	114	1.57	1.57	3.99	3.99		
	124	1.14	3.42	3.14	3.14		
5-axles truck	127	1.43	3.71	2.85	2.85	2.85	
	144	1.43	2.85	2.85	2.85	2.85	
6-axles truck	1127	1.43	1.43	3.85	3.14	3.14	3.14
	147	1.43	2.85	2.85	2.85	2.85	2.85

If the wheel load center is directly above the piezoelectric transducer, the electric energy converted by piezoelectric transducer under single axle load is shown in Table 4.

Table 4. Converted and output electricity under different axis loads

Vehicle type	Converted electricity($\times10^{-4}$ J)						Output electricity($\times10^{-4}$ J)					
	Axle1	Axle2	Axle3	Axle4	Axle5	Axle6	Axle1	Axle2	Axle3	Axle4	Axle5	Axle6
Minibus	18	99					14	77				
Bus	203	810					157	629				
2-axles truck	73	203					46	129				
	203	1369					129	869				
3-axles truck	203	292	1823				125	180	1126			
	203	980	980				125	606	606			
4-axles truck	245	245	1588	1588			150	150	972	972		
	130	1167	980	980			79	714	600	600		
5-axles truck	203	1369	810	810	81		112	758	449	449	449	
	203	810	810	810	81		112	449	449	449	449	
6-axles truck	203	203	1477	980	98	98	115	115	838	556	556	556
	203	810	810	810	81	81	115	460	460	460	460	460

Different types of vehicles have different speeds, and their acting time on piezoelectric transducers are different. The action time of various vehicles on piezoelectric transducers are shown in the right two columns of Table 1. If the two ends of the piezoelectric transducer are connected with an external circuit, the output energy of the piezoelectric transducer under a single axle load can be obtained by integrating the power of the circuit load. The output energy can be calculated by formula (15)~ (19). The output energy is shown in Table 4.

$$p_0(t) = \frac{d_{33}^2 F_{\max}^2 \omega^2 \cos^2(\omega t) R}{\omega^2 C^2 R^2 + 1} \quad (15)$$

$$\omega = \frac{2\pi}{2T} \quad (16)$$

$$T = \frac{2r}{v} \tag{17}$$

$$E_o = \int_0^{2T} p_0(t)dt \tag{18}$$

$$E_o = \frac{d_{33}^2 F_{\max}^2 \omega^2 RT}{\omega^2 C^2 R^2 + 1} \tag{19}$$

Where, T is the equivalent action time of load and E_0 is the output energy.

Under daily traffic, the converted energy and output energy of a single piezoelectric transducer can be calculated by formula (20) and (21). The converted energy in Table 5 shows that the total energy conversion of a single piezoelectric transducer with one piezoelectric ceramic is 1560.95 J under the above seven types of vehicles. Energy conversion is not only affected by axles loads and axles speeds, but also by the number of axles. For example, the daily traffic volume of minibuses is 9754, accounting for 64.6% of the total traffic volume. However, the energy conversion is only 114.60 J, accounting for 7.34% of the total energy conversion. Conversion energy of axle-heavy vehicles is not necessarily ahead. For example, 5-axle trucks, whose total vehicle weight is about 45-48 t and average axle load is 9-10 t, however, their traffic volume is only 241, accounting for 1.60% of the total traffic volume. The low traffic volume leads to the daily energy conversion of only 95.63 J, accounting for 6.13% of the total daily energy conversion. Under the daily traffic volume, the largest contribution of energy conversion of piezoelectric transducer is 6-axle truck. Although the traffic volume of 6-axle truck is 1797, which is less than 20% of the daily traffic volume of passenger cars, the energy conversion reaches 816.85 J, and the energy conversion contribution exceeds half of the total energy conversion, which is 52.33%.

$$E_{ctotal} = \sum_{k=1}^{o}\sum_{l=1}^{p}\sum_{m=1}^{q} E_c \tag{20}$$

$$E_{ototal} = \sum_{k=1}^{o}\sum_{l=1}^{p}\sum_{m=1}^{q} E_o \tag{21}$$

Where, q is the number of axles of each vehicle type, p is the daily traffic volume of each vehicle type, o is the number of types of vehicles.

Table 5. Conversion and output of electric energy under daily traffic volume

Vehicle type	Axle type	Daily traffic volume	Conversion Energy (J/veh)	Output Energy (J/veh)	Conversion Energy (J/daily traffic)	Output Energy (J/daily traffic)
Minibus	11	9754	0.0117	0.0091	114.5997	89.0150
Bus	11	695	0.1013	0.0787	70.3917	54.6784
2-axle truck	11	257	0.0275	0.0175	7.0801	4.4924
	12	1767	0.1572	0.0997	277.7583	176.2388
3-axle truck	112	211	0.2317	0.1431	48.8965	30.2017
	14	30	0.2163	0.1336	6.4902	4.0088
4-axle truck	114	242	0.3666	0.2243	88.7283	54.2864
	124	106	0.3257	0.1993	34.5270	21.1246
5-axle truck	127	226	0.4003	0.2216	90.4610	50.0915
	144	15	0.3444	0.1907	5.1654	2.8603

Table 5. Conversion and output of electric energy under daily traffic volume(continued table 5)

Vehicle type	Axle type	Daily traffic volume	Conversion Energy （J/veh）	Output Energy （J/veh）	Conversion Energy （J/daily traffic）	Output Energy （J/daily traffic）
6-axle truck	1127	921	0.4823	0.2737	444.2084	252.1053
	147	876	0.4254	0.2414	372.6390	211.4892
Total		15100	3.0906	1.8329	1560.9457	950.5925

When the external circuit load is 20 M Ω, the daily output energy of the piezoelectric transducer is 950.59 J, which meets the energy consumption requirement of 864 J per day for low-power equipment with 10 mW power. In the daily output energy of piezoelectric transducer, the energy output contributing by a minibus is 89.02 J, accounting for 9.36% of the total energy output. Daily energy output of 6-axle truck is 463.59 J, and its ratio to daily energy output is 48.77%. The energy output ratio of buses is 5.75% higher than its energy conversion ratio of 4.50%, and the energy output ratio of six-axle trucks is 5.57% lower than its energy conversion ratio of 6.13%. The reason is that the fast speeds of minibuses and buses make up for the shortage of energy output and the low speeds of 5-axles and 6-axles trucks reduces their energy conversion ratio.

5. CONCLUSION

(1) By simplifying the vehicle load to half sinusoidal load, a simpler mechanical-electrical coupling model of piezoelectric transducer for road can be derived. The model shows that the energy output of road piezoelectric transducer is not only related to the parameters of piezoelectric material itself, but also to the vehicles loads and their driving speeds.

(2) The test results of piezoelectric transducer's electrical performance support its mechanical-electrical coupling model, and the connection mode of piezoelectric ceramics affects the energy output of piezoelectric transducer. When piezoelectric ceramics are connected in parallel, the load power first increases and then decreases with the load resistance. The more the number of parallel connections, the lower the maximum load power, and the optimal load corresponding to the maximum power decreases with the increase of the number of parallel connections. When piezoelectric ceramics are connected in series, the maximum load power also decreases with the increase of the number of series connections, but the optimal load is positively correlated with the number of series connections.

(3) Under the daily traffic volume of highway, the daily energy output of piezoelectric transducer embedded in the surface of pavement can reach 950.6J, and its energy output can meet the energy demand of low-power equipment with power of 10 mW. The six-axles truck contributes the most to the energy output, and its energy output proportion is as high as 52.3%.

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