Journal of Newviews in Engineering and Technology (JNET)
Vol 1, Issue 1, December, 2019
ilable online at http://www.rsujnet.org/index.php/publications/2019-edition

Design and Fabrication of Speed Bump Power Generation System

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ABSTRACT

This study explores the practicality of power generation from road speed bumps by harvesting the energy of moving vehicles using a mechanical speed bump design with rack-and-pinion mechanism and spring system. It includes design analysis and prototype fabrication. The model design using Autodesk Inventor helps to validate the practicality of the system design in addition to the prototype fabrication. An experimental test and a theoretical energy assessment were carried out when an average weight of 392N was applied on the fabricated prototype. In this analysis, the mechanical input power, electrical output power and energy conversion efficiency were evaluated as 203.84W, 1.112W and 0.6%, respectively. A MATLAB program code consistent with this performance was obtained for evaluating the actual performance of the system, from which an average weight of 10.91kN acting on the tyres of vehicles generate 32.52W of power. The proposed system design gives new impulse to research on renewable power systems.

Keywords: *Energy Harvesting, Mechanical Speed Bump (MSB), Spring System, Rack-and-Pinion Mechanism, Vehicle Weight.*

Cite This Article: Gbaarabe. B., Hart, H. I., & Nkoi, B, (2019). Design and Fabrication of Speed Bump Power Generation System. Journal of Newviews in Engineering *and Technology (JNET)*, 1 (1), 91-100.

1.0 INTRODUCTION:

Energy plays the most vital role in the economic growth, progress, and development of any nation (Oyedepo, 2012). Energy is the ability or capability to do work, where work is not constrained only to the application of force that produce motion over a distance but includes any phenomenon that produces a change of location, orientation, speed, temperature, chemical and nuclear compositions in the affected system which may be as small as the nucleus of an atom, a biological organism or a large machine (Hart, 2018). Energy is conserved and the law of conservation of energy states that energy can neither be created nor destroyed, but can be converted from one form to another. Electricity is a form of energy that drives our daily lives and is mainly obtained by converting mechanical energy into electrical energy.

The usage of energy has increased substantially over the past decades, leading to an energy crisis. The problems associated with energy crisis such as climate change, shortage of fossil fuels, and global energy demand are continuously increasing, which suggest the need for solutions. The best possible solution to energy crisis is the energy transition to renewable energy sources (Renewable Energy Policy Network for 21st Century, 2005).

The newest renewable energy source is the energy of moving vehicles that is harvested by MSB (Rhodri, 2009). The speed reduction of vehicle while encountering speed bumps on our road ways results in huge kinetic energy loss, which is dissipated into potential energy in accordance with the law of conservation of energy (Todaria *et al.*, 2015). Thus, on all the speed bumps on our roadways there are energy wastages. An electro-mechanical system that would harvest this energy and converting it to electricity is the proposed speed bump power generation system (SBPGS) (Saneifard *et al.*, 2009).

The system is designed to function as a road safety device and power generation system. The input energy into the system is the energy of the moving vehicles, which is abundantly available on our roadways daily, thus considered a renewable source of energy (Mark, 2016). With

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the global energy transition from fossil fuels to renewable energy sources, it could be designed to replace the conventional speed bumps which are routinely installed on our roadways without following proper engineering guidelines (Parkhill *et al.,* 2009). This study is set out to explore the practicality of power generation from speed bumps on our roadways. It includes design analysis and prototype fabrication.

In most of the literatures reviewed, it was observed that speed bumps now get a new role as a source of renewable energy. The work of Aswalthaman and Priyadharshini (2011) clearly explains the working principle, practical implementation and advantages of power generation from speed breakers.

Todaria *et al.* (2015) proposed a speed bump energy harvester that is expected to provide sufficient electricity for many road side devices. In their work an in-field test was done by driving a vehicle through the speed bump energy harvester prototype at 2km/h and a power output of 200W was achieved.

Olugboji *et al.* (2015) worked on modeling and design of an auto-street light generation speed breaker mechanism. The speed breaker mechanism was developed using a static analysis of the spring and computational fluid dynamics (CFD) analysis of the air flow using SolidWorks software. The test results revealed that the mechanism generated an average of 6VDC, an indication that the speed breaker mechanism is a feasible source of renewable energy and will be beneficial on a larger scale.

Iyen *et al.* (2017) designed and constructed a prototype speed bump power generator using the rack and pinion mechanism and conducted an experimental study on the system performance. The result showed that electrical power of up to 1.9kW could be generated from the system.

Jagtap *et al.* (2014) compared different mechanisms for electricity generation using speed breakers. Rack-and-pinion mechanism was found to be the most suitable mechanism for more desirable power output.

Sheikh and Din (2018) presented a paper on comparative overview between mechanical speed bumps and speed bumps constructed using asphalt. A critical speed change analysis was conducted by the help of radar gun. The result showed that mechanical speed bumps are better in reducing the speed of vehicles than the speed bumps constructed by asphalt material.

Having reviewed the relevant literatures, the input energy that is widely considered for power generation using the MSB is the energy of moving vehicle. The convenient and efficient mechanism to harvest this energy is the MSB design with rack-and-pinion mechanism and spring system. However, there are limitations noted in its previous designs. The weight exerted on the MSB would not exceed the compression strength of the spring system. Thus, to harvest energy from all moving vehicles on our roadways and also prevent system failure, different MSB would be installed for different vehicle weight categories, which may result in vehicle restrictions on certain parts of the roadways, which may be impracticable.

To address this gap, this study designs the MSB with a spring system as shown in Figure 1, in which two compression springs are arranged in parallel to drive the mechanical energy into the system when the vehicle passes over the MSB and four suspension springs to support the impact of the tyres over the MSB, thus enabling the passage of all vehicle weight categories.

2.0 MATERIALS AND METHODS:

Materials for the prototype fabrication, design analysis, experimentation and performance evaluation of the SBPGS are presented.

2.1 Operation of SBPGS

The SBPGS comprises of two basic parts; Mechanical Speed Bump (MSB) and Energy Storage System (ESS).

2.2 Operation of MSB

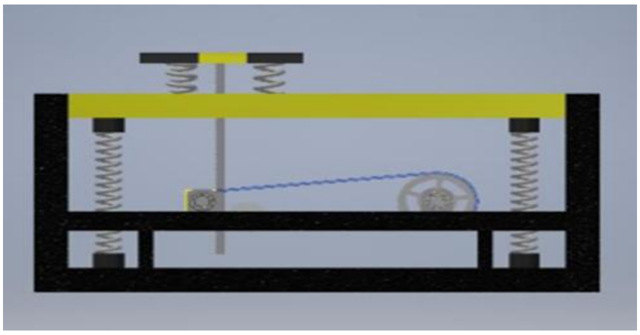

Figure 1(a): Model of the MSB in 2D

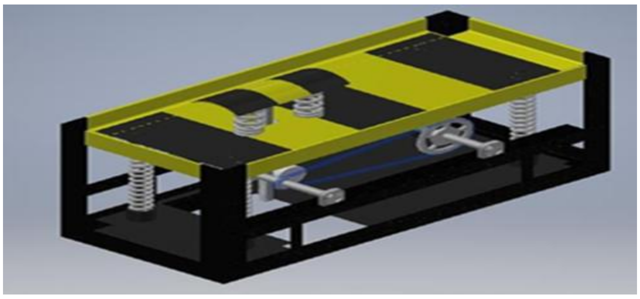

Figure 1(b): Model of the MSB in 3D

The design of the MSB starts with making preliminary sketches that were then drawn using Autodesk Inventor as shown in Figure 1. MSB is made of two units, Speed Bump Cover (SBC) unit and Energy Harvesting (EH) unit

2.2.1 Speed Bump Cover (SBC) Unit

The SBC unit has a geometrical circular profile of the convectional speed bump, two compression springs, a rack and a base plate. The height of the SBC was kept at 150mm and maximum compression of the SBC is 25mm. The compression springs and rack are attached to the SBC. The springs are used to support and guide the SBC on a base plate placed on four suspension springs that are placed at the corners of the frame of the EH unit as shown in Figure1.

When a vehicle passes over the MSB, the tyres exert force on the SBC, the SBC then depresses, the springs attached to the SBC compresses and the rack that is also attached to the SBC moves downward in translational motion. When the two springs compressed to their maximum, the rack reaches the motion limit and stops moving, then the four suspension springs placed beneath the speed bump cover support the impact of the tyres over the MSB. The two compression springs which are arranged in parallel then rebound to their original position by a restoring force the springs developed during compression. The rack works as an input to the EH unit.

2.2.2 Energy Harvesting (EH) unit

The EH unit includes the pinion gear, shafts, bearings, flywheel, large sprocket, freewheel, roller chain, suspension springs, pulley and DC generator, all housed in a frame under the SBC for water proof. A rack connects the EH unit with the SBC unit. A vehicle passing over the SBC will cause translational motion in the rack, which in turn is converted into rotational motion by the pinion gear. The teeth of the rack are in contact with the pinion gear with a pulley placed at the back of the rack to keep them in mesh while the rack moves up and down in its position. The pinion shaft has a large sprocket connected to it, which rotates according to the rotation of the pinion gear, this sprocket is connected to a freewheel sprocket by a roller chain. The pinion shaft engages the freewheel sprocket through the chain to drive the generator shaft. The rotation of freewheel sprocket is magnified according to the gear ratio of the two sprockets. After the vehicle passes over the SBC, the rack moves upward under the spring force. During this process the freewheel sprocket disengages the pinion shaft from the generator shaft. The engagement and disengagement of the pinion shaft from the generator shaft by the freewheel sprocket results in the generator shaft being driven in one direction, irrespective of the direction of the movement of the rack. The flywheel stores the rotational energy available at the freewheel sprocket and feed into the rotor of a linked DC generator and an emf is induced according to Faraday’s law. This emf is transferred through the output wires to the Energy Storage System.

2.3 Prototype Fabrication

In fabricating the prototype, all components which help the desired working of the system

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were considered. Appropriate materials that would withstand high strength and provide a good balance between cost and power generation were obtained after relevant design calculations for the specifications. The prototype was finally assembled as shown in Figure 2. The assembled dimensions are 304.8mm x 990.6mm x 450mm and the prototype is fabricated to1:1 scale factor of the actual MSB and is engineered using spring system that could be tested with a weight of about 392N for the performance evaluation.

Figure 2: Fabricated prototype of MSB

2.3 Experimentation and Evaluation

For testing the performance of the fabricated prototype, maximum compression, compression time on spring and translational speed of rack are calculated. The output wire from the DC generator is connected to multimeter and a known weight is applied by pushing on the SBC for a number of times. The resulting voltage and current measured by the multimeter are recorded. Thus, the electrical power output is calculated using Ohm's law. For the applied weight, the mechanical power input transmitted to the generator and energy conversion efficiency of the system are calculated.

2.4 Mathematical Formulation

The mathematical formulations to achieve the design are as follows:

2.4.1 Spring System

The spring design formulas are given by

$$k = \frac{F_r}{y} \qquad (1)$$

$$k_{eq} = \sum_{i=1,2} k_i = 2k \qquad (2)$$

$$y = L_o - L_s \qquad (3)$$

$$t = 2\pi\sqrt{\frac{m_i}{k_{eq}}} \qquad (4)$$

where k = spring rate (N/mm), F_r = force on the rack (N), y = spring deflection of each spring (mm), k_{eq} = equivalent spring rate (N/mm), L_o = free length of the spring(mm), L_s = solid length of the spring (mm), m_i = mass incident (kg), t = spring compression time (s) (Rao, 2004; Shigley & Mischke, 2015).

2.4.2 Rack and Pinion Mechanism

Designing rack and pinion mechanism is primarily based on three factors, the force on the rack (tangential force), the torque on the pinion and the rotational speed of the pinion (Collins, 2019). They are given by the formulas

$$F_r = m_i g \qquad (5)$$

$$\dot{y} = \frac{y_{eq}}{t} \qquad (6)$$

$$\omega = \frac{2z\dot{y}}{d_p} \qquad (7)$$

$$\tau_p = F_r \frac{d_p}{2000} \qquad (8)$$

$$\tau_d = \tau_p S_F \qquad (9)$$

where $\dot{y}$ = translational speed of rack (m/s), y_{eq} = equivalent spring deflection(mm), ω = rotational speed of generator (rad/s), z = gear ratio of the two sprocket, d_p = diameter of pinion(m), τ_p = applied torque at pinion (Nm), τ_d = design torque (Nm), S_F = factor of safety (range between 1.0 and 4.0) (Andantex, 2007; Shigley & Mischke, 2015; Todaria *et al.*, 2015).

2.4.3 Harvested Energy

Mechanical Energy:

The translational and rotational motions of the rack and pinion gear drive the rotational motion of the generator, which is the power input into the system (Todaria *et al.*, 2015). The power input is given by

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$$P_{in} = \tau_d \omega \qquad (10)$$

where P_{in}= power input (W), (Andantex, 2007).

Electrical Energy:

The voltage and current produced by the generator is proportional to rotational speed and torque of the generator, respectively

$$V = K_v \omega \qquad (11)$$

where K_v = Generator voltage constant (Vs/rad), V= Voltage (V) (Todaria *et al.,* 2015)

$$I = \frac{\tau_d}{k_t} \qquad (12)$$

where I = Current (A), K_t = Generator torque constant (Nm/A) (Eitel & Collins, 2017).

The power output of the generator is given by

$$P_{out} = IV \qquad (13)$$

where P_{out} = power output (W).

2.4.4 Energy conversion efficiency

Energy conversion efficiency is given by formula

$$\eta = \frac{P_{out}}{P_{in}} \qquad (14)$$

2.5 Vehicle Weight

The system is designed for Gross Vehicle Weight Rating (GVWR) of up to 294kN, which is the permissible maximum GVWR of vehicle on our highway (National Road Traffic Regulation, 2012). But two identical MSBs would be installed together in series at a particular location and their total length amounts to the average width of a vehicle. Thus, at any given instance only one tyre is passing on each MSBs and each carrying about one-quarter of the GVWR of the vehicle.

Table 2: Gross Vehicle Weight Rating (GVWR)

Vehicle Categories	Gross Vehicle Weight Rating (kN)	Weight on a Tyre (kN)
Taxi Cab	18.85	4.714
Passenger car	27.65	6.909
Saloon car	14.31	3.577
Sport utility vehicle	20.70	5.174
Sienna	17.66	4.420
Station wagon	16.42	4.106
Passenger van	21.52	5.380
Cargo van	18.72	4.684
Pick up	27.78	6.948
18 Seater bus	35.48	8.870
Coaster bus	23.85	5.968
Luxury Bus	75.46	9.437
Police interceptor utility	21.26	5.312
Light armored Vehicle	44.10	1.103
Medium Truck 2-Axles(single tyred)	74.48	1.862
Medium Truck 2-Axles(Twin-tyred)	80.36	2.009
Heavy Truck 3-Axles	137.2	2.286
Heavy Trucks 4-Axles	176.4	2.205
Heavy Truck 5-Axles	235.2	2.352
Heavy Truck 6-Axles	294.0	2.450

Source: Survey conducted in Port Harcourt

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3.0 RESULTS AND DISCUSSION:

The results of the study are presented and discussed as follows:

3.1 Spring Parameters

The prototype is designed with the compression springs of the following parameters:

For the experiment, the incident mass on the speed bump (m_i) = 40kg

Recall Equation 5; the average exerted force on the spring (F_r) = 40kg x 9.8m/s^2 = 392N

Free length of the spring (L_o) = 150mm,

Solid length of the spring (L_s) = 25mm

Recall Equation 3; y = 150 – 25 = 125mm = 0.125m

Recall Equation 1; spring rate (k) = $\frac{392}{125}$ = 3.136N/mm = 3136N/m

Therefore, the equivalent spring rate of the two springs (k_{eq}) = 2(3136N/m) = 6272N/m

3.2 Experimental Result

Table 3 shows the results of the experiment conducted on the fabricated prototype, which is the resulting voltage and current recorded by the multimeter by applying an average weight of 392N on the Speed Bump Cover.

Table 3: Summary of the Experimental Test Result

S/NO	Voltage(V)	Current (A)
1	1.56	1.02
2	1.50	0.92
3	1.36	0.84
4	1.27	0.65
5	1.24	0.55
Average	**1.386**	**0.802**

3.3 Design Analysis

Analysis of the Power Output:

From Table 3, I = 0.802 A, V = 1. 386V, Recall Equation 11, P_{out} = 0.802 x 1.386 = 1.112W

Analysis of the Spring Compression Time:

Recall Equation 4; m_i = 40kg, k_{eq} = 6272N/m

$$t = 2\pi\sqrt{\frac{40}{6272}} = 0.5s$$

Analysis of the Translational Speed of Rack:

Recall Equation 6; y_{eq} = 0.125m, t = 0.5s, $\dot{y} = \frac{0.125}{0.5}$ = 0.25m/s

Analysis of the Rotational Speed of Generator:

$\dot{y}$= 0.25m/s, $r_p = \frac{d_p}{2}$ = 20mm = 0.02m, $z = \frac{38}{18}$ = 2.1 (Design and fabrication manual).

Recall equation 7; $\omega = \frac{2.1 \text{ x } 0.25}{0.02}$ = 26rad/

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Analysis of the Pinion Torque:

Recall Equation 8; Fr = 392N, d_p = 40mm,

Recall Equation 9; τ_p= 7.84Nm, S_F = 1.0,

τ_d = 7.84 x 1 = 7.84Nm

Analysis of Power Input:

Recall Equation 10; τd = 7.84Nm, ω = 26rad/s

Pin = 7.84 x 26 = 203.84W

Analysis of Energy Conversion Efficiency:

Recall Equation 11; P_{out} = 1.112W, P_{in} = 203.84W

$$\eta = \frac{1.112}{203.84} = 0.006$$

This implied that for every 392N weight exerted on the MSB, the mechanical input power can be analyzed and 0.6% of the mechanical input power would be converted into electrical output power.

3.4 Result of Weight Variation on MSB

The Gross Vehicle Weight Ratings collected through a survey in Port Harcourt contained in Table 2 were inputted in MATLAB code. The MATLAB Program code obtained for the design analysis comprises of parameters for evaluating the actual performance of the system. The results are shown in Table 4 and Figure 3.

Table 4: MATLAB Program code Results

S/N	Weight on MSB (kN)?	Power output (W)
1	3.5770	19.711
2	4.1060	21.119
3	4.4198	21.910
4	4.6844	22.557
5	4.7138	22.627
6	5.1744	23.707
7	5.3116	24.019
8	5.3802	24.174
9	5.9682	25.461
10	6.9090	27.394
11	6.9482	27.471
12	8.8690	31.037
13	9.4374	32.016
14	11.025	34.605
15	18.620	44.971
16	20.090	46.713
17	22.050	48.938
18	22.863	49.833
19	23.520	50.543
20	24.500	51.586

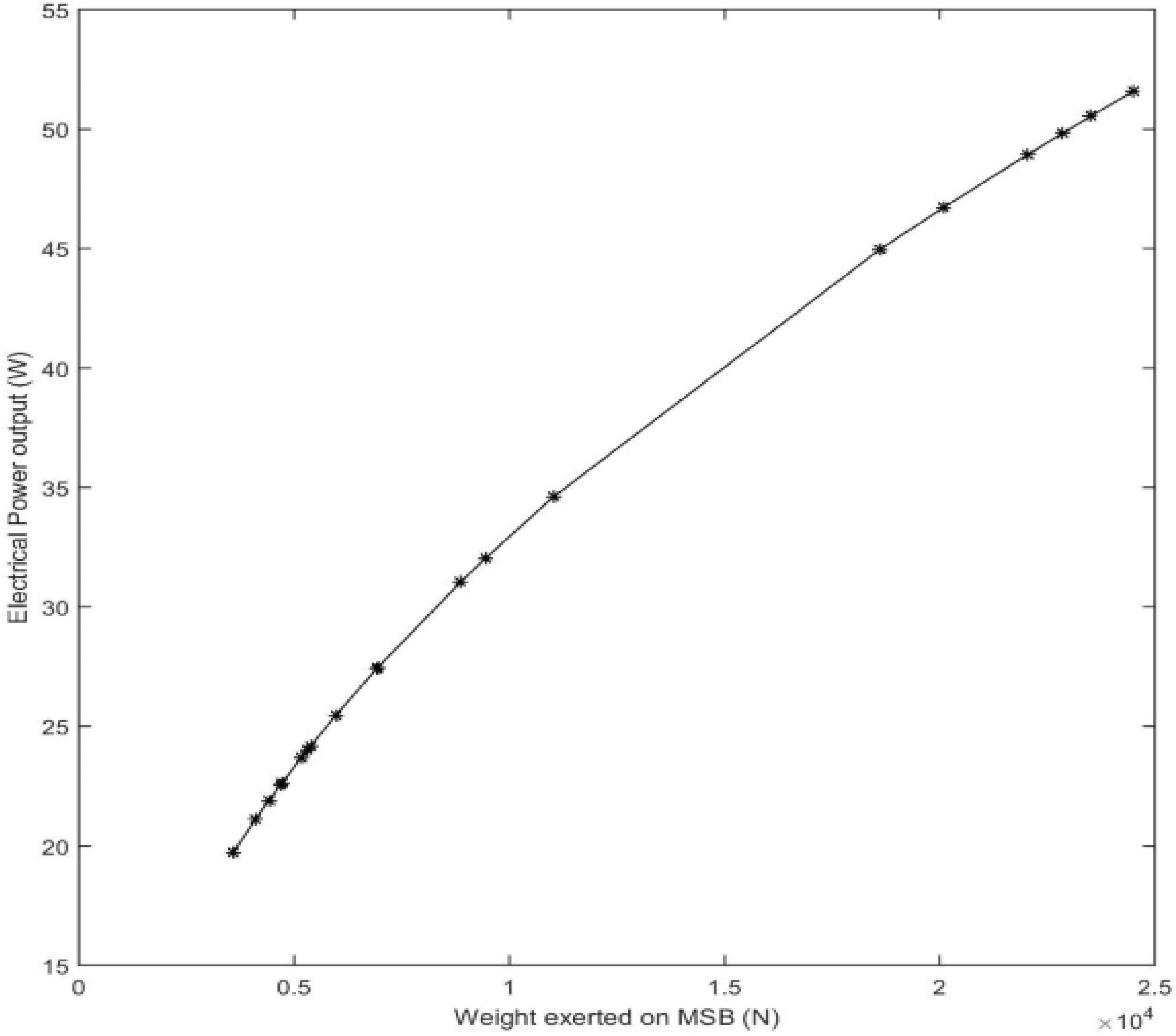

Figure 3: Graph of Electrical Power Output against Weight Exerted on MSB

Table 4 and Figure 3 show the results from the MATLAB program code. It is observed that increase in the weight on the MSB increases the output power. An output power of 32.52W was generated for an average weight of 10.91kN acting on the tyres of vehicles passing on the MSB.

4.0 CONCLUSION:

This study explores the practicality of power generation from road speed bumps by harvesting the energy of moving vehicles using MSB design with rack-and-pinion mechanism and spring system. It includes design analysis and prototype fabrication. The study which achieved its set objectives is summarized as follows:

(i) Model of the MSB design using Autodesk inventor helps to validate the practicality of the system, in addition to the prototype fabrication.

(ii) An experimental test and a theoretical energy assessment were carried out when an average weight of 392N was applied on the fabricated prototype to analyze the power input and output of the system. From this analysis the mechanical power input, electrical power output and energy conversion efficiency were evaluated as 203.84W, 1.112W and 0.6%, respectively.

(iii) A MATLAB program code consistent with this performance was developed for evaluating the actual performance of the system, from which an average weight of 10.91kN acting on the tyres of vehicles plying our roadways, generates 32.52W of electrical power.

In conclusion therefore, this study has demonstrated that SBPGS can harvest energy of moving vehicles on our roadway using MSB and converts it to electrical energy. This would add up to renewable power generation in countries of the world especially the developing ones.

5.0 ACKNOWLEDGEMENT

The authors sincerely thank the staff of Rivers State University Mechanical Engineering Workshop, especially the workshop manager, Mr. Anthony A. Luke, Head of Welding and Foundry Section, Mr. Michel Samuel, Mr. Loveday Biribo and Mr. Joseph Bekee, for their unwavering assistance in the MSB prototype fabrication.

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NOMENCLATURE

d_p	Diameter of pinion (m)
EH	Energy harvesting
F_r	Force on the rack (N)
I	Current (A)
k	Spring rate (N/mm)
K_v	Generator voltage constant (Vs/rad)
MSB	Mechanical Speed Bump
m_i	Mass incident on the speed bump (kg)
P_{in}	Power input (W)
P_{out}	Power output (W)
SBC	Speed bump cover
t	Spring compression time (s)
SBPGS	Speed bump power generation system
S_F	Factor of safety
V	Voltage (V)
y	Spring deflection of each spring (mm)
$\dot{y}$	Translational speed of rack (m/s)
z	Gear ratio of the two sprockets
ω	Rotational speed of generator (rad/s)
τ_p	Applied torque at pinion (Nm)
τ_d	Design torque (Nm)
η	Energy conversion efficiency (%)