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Modeling and Simulation of a Speed Breaker Power Generator

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ABSTRACT

This study demonstrates the power generating performance and structural integrity of a speed breaker power generator, which is designed to generate power from road transportation. A model of the proposed system was designed with CATIA and simulated using ANSYS software. The system employs the principle of piezoelectric effect to convert the wasted kinetic energy of vehicles as they go over the speed breaker into useful electrical energy. The method adopted for this energy conversion utilizes the rack and pinion mechanism. Here, a rack and pinion are integrated beneath the speed breaker under the ground, in such a way that, as the vehicle passes over the speed bump, the linear displacement of the bump is converted by the rack into rotational motion In the pinion, and this was able to drive the shaft at the generator. Calculations and results show that the system could generate an average of 115.9 KW in 24 hours, with variation depending on the volume of traffic. Also, Structural analysis in the areas of stress levels and total deformation experienced by the system was carried out. The results obtained from ANSYS MECHANICAL justified the structural integrity of the system as safe for the stress and forces exerted on it by vehicular traffic. In conclusion, the power generated from this system proved capable of powering certain road electronic appliances like Streetlights, Traffic lights, and some LED displays, and this contributes to the development of sustainable energy resources, especially in Urban infrastructure.

1. Introduction

Energy stands as the fundamental and indispensable requirement for all life on our planet. Presently, the majority of our energy comes from conventional sources, which, unfortunately, are non-renewable and have been extensively depleted [1]. This depletion, coupled with the fact that combustion products from conventional sources, such as fossil fuels, contribute to greenhouse gasses responsible for global warming, underscores a critical global environmental challenge. In light of these concerns, there is a pressing need for a transition from conventional to more sustainable and ample energy sources—renewable energy. Renewable energy sources offer a promising alternative, not only for their capacity to reduce carbon dioxide emissions and mitigate pollution but also for their potential to preserve fossil fuel reserves and mitigate depletion issues. This shift is particularly crucial given the wide-ranging applications of energy resources in electrical power generation, whether derived from renewable or non-renewable sources. In recent times, we have seen breakthroughs in areas of solar and wind power generation as alternate energy sources in meeting the escalating energy demands. However, the ever-growing need necessitates an exploration of additional energy supplies that are not only efficient but also conservative in their utilization.

Road power generation is an alternative technology which uses pressure due to the weight of vehicles for the generation of power. This technological innovation of alternative energy focuses on the concept of power generation using speed breakers. Speed Breakers are structures on roads designed to slow down vehicles as they pass over them. A large amount of energy is wasted by these vehicles on the speed breakers through friction every time they pass over it. Therefore, a small-scale model of a generator is designed to convert the kinetic energy generated by vehicles passing over speed breakers into electrical power, presenting a potential solution for addressing energy shortages.

Speed breaker is the newly emerging technology employed in renewing the wasted energy (kinetic) of a vehicle into electrical energy during the passing time through every speed-breaking hump [2]. Existing literature has shown significant mechanical improvement in the mode of conversion of energy from the vehicle to the generator, as we progress from one mechanism to another. Some of the mechanisms involved in this process include; The Roller mechanism, the Crankshaft Mechanism, the Hydraulic mechanism, and the rack and pinion mechanism. In the Roller mechanism, according to Y. Siva Mallesh and other researchers, they found that the efficiency of the system depends on the speed of the vehicle. i.e.; The speed of the vehicle is directly proportional to the efficiency of the system [3]. Here, the speed breaker is a roller at both ends and they are bearing supported, as vehicles pass over the speed breaker, due to friction, the bearing support causes the roller to generate circular motion. Those circular motions are transferred to the generator by using the available transmission system (belt, gear train chain, sprocket, etc). One major challenge of this mechanism is that the system tends to experience slipping as vehicles goes passed it, and this eventually affects its efficiency.

In the Crank Shaft mechanism of power generation, the crank shaft uses kinetic energy to push down the piston for linear motion to occur, since crank is designed on the basis of inertia [3]. The crank itself makes the one half of the revolution in order to push the piston up. In that manner, the crank is able to create rotary motion which is sent to the generator by means of gear trains for power generation. This method of power generation brings about too much heat and vibration because of too many moving parts [3]. The Hydraulic mechanism of energy harvesting by speed breakers, gives better output performance when compared to the crank shaft mechanism [3]. This is due to the fact that the introduction of the hydraulic press into the system contributes to smoother movement, minimizing friction & optimizing the overall efficiency of the energy conversion process [4]. Here, the speed breaker is a spring that is supported at both ends in order to produce linear motion. A piston compresses the oil beneath the speed bump when the car drives over it.

The accumulator is the destination of this compressed oil. The motor, which produces torque and electrical energy, is additionally connected to the accumulator. Sanjida Parvin noted that as the vehicle passes over the speed bump, a piston compresses the oil provided under it. This compressed oil travels to the accumulator. The accumulator is further connected to the motor which generates torque and the torque generates the electrical energy. This system produced the highest efficiency when compared to the others, because of its limited moving parts. Its major challenge is that it is too expensive to setup and maintain [4].

This Paper is looking to introduce the concept of kinetic energy harvesting via speed breakers, using a Rack and Pinion as its mechanism. Two half pinions situated at both sides of the rack are connected to a set of gears. One pinion is connected and rotates when the rack is moving downwards and disconnects when the rack reaches the bottom position. When the rack is moving upwards, it connects with the other pinion and hence rotational motion is ever present in the system. The pinions are connected to two additional gears that help keep the motion of the half pinions continuous when they are disconnected from the rack. A third gear at the center is used to transfer the pure rotational motion into the gear that directly drives the input shaft (rotor) of the generator. The teeth on the rack act upon those of the semicircular tooth pinions and the spur gears attached to the pinions operate on the center gear which is responsible for driving the gear that rotates the input shaft of the generator. The power harvested from the linear motion of the rack to the rotational motion of the shaft is stored using an EMF power cell (battery) for use at a later time.

One of the significant challenges facing the world today revolves around the energy crisis, with conventional power generation methods contributing extensively to pollution [5]. While there exist alternative means such as wind, solar, and wave energy, the rapid evolution of technology around these non-conventional methods has hindered their widespread adoption. In tandem with pollution from power generation, the increasing number of vehicles on the road compounds environmental issues. This continuous strain on our environment is further exacerbated by the high costs associated with acquiring fossil fuel energy. Consequently, there is a pressing demand for low-cost and easily accessible resources. This project aims to contribute to environmental preservation and mitigating pollution to a certain degree.

There are an estimated 2.2 billion registered motor vehicles (including motorcycles) globally, a number that is expected to increase in the years to come and double by 2040 [6]. There is a valuable opportunity to harness and convert the kinetic energy wasted during vehicle movement. Introducing specialized mechanisms under speed bumps on roads provides a means to achieve this goal. The envisioned project seeks to capitalize on the abundance of vehicles on the road—whenever a vehicle traverses the speed bump, it captures the kinetic energy and converts it first into mechanical energy and subsequently into electrical energy. This innovative approach not only utilizes the otherwise wasted kinetic energy of vehicles but also contributes to reducing environmental pollution. Simultaneously, the project addresses the demand for low-cost and easily accessible energy resources, aligning with the broader goal of sustainable and Eco-friendly energy solutions.

1.2 Governing Equations of the System

The system is basically made up of three (3) major components whose design parameters would be crucial to properly design the system to resist internal stress due to varying loads from the vehicles as they go over it. These parts are; (a) The Springs (b) The Gear drives (c) The Rack and Pinions. The sets of governing equations to be used for each of these component design parameters is shown in the following equations below.

Equation (1) to (5) are the governing equations for the Spring parameters.

$$K = \langle \left(4C - \frac{1}{4}C - \frac{4}{}\right) > \frac{\frac{0.615}{C}}{}\rangle \tag{1}$$

$$\tau = 8WCK > \pi d^2 > \tag{2}$$

$$\delta = 8WD^3 n > Gd^4 > \tag{3}$$

$$Ls = N > d > \tag{4}$$

$$P = L > N - 1 > \tag{5}$$

Equation (6) to (8) are the governing equations for the Gear drives (including the rack and pinion) parameters.

$$D = Z > m > \tag{6}$$

$$P = \pi D > T > \quad (7)$$

$$t = \frac{1}{2} > P > \quad (8)$$

Equation (9) and (10) are the governing equations for the power output.

$$W = F > s > \quad (9)$$

$$P = W > t > \quad (10)$$

2. Methodology
2.1 Proposed Method

The method proposed in this project is the use of the rack and pinion system, as stated earlier in the introduction. The rack and pinion mechanism in CATIA is illustrated in Figure 1 below, and the principle employed in this mechanism involves efficiently converting the linear motion of the vehicles as they pass over the hump into rotational mechanical energy using the rack and pinion mechanism.

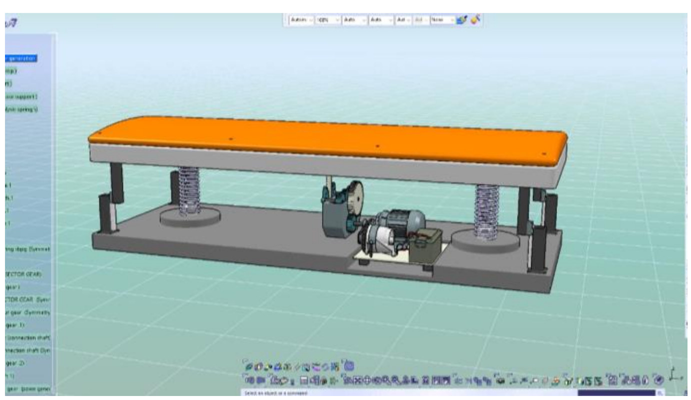


Figure 1. The rack and pinion mechanism in CATIA

2.2 Design Calculations
Assumptions made:

I. Width of the bump = 3.5m (which is the average width of a road per lane, as the bump is expected to spread across a whole lane)
II. Vertical (linear) displacement of vehicles on the springs as they pass over the speed breaker = 0.12m (this value is an assumed value, depending on the designer's choice of spring design)
III. The system is expected to endure a load of 5000N which is the average weight of a vehicle's tire expected to pass over it.

A. Speed bump specifications:

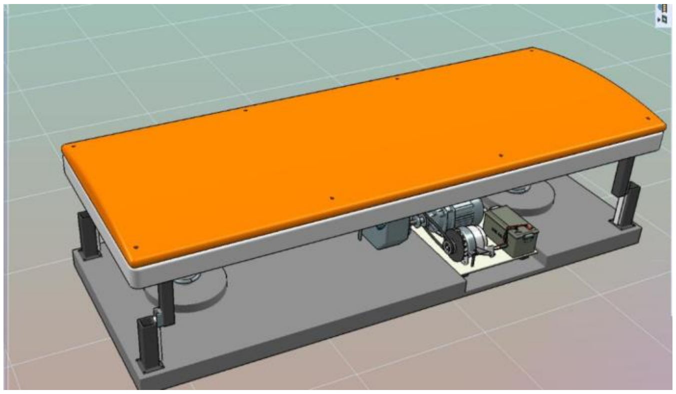


Figure 2. The speed bump Design

The Figure 2 above is a representation of the speed bump Design according to specifications and assumptions as outlined below.
i. Length = 3.5 m (width of the road)
ii. Height = 4 inches (Standard Speed breaker sizes)
iii. Width = 1.5 m (Standard Speed breaker sizes)

B. Spring Parameters and Design:

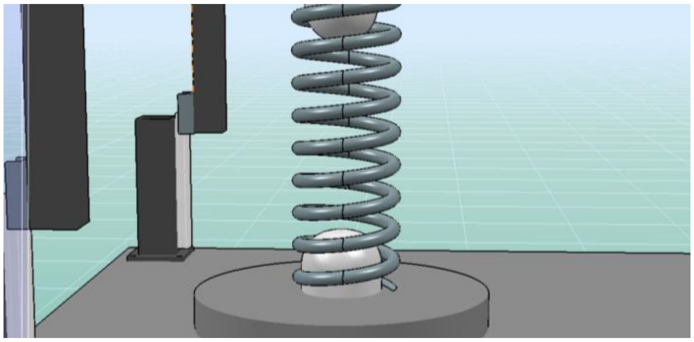


Figure 3. The springs

The springs, as shown in the Figure 3, are the major load carriers of this system, as such careful design analysis needs to be carried out in order to avoid the system from failing under varying stress.

Material Selected: Patented cold drawn steel wire (ASTM A227, CLASS 1)

Ultimate Tensile Strength (UTS) of material selected: 1090 N/mm² (1090 X10^6 N/m²)

Modulus of Rigidity (G) of material selected = 81000 N/mm² (81 X10^9 N/m²)

Load (W) of vehicle expected to withstand = 5KN

Deflection (δ) = linear displacement of vehicle = 0.12m

Spring index (C) = 6

i. Calculating the wire diameter, 'd'

The allowable stress, 'τ ' is given as;

τ = UTS/2

Where UTS is the Ultimate Tensile Stress of material selected

τ = 1090/2 = 545 N/mm²

The Wahl's correction Factor, K

K ={(4c - 1)/(4c - 4) + 0.615/C}

K = {(4(6) - 1)/(4(6) - 4) + 0.615/6}

K = 1.2525

Therefore;

The wire diameter is related to the stress as follows:

$\tau = (K \times 8WC)/\pi d^2$

$d = [(1.2525 \times 8 \times 5000 \times 6)/(\pi \times 545)]^{½}$

d = 13.25mm (13mm)

ii. The mean coil diameter; D

C = D/d

D = C x d,

$D = 6 \times 13$

$D = 78mm$

iii. The number of active coils; n

$\delta = 8WD^3n/Gd^4$, $n = Gd^4\delta/8WD^3$

$n = (81000 \times 13^4 \times 120)/(8 \times 5000 \times 78^3)$

$n = 14.625 \approx 15$

iv. The Free Length of Spring: L

For square-end springs, each end coil is inactive and the number of active coil relates to the total number of coils as;

$n = N - 2$

where n = number of active coils

N = Total number of coils

Total number of coils, N = 17

The Solid length of the spring when all the coils is touching is given as; L_s

$L_s = N \times d$, $L_s = 17 \times 13 = 221$ mm

The total axial gap between the coil will be (N-1) = 16 mm (after deflection)

Therefore;

The free length (L) = Solid length + Total axial gap + δ

The free length (L) = 221 + 16 + 120

L = 357 mm

v. The pitch of the coil; P

P = Free Length/(N-1)

P = 357/16

P = 22.313 mm

C. The Frame (Top and base) Parameters and design:

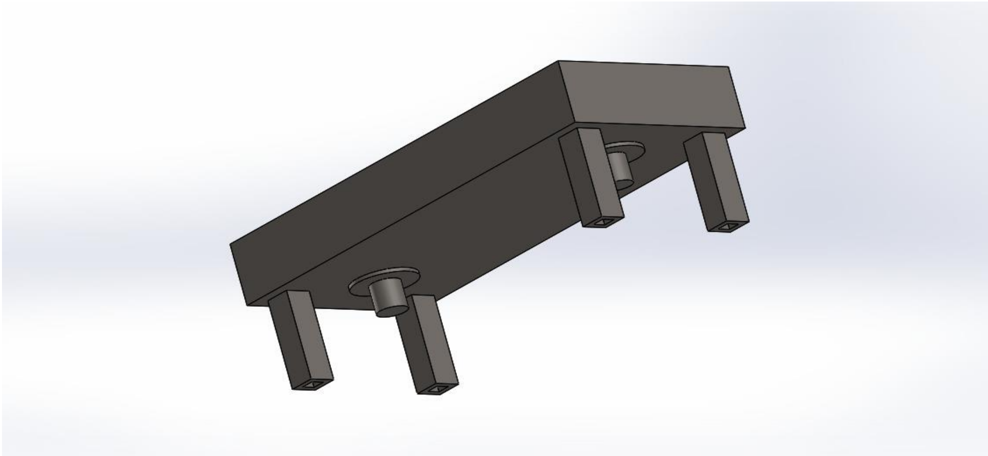


Figure 4. The frames at the top and the base of the system

Figure 4 represents the frames at the top and the base of the system. These are another load carriers of this system, therefore it is important that design analysis is carried out to avoid failure of the system.

Assumptions made:

i. The length of the top plate will be equal to that of the speed bump = 3.5m

ii. The width of the top plate will be equal to that of the speed bump = 1.5m

iii. The material to be selected for use; Cast Iron (Ductile iron ASTM A536 GRADE 60-40-18)

iv. Ultimate Tensile Strength (UTS)= 413 Mpa (413 N/mm^2)

v. Yield Tensile Strength = 276 Mpa (276 N/mm^2)

vi. These parameters are same for the base plates

Here we will calculate the "safe" thickness 't' of the rectangular plate under the known conditions;

First, we calculate the volume from the weight and density of the rectangular cast iron.

The weight of vehicle = 5000N

Density (cast iron) = 7850 kg/m^3

Density = Weight/Volume

Volume = Weight/Density;

Volume = 5000/7850

Volume = 0.637m^3

Thickness (t) = Volume/Area

Area = Length × breadth

Area = 3.5 × 1.5

Area = 5.25 m^2

Thickness = 0.637/5.25

Thickness (t) = 0.121m

D. Rack and Pinion Design:

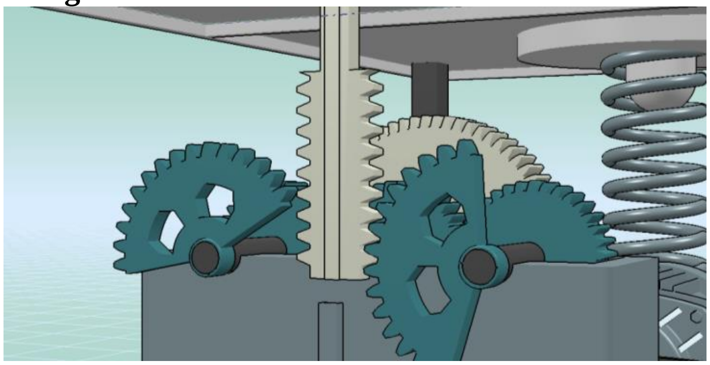


Figure 5. Rack and Pinion

Designing rack and pinion for every 120 mm (0.12m) displacement of rack and one revolution of pinion as shown in figure 5 above.

Parameters:

Number of teeth (T) = 17

Pressure angle = 20° Involute

Module (m) = 6mm

Pitch Diameter = T x m

D = 17 x 6 = 102mm

Mounting Distance (s) = 120mm

Rack pitch height (H) = Mounting distance - Pitch radius of rack

H = 120 - (102/2) = 171mm

Circular pitch of pinion = (2πr)/T = (2π x 51)/17 = 18.85mm

Linear Pitch (Rack) = Circular Pitch = 18.85mm

Tooth thickness = Circular Pitch/2 = 9.42mm

Addendum = Module = 6mm

E. Gear Design:

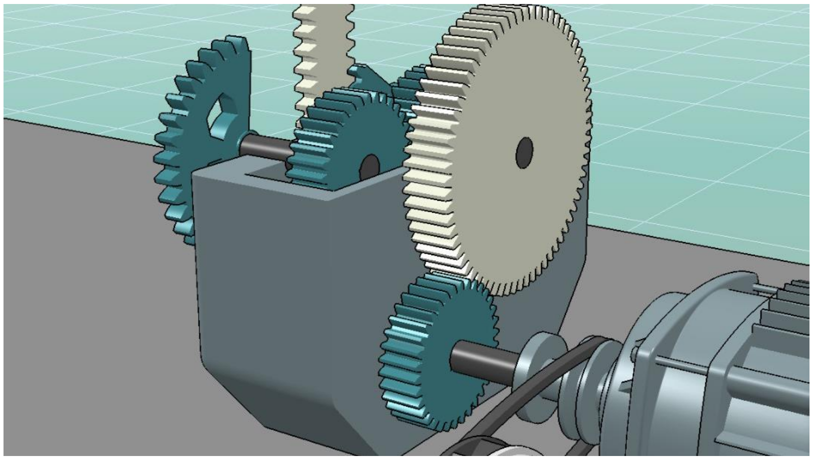


Figure 6. The Gear

Here, the gear parameters for the gear sets (small and large gear), as shown in figure 6, is determined.

No of teeth (T) =15:75 (15 and 75 for the small and large gear, respectively)

Pitch diameter (D) = z*m

Pitch diameter (D) =15*2.5 = 37.5mm (for the small gear)

Pitch diameter (D) = 75*2.5 = 187.5mm (for the large gear)

Circular pitch (P) = [2π*(37.5/2)]/15 = 7.85mm (same for both small and large gear)

Tooth thickness (t) = ½*circular pitch

Tooth thickness =1/2*7.85

Tooth thickness = 3.925mm.

Three gears of same pitch diameter are to be made; These are the gears which are connected to the pinions by means of shafts.

Therefore, we calculate for the parameter of one of the gear (the middle one) and use same values for the others (two end gears) as the gears are intended to be of same sizes.

Pitch diameter of middle gear = [rack thickness +(2*radius of pinion)]/2

Pitch diameter = [60+(51*2)]/2 = 81mm

Module of these gear set is taken as 2

Number of teeth = pitch diameter/2

Number of teeth =81/2 = 41

Circular pitch = [2π*(81/2)]/41 = 6.21mm

Since the gear ratio has to kept same

N1:N2:N3::1:1:1

All three gears will be the same

2.3 Power Output Calculation

Parameters:

The Maximum weight of a tyre = 5 kN

Displacement of Rack (Rectilinear displacement of vehicles) = 120 mm

Therefore,

The Maximum Power output produced by the System is given by;

Work done = load (Newtons) x Displacement of the rack (meters)

Work done=5000 x 0.12 = 600 Joules

Power produced = Work done per second

For a period of 1 minute (60 seconds), the maximum power produced is…

Power produced = 600/60 = 10 W

Similarly, for other vehicles with tyres' weight of 2875 N, 3750 N, 4000 N and 4500 N, the power produced are 5.75 W, 7.5 W, 8 W, and 9 W respectively.

Hence, the Average Power from all the different vehicles is 8.05 W per minute.

Therefore, average power produced per hour by an average of 10 cars passing is;

8.05 x 60 x 10 = 4.83 kW

The Average amount of power that can be produced in one day (24 hrs) is;

4.83 x 24 = 115.9 kW

2.4 Power Output Applications

The goal of the speed breaker power generator is to generate enough power to run other electrical appliances on the road like; the Street light, Traffic lights, and other LED display devices. Therefore a breakdown of the power requirements of these devices will be carried out to check if the 115.9 kW power produced in a day is sufficient to run these devices.

i. Street lights:

Street lights use a 30 W bulb. If we use 100 Street Lights in a 1km radius with each light running for approx 12 hours, it will consume **36 kW** of power.

ii. Traffic Signals:

Traffic Signals use about 20W LED lights. If we operate 20 signals with 3 sections each for 24 hours, it will consume **28.8kW** of power.

iii. LED displays:

LED displays consume around 150W of power. If we operate 6 LED displays for 24 hours, it will consume **21.6 kW** of power.

Adding all these power together gives a total of about **86.4 kW**. Therefore, we can run these devices with our generated power.

2.5 Computational Analysis.

Every Structural design must be able to withstand failure, otherwise the design is not safe for implementation.

Computational Analysis was carried out to analyse the structural Integrity of our proposed model; speed breaker power generator, using ANSYS workbench, in order to test for both its von-Mises Equivalent stress and Total deformation experienced with respect to the load (5000 N) acting on it.

The Colour contours on the surface of each analysed structure indicates the intensity of stress concentration on the structure in increasing order from blue to red. There's a colour ledger beside the components that shows different values of the parameter being analysed, with the least value taking the blue Colour and the maximum value being indicated by the red.

3. Results and Discussion

Table 1: A Summary of the weight of each vehicle type; Small cars, Sedans, SUVs, Pickup Trucks, and Mini Buses and the corresponding power output

S/N	Vehicles	Weight of the tyre (N)	Power Output (W)
1	Small Cars	2875	5.75
2	Sedans	3750	7.5
3	SUVs	4000	8
4	Pick-up Trucks	4500	9
5	Mini Buses	5000	10

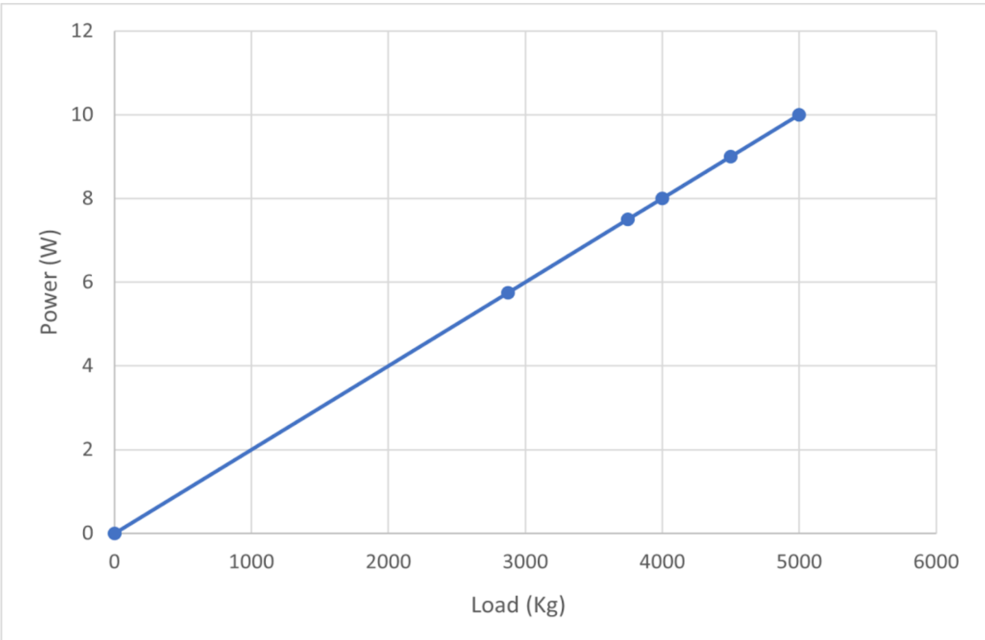
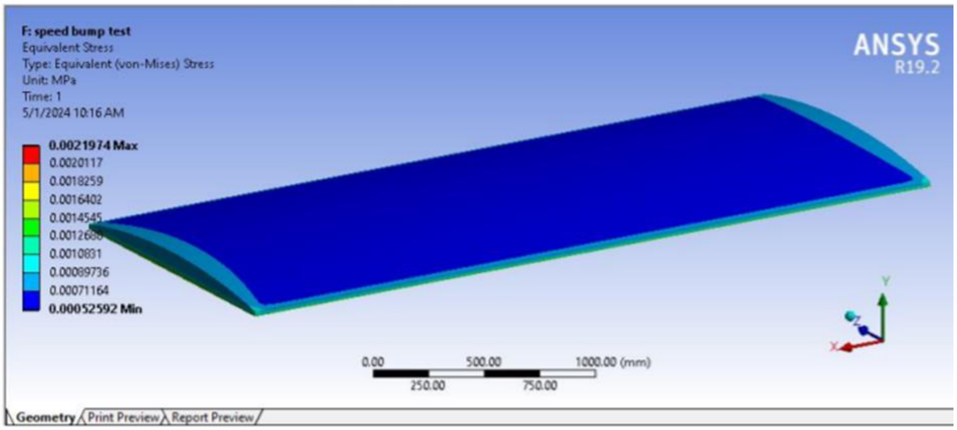


Figure 7. A Plot of Power Against Load

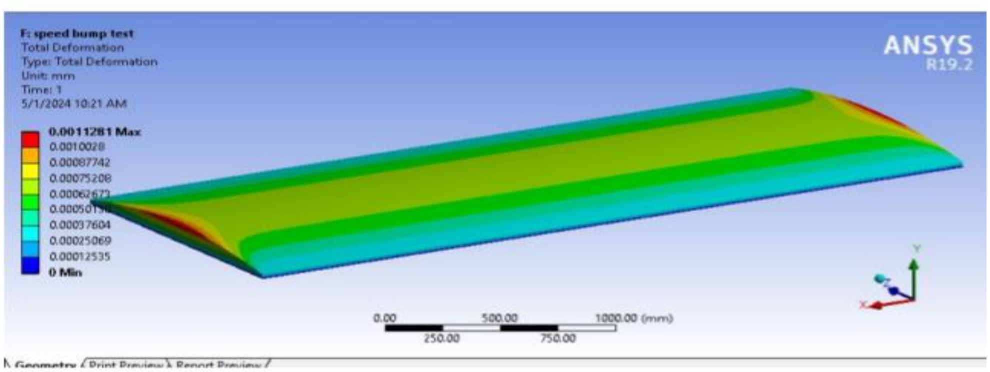
Model (F4) > Static Structural (F5) > Solution (F6) > Equivalent Stress



Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1.	5.2592e-004	2.1974e-003	5.9068e-004

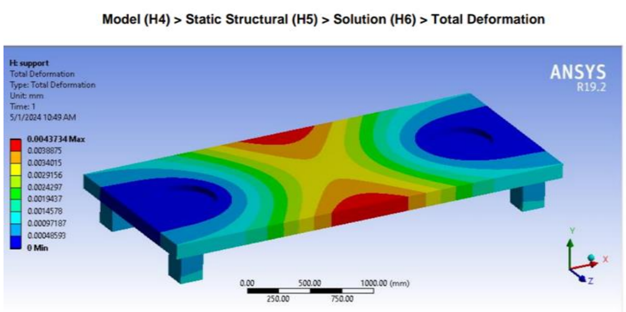
Figure 8. Analysis of the PVC speed bump

Model (F4) > Static Structural (F5) > Solution (F6) > Total Deformation



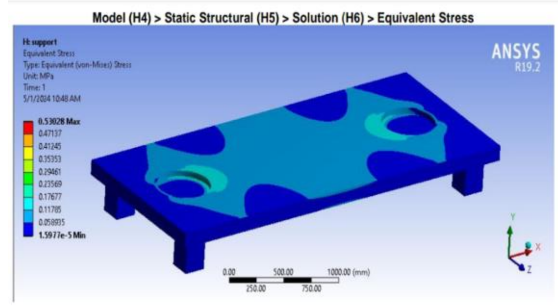
Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1.	0.	1.1281e-003	2.7486e-004

Figure 9. Total Deformation Analysis



Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1.	0.	4.3734e-003	1.5317e-003

Figure 10

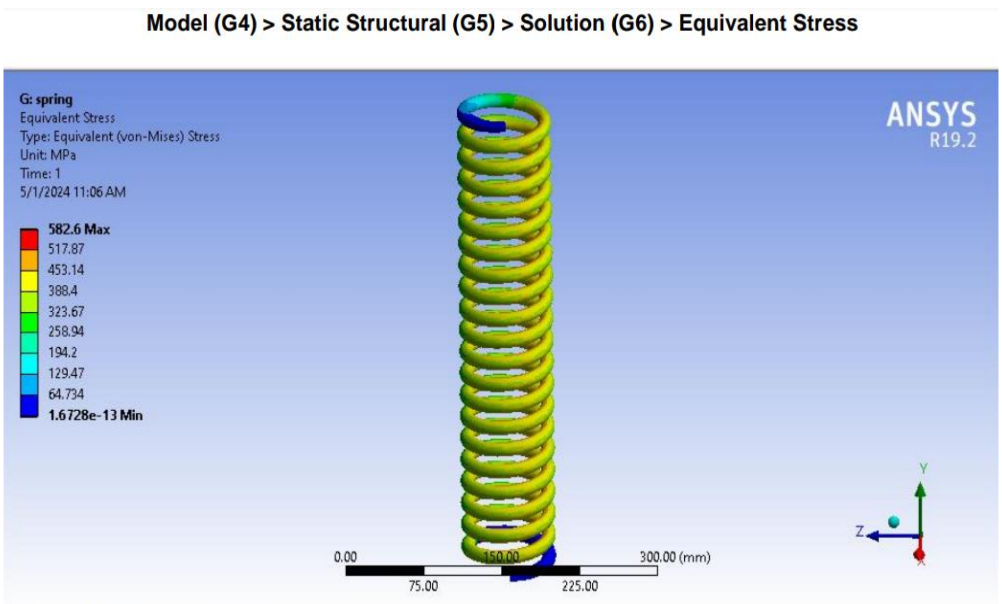


Model (H4) > Static Structural (H5) > Solution (H6) > Equivalent Stress

Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1.	1.5977e-005	0.53028	4.0641e-002

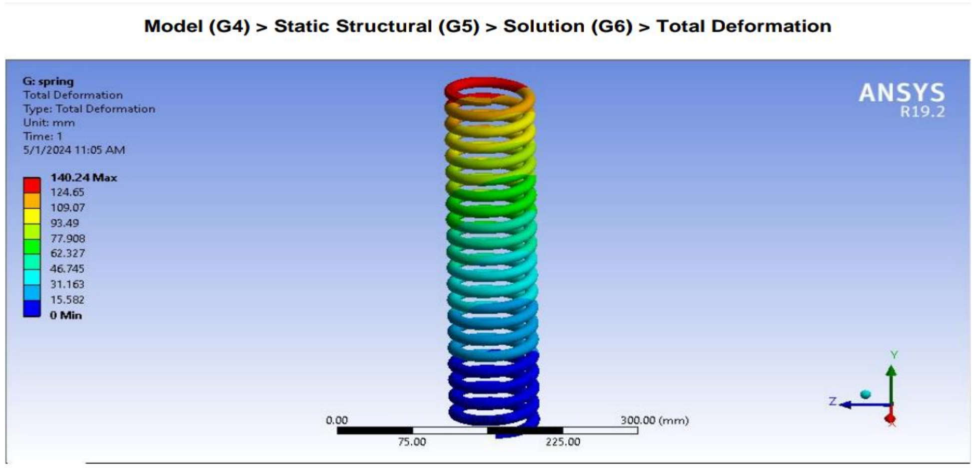
Figure 11

Figure 10 and 11. The total deformation and von-Mises stress analysis of the top and bottom frame sections respectively



Time [s]	Minimum [MPa]	Maximum [MPa]	Average [MPa]
1.	1.6728e-013	582.6	284.15

Figure 12. Equivalent Stress analysis of the spring



Time [s]	Minimum [mm]	Maximum [mm]	Average [mm]
1.	0.	140.24	55.18

Figure 13. Total Deformation Analysis of the Spring

Table 1 above summarizes the weight of each vehicle type; Small cars, Sedans, SUVs, pickup trucks, and minibuses and the corresponding power output as calculated. As expected, a direct correlation between the vehicle weight (load) and the generated power was observed. Starting with the vehicle with the least weight; Small cars, the power produced in 60 seconds was 5.75 Watts. As the weight of the cars passing over the system increased from small cars to minibuses, the power generated also increased, with 10 Watts being the highest power generated from the minibuses. The data from the graph of Figure 7 above show a similar trend to those in Table 1; a linear relationship between power output and load. Smaller vehicles, such as small cars (2875 N), produced the lowest power (5.75 W), while heavier vehicles like mini buses (5000 N) generated the highest power (10 W). These results confirm the functionality of the rack and pinion mechanism in converting the kinetic energy of vehicles into electricity.

Figure 8 demonstrates that the analysis of the PVC speed bump is structurally safe. The average von-Mises stress (5.9068e-4Mpa) within the speed bump remains well below the maximum yield stress (2.1974e-3Mpa) indicated by the color ledger. This confirms the material's suitability for the application. Also, according to Figure 9, the total deformation analysis further supports the structural integrity of the speed bump, as the average deformation (2.7486e-4mm) does not exceed the maximum deformation (1.1281e-3mm). The observed colour distribution across the structure also suggests minimal deformation under the applied load, validating its reliability for real-world implementation.

Figure 10 and Figure 11 represent the total deformation and von-Mises stress analysis of the top and bottom frame sections. These parts were analyzed to evaluate their ability to support the speed bump and connect to the springs. The analysis results indicate that the frame design is safe under the specified load. However, the total deformation analysis reveals a region of high-stress concentration (red colour) around the edges of the frame. This is attributed to the sharp edges, which tend to concentrate stress. While the overall system experiences safe deformation with an average value (1.5317e-3mm) which is well below the maximum total deformation (4.3734e-

3mm), future design iterations may consider incorporating rounded edges to mitigate stress concentration in these areas.

Figure 12 and Figure 13 shows the result of the equivalent stress and total deformation analysis of the spring. The springs are critical components as they bear the primary load from vehicles. The analysis simulated a 2500 N load on a single spring, considering the series configuration that distributes the load equally. The equivalent stress analysis showed an average of 284.15Mpa which is less than the maximum allowable stress value of 582.6Mpa. This suggests that the designed spring experiences relatively low stress under the applied load, indicating structural stability based on the colour contours and stress values. Similarly, the total deformation analysis shows minimal deformation within the spring, further supporting its structural integrity under the expected operating conditions.

4. Conclusion

The findings from this study demonstrate the potential of the speed breaker power generator as a viable source of renewable energy. The positive correlation between vehicle weight and power output highlights the system's ability to harness the kinetic energy of traffic flow. The estimated power generation capacity suggests the feasibility of powering essential roadside applications like streetlights, traffic signals, and LED displays.

The FEA results demonstrate that the proposed speed breaker power generator design exhibits satisfactory structural integrity under the anticipated load (5000 N). The analyses of the speed bump, frame, and springs using von-Mises stress and total deformation confirm the system's ability to withstand operational stresses without failure. Further design optimization focusing on mitigating stress concentrations around the frame edges may be considered for future iterations.

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