Performance Evaluation and Parameter Sensitivity of Speed Bump Energy Harvester Passed by Various Vehicles

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Abstract. Commonly, road bumps are used to reduce vehicle speeds thus improving safety for pedestrians. Recently, there is an increased interest to exploit road bumps in developing energy harvesting. This paper compares the vehicle suspension dynamics when pass over conventional and energy harvesting speed bumps with different speeds. Numerical simulations are based on various types of vehicles including passenger cars, buses, and trucks. Results show that at lower speeds, vehicles give better performance in case of energy harvesting speed bumps than conventional bumps and this performance is more improved for heavy duty vehicles. Additionally, the sensitivities of suspension performance and harvestable power to the speed bump energy harvester, [SBEH], parameters are investigated and addressed. This parameter sensitivity study demonstrates that SBEH mass, SBEH equivalent damping, and the maximum allowable displacement of the bump have significant effect on the suspension performance and the harvestable power. So we use also Genetic Algorithm (GA) based on multi-objective optimization techniques to search the optimal values of these significant parameters of the SBEH considering the trade-off between ride comfort, road handling, and harvested energy.

Keywords: Vehicle suspension; Speed Bump; Energy harvesting, Dynamics of multi degree of freedom, Genetic Algorithm Optimization.

1. Introduction:

No doubt that, the tremendous vehicular growth through last century leads governments to try to control the traffic problems. Speed bumps are often used on private roads in areas such as the grounds of universities and camping sites to encourage motorists to travel at low speeds [1]. There is a large numbers of published studies describing different designs of speed bumps [2]- [3]- [4] [5]. Ardeh et al. [6] presented a new approach to the shape optimization of road speed humps. During the last two centuries, energy consumption has increased rapidly due to population growth and technology improvements [7]. Because fossil fuels are finite and environmentally costly and due to the urgent need to clean energy, several recent studies have been carried out on energy harvesting to reduce the energy shortage problem. By means of piezoelectric materials [8] or electromagnetic devices [9] free clean energy can be acquired from environment. Due to the increased number of speed bumps on roads, innovative techniques are required for harvesting the wasted kinetic energy as much as possible [10]. Recent developments in this field have led to a renewed interest in harvesting energy from speed bumps. Zuo et al (2015), proposed a novel speed bump energy harvester, which can generate large-scale electrical energy when vehicles pass over it [11]. On the other hand, many attempts had been done in suspension systems design to ensure the safety and ride comfort of the driver. Active and semi-active systems are studied in the last decades to achieve these goals [12].

In this paper, Numerical simulations based on various types of vehicles are performed, in order to compare the vehicle suspension dynamics when pass over conventional and energy harvesting speed bumps with different speeds. Results show that vehicles provide better performance in case of energy harvesting speed bumps than conventional bumps if the entrance speed is smaller than a certain value. Especially for heavy duty vehicles, this performance is more improved. The parameters of SBEH are also studied to highlight the parameters that have a significant effect on suspension performances and energy harvesting. This parameter sensitivity study demonstrates that the values of SBEH mass, SBEH equivalent damping, and the maximum allowable displacement of the bump should be carefully selected. These significant parameters of SBEH are also optimized using GA for suspension performances and energy harvesting, which can guide the design of SBEH. The paper is organized as follows. In Section 2, the design principle of SBEH is briefly reviewed, and the interaction between models of SBEH, conventional bump, and the vehicles are created. In Section 3, suspension performance indices and energy harvesting are introduced. In Section 4, simulations for both conventional bump and SBEH are conducted on various vehicles and the results are given. In Section 5, parametric study of SBEH is carried out. In Section 6, optimal selection of SBEH significant parameters is obtained by considering the ride comfort, road handling, energy harvesting and the trade-off between these performances.

2. Modeling and Road Dynamics:

2.1. Vehicle modeling

Researchers use the quarter car model extensively in studying the vehicle dynamics due to its simplicity. This model may be considered as a 2-DOF model or 3-DOF model, if seat is considered, depending on the degree of simplification. In this work, the driver and his seat are assumed to be rigidly connected to the vehicle body. The 2-DOF model consists of the wheel and its attachments with mass M_u stiffness K_t, sprung mass M_s, and suspension stiffness K_s and damping C_s.

2.2 Input Modeling:

In general, a typical road is characterized by the existence of large isolated irregularities, such as potholes or bumps. In the present work, two model inputs are considered. The first one is a fixed trapezoidal speed bump. The second input is a trapezoidal speed bump energy harvester, which can be modeled as a moving speed bump.

2.2.1. Modeling of conventional trapezoidal speed bump:

Speed bumps should have height 7.6-15 cm and, travel length 30-90 cm, with vehicular passing speeds around 8 km/hr or less [13]. Hence, the geometrical dimensions of the used trapezoidal speed bump are selected as shown in Fig.1. Trapezoidal bump consists of three segments of different equations.

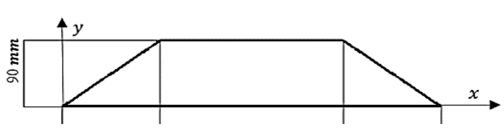

Fig.1 Conventional Trapezoidal Speed Bump

The vertical deflection depends on the segment at which the interaction occurs in Fig. **2**. The equation of the vertical deflection may be written as:

$$y = \begin{cases} 1.125\,x, & 0 \le x \le 80 \\ 90, & 80 \le x \le 230 \\ -1.125\,x + 348.75, & 230 \le x \le 310 \\ 0 & 310 < x \end{cases} \tag{1}$$

The contact between the vehicle model and the conventional bump includes 4 stages as shown in Fig. **2**.

The two equations of motion represent the model can be written as follows:

$$M_s \ddot{x_s} + c_s(\dot{x_s} - \dot{x_u}) + k_s(x_s - x_u) = 0 \tag{2}$$

$$M_u \ddot{x_u} + c_s(\dot{x_u} - \dot{x_s}) + k_s(x_u - x_s) + k_t(x_u - x_o) = 0 \tag{3}$$

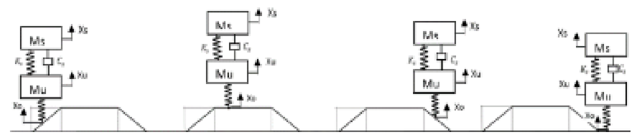

Fig. 2 Stages of interaction between vehicle and the bump

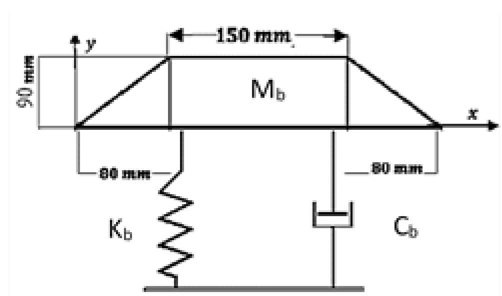

Fig.3 Equivalent Model of SBEH

The speed bump harvester shown in Fig.3 can be modeled as a trapezoidal bump with mass   based on spring with stiffness and equivalent damper [11]. The mass includes two terms; the mass of the speed bump cover   and the equivalent mass of the energy harvester unit, which can be expressed in terms of the following equation:

$$M_e = \frac{J_p + J_c + n^2 J_m}{r^2} \tag{4}$$

Where, J_c, J_p and J_m are the inertia of coupling shaft, pinion gears and generator respectively. The n is the gear ratio of the gear box and r is the pinion gear radius. So, the total mass of the unit may be expressed as:

$$M_b = M_c + M_e \qquad (5)$$

The stiffness K_b represents the total stiffness of the four supporting springs. The springs have function to provide rebounding force to the speed bump so that it can be returned to its original position upon load removal. They are preloaded at 5% displacement in addition to the static weight so that, the speed bump can rebound quickly under the damping force induced by the harvester.

There are two kinds of damping in energy harvester unit. The first one is the mechanical damping, C_m, The second one is the electrical damping, C_e, which caused by internal circuit resistance and electrical load on the generator. The electrical damping may be modeled as the following equation [9]

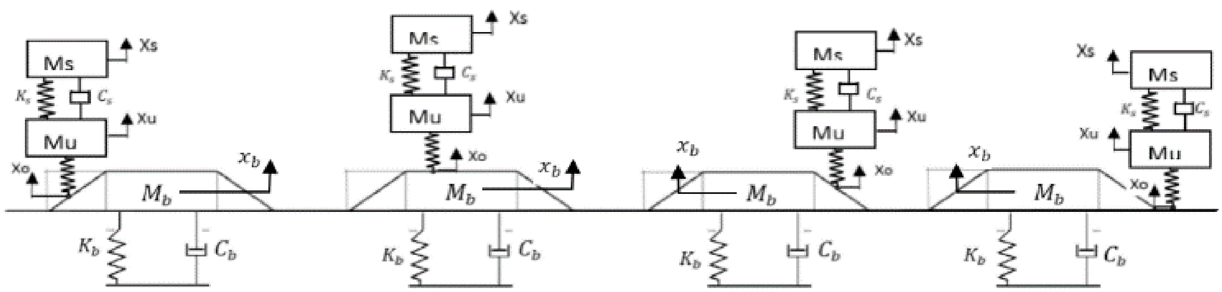

Fig.4 Stages of interaction between vehicle and SBEH model

$$C_e = \frac{K_t\, K_g\, n^2}{(R_i + R_e)\, r^2} \qquad (6)$$

Where, K_g, K_t and R_i are voltage constant, torque constant and internal circuit resistance and R_e is the external load connected to the output from the generator.

Thus the total damping of the model becomes:

$$C_b = C_m + C_e \qquad (7)$$

Where, C_m is the mechanical damping caused by the energy loss in the moving parts. For simplification, this mechanical damping ratio of 10% has been assumed for the harvester [9].

The displacements of the speed bump, $\boldsymbol{x_b}$, in both downwards and upwards directions are restricted with stoppers which limit the motion of the bump in both directions. Therefore, the maximum speed bump displacement can be limited and defined by $\boldsymbol{x_{bmax}}$.

The study of vehicle dynamics in this work depends mainly on which speed bump the vehicle passes over. In case of passing over the conventional fixed speed bump, the model can be treated as two degree of freedom. On the other hand, while passing over the **SBEH**, the model is complicated to be three degree of freedom model. The contact between the vehicle model and the **SBEH** includes also 4 stages as shown in Fig.4. However, in case of **SBEH**:

During the first three stages, the model is treated as one system of three DOF whose governing equations can be written as follow:

$$M_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_u) + k_s(x_s - x_u) = 0 \qquad (8)$$

$$M_u\ddot{x}_u + c_s(\dot{x}_u - \dot{x}_s) + k_s(x_u - x_s) + k_t(x_u - x_o) = 0 \qquad (9)$$

$$M_b\ddot{x}_b + c_b\dot{x}_b + k_b x_b - k_t(x_u - x_o) = F_{preload} - F_g \qquad (10)$$

Where F_g is the weight of the vehicle and its attachments and $F_{preload}$ is the preloaded spring force which can be taken as 5% of the maximum allowable displacement x_{bmax}.

In the last stage, the model is treated as two separate systems, the two DOF vehicle model and the one DOF **SBEH** model as follow:

The 2 DOF vehicle model:

$$M_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_u) + k_s(x_s - x_u) = 0 \qquad (11)$$

$$M_u\ddot{x}_u + c_s(\dot{x}_u - \dot{x}_s) + k_s(x_u - x_s) + k_t x_u = 0 \qquad (12)$$

And the **SBEH** model:

$$M_b\ddot{x}_b + c_b\dot{x}_b + k_b x_b = F_{preload} \qquad (13)$$

These equations are valid when the [**SBEH**] displacement $x_b < x_{bmax}$ and there is a full engagement between the bump and the harvesting unit.

3. Road Vehicle Dynamics:

This section will discuss the parameters and the performance indices including energy, body acceleration, and dynamic tire load.

3.1. Ride Comfort Parameter:

The main function of vehicle suspension system is to isolate the vehicle body from the road surface irregularities, i.e., to minimize the body acceleration $\ddot{x}_s$, which is the measure of the ride comfort parameter, i.e. acceleration of the sprung mass [12].

3.2. Road Handling:

The second function of vehicle suspension system is to maintain the contact between the wheels and the road surface to ensure adequate adhesion during acceleration, braking and/or cornering. The second function is said to be road handling and is measured by the ratio of the dynamic tire load over the static tire load. Where:

$$\mu = \frac{k_t(x_u - x_o)}{(M_s + M_{us})g} \tag{14}$$

3.2. Power Harvesting:

The main function of the speed bump energy-harvesting unit is to collect the available power from the motion of the speed bump excited by the passing vehicles as well as it encourage motorists to travel at low speed. Therefore, the max energy available for harvesting is equal to the dissipated energy in the equivalent viscous damping of the **SBEH**

$$P = C_b \dot{x_b}^2 \tag{15}$$

The amount of the harvested power depends mainly on the efficiency of the **SBEH** components and mechanism.

4. Simulation and Results:

In this section, the simulation based on a typical passenger car's parameters will be carried out. Both the nominal parameters of the quarter car model are listed in Table 1, and the parameters of SBEH model listed in

Table ***2*** are borrowed from Ref.[10] according to fabricated prototype. Simulation analysis is carried out to solve the numerical solution to the interaction models of SBEH and vehicle by using commercial software, MATLAB.

Table 1 Vehicles Parameters

	$\boldsymbol{m_u}$ k_g	$\boldsymbol{m_s}$ k_g	$\boldsymbol{k_t}$ $\frac{KN}{m}$	$\boldsymbol{k_s}$ $\frac{KN}{m}$	$\boldsymbol{c_s}$ $\frac{N.s}{m}$
Car	36	240	160	16	980
Bus	250	2250	800	150	10000
Truck1	550	4450	1705.45	622.18	26582
Truck2	500	4500	2000	400	10000

Table 2 SBEH Model Parameters

Parameter	**Description**	**Value**
r	Pinion Gear radius	0.0254 m
M_c	**SBEH** cover Mass	150 kg
M_e	Equivalent mass	620 kg
K_b	**SBEH** stiffness	130000 N/m
C_e	**SBEH** electrical damping coefficient	400 $N.s/m$
n	Gear Ratio	$1:50$

4.1 Suspension Performance indices:

Results are generated for the vehicle suspension system performances when crossing both conventional model and SBEH speed bump with different speeds to study the effectiveness of the **SBEH** model. Performance ratio parameter is generated by dividing results from the SBEH model by results from conventional bumps for the different vehicles. Fig. **5**(a, b, and c) show the ratio of the RMS value of road holding, suspension working space, and ride comfort at vehicle speed range of 5-45 km/hr. The road holding and the ride comfort ratios are below 1 for the passenger car at speeds below 10 km/hr. This critical speed increases for heavy-duty vehicles like bus (~25 km/hr), and trucks (~40 km/hr). Hence; energy harvesting bumps provide better performance for vehicles below this critical speeds than conventional fixed bumps.

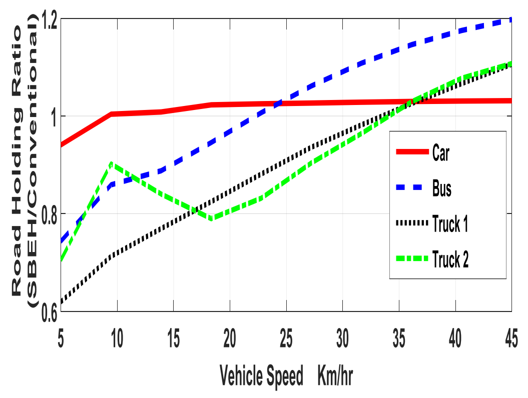

Fig. 5-a: Effect of vehicle speed on Road holding

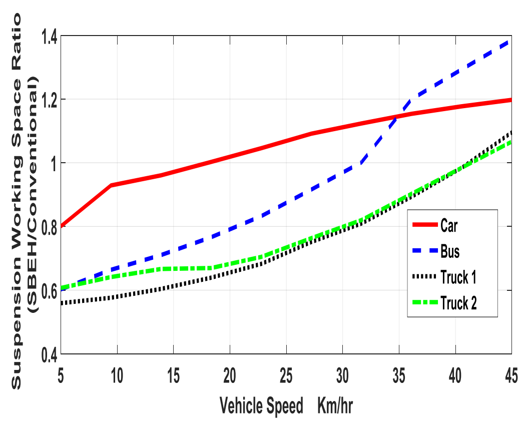

Fig. 5-b: Effect of vehicle speed on Suspension working space

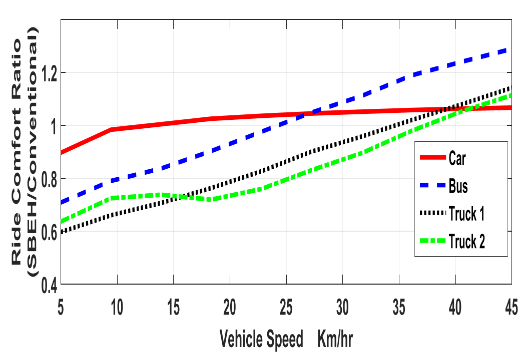

Fig. 5-c: Effect of vehicle speed on Ride comfort

4.2 Study of Parameter Sensitivities:

Further studies are conducted to investigate the sensitivities of suspension working space, ride comfort, road holding, and harvestable power to the operating conditions, including the vehicle speed, stiffness preload, and max displacement of **SBEH**, as well as the **SBEH** parameter changes, including mass, stiffness and damping of the **SBEH**,. These studies are important to understand the tradeoff among power, RH, and Ride comfort, and to guide the designer of speed bump energy harvesters.

4.2.1. Speed effect:

Fig. ***6*** show the effect of vehicle speed on the suspension performance indices and the harvested power for each vehicle model. As we can see in Fig.6-a, the speed has a bad effect on the stability of the vehicle (RH) and the ride comfort, and these stability and ride comfort are more deteriorated specially for light car at a speed of 10 km/hr. On the other hand the speed has a good effect on the harvested power for heavy-duty vehicles while it has a bad effect on light cars. The traveling speed improves the sws as shown in fig 6-b.

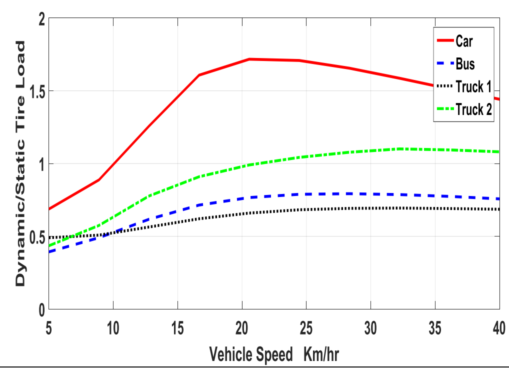

Fig. 6-a: Effect of Vehicle Speed on vehicle road holding when pass over **SBEH**

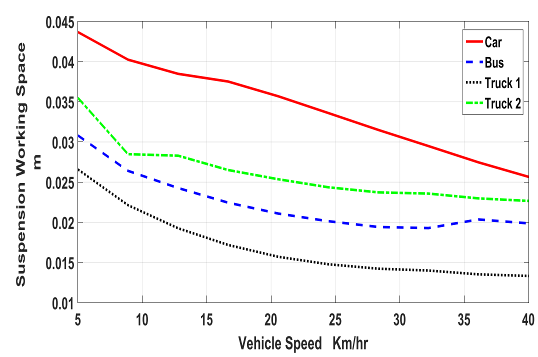

Fig. 6-b: Effect of Vehicle Speed on vehicle suspension working space when pass over **SBEH**

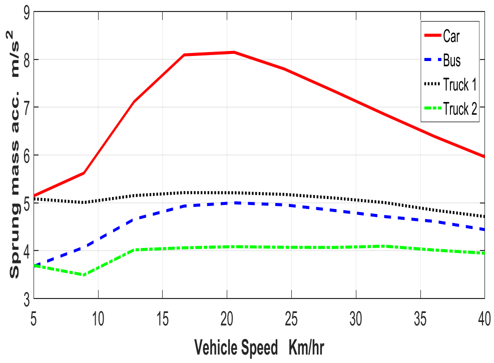

Fig. 6-c: Effect of Vehicle Speed on vehicle ride comfort when pass over **SBEH**

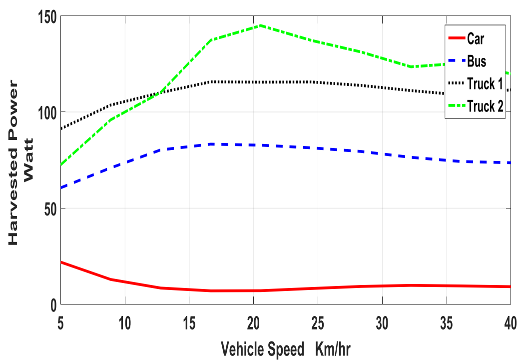

Fig.6-d: Effect of Vehicle Speed on Harvested power from **SBEH**

4.2.2. SBEH Maximum Displacement effect:

Fig.7 show the effect of SBEH maximum displacement on the suspension performance indices and the harvested power for each vehicle model. Results are evaluated for each model when passing over SBEH with speed of 10 km/hr while the SBEH displacement varies from 2 cm to 8 cm and other values of the SBEH are chosen to be nominal values in table 2.

The max. Displacement of **SBEH** almost has no effect on light vehicle performance. For heavy-duty vehicles, the harvested power increases as the maximum displacement increases (which can be the result of more space for the bump stops). Its value must be chosen carefully (~ 5-6 cm) for road holding, ride comfort, and suspension working space.

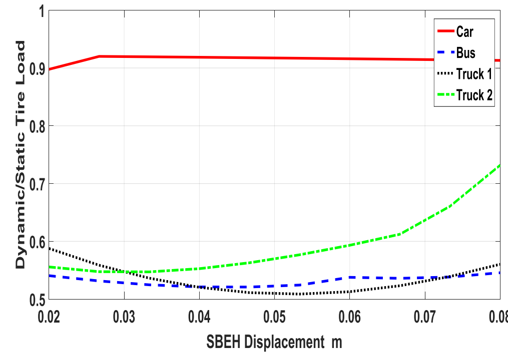

Fig.7-a: Effect of **SBEH** max displacement on vehicle road holding

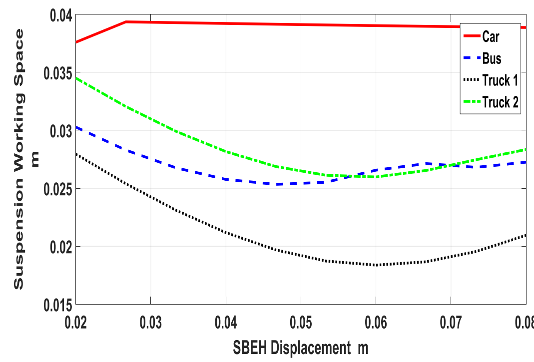

Fig. 7-b: Effect of **SBEH** max displacement on vehicle suspension working space

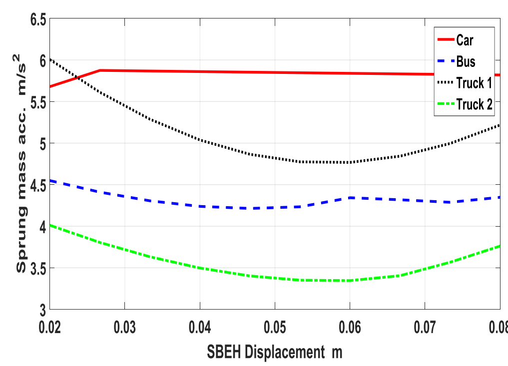

Fig. 7-c: Effect of **SBEH** max displacement on vehicle ride comfort

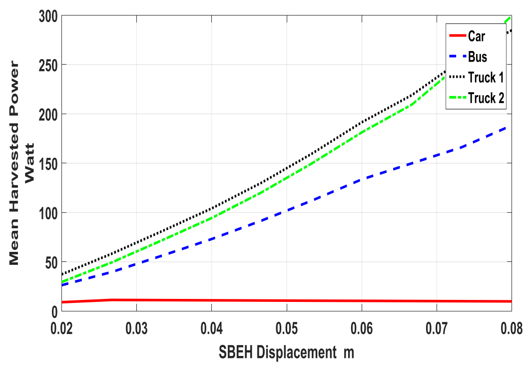

Fig. 7-d: Effect of **SBEH** max displacement on Harvested power from **SBEH**

4.2.3. SBEH Mass effect:-

Fig. ***8*** show the effect of SBEH mass on the suspension performance indices and the harvested power for each vehicle model. Results are evaluated at speed of 10 km/hr with changing SBEH mass from 400 kg to 1500 kg and other values of the SBEH are chosen to be nominal values in table 2.

It can be seen that SBEH mass contributes negative effects on both the suspension system performance (road holding, SWS, and ride comfort) and the generated power from the bump for all vehicle models.

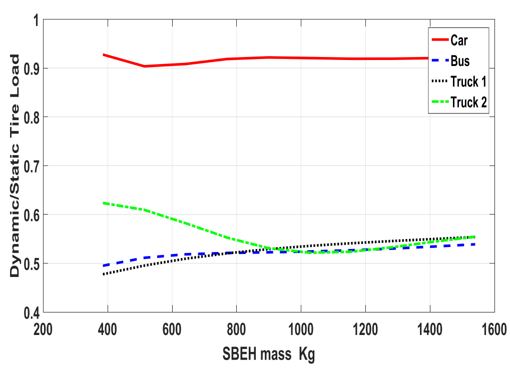

Fig. 8-a: Effect of **SBEH** mass on vehicle road holding

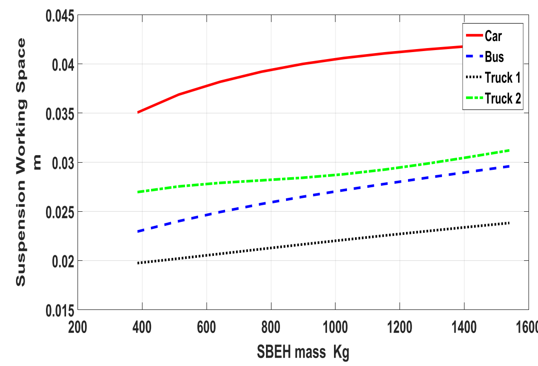

Fig. 8-b: Effect of **SBEH** mass on vehicle suspension working space

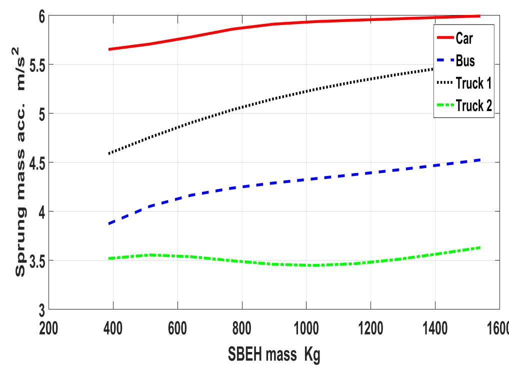

Fig. 8-c: Effect of **SBEH** mass on vehicle ride comfort

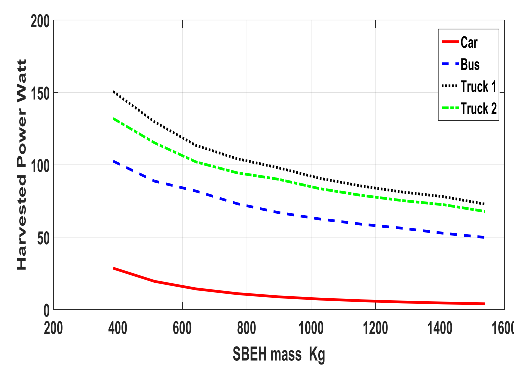

Fig. 8-d: Effect of **SBEH** mass on Harvested power from **SBEH**

4.2.4. SBEH Stiffness effect:

The effect of the **SBEH** stiffness is shown in Fig. ***9***. SBEH stiffness varies from $0.5K_{b\_nominal}$ to $2K_{b\_nominal}$. Despite the wide range of changing the stiffness, it is clear that it has nearly no effect on both suspension performance and energy harvesting for any vehicle model.

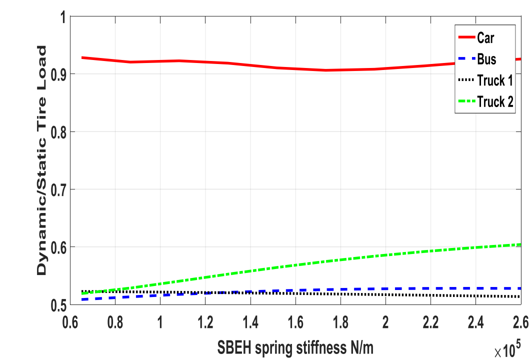

Fig. 9-a: Effect of **SBEH** stiffness on vehicle road holding

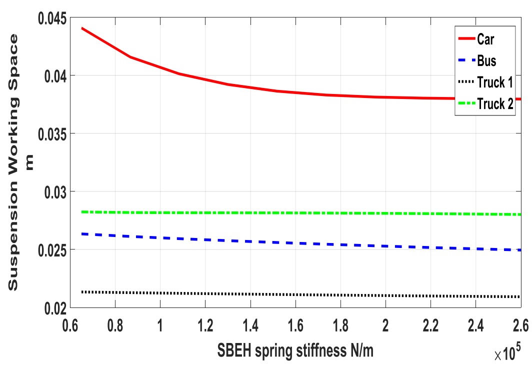

Fig.9-b: Effect of **SBEH** stiffness on vehicle suspension working space

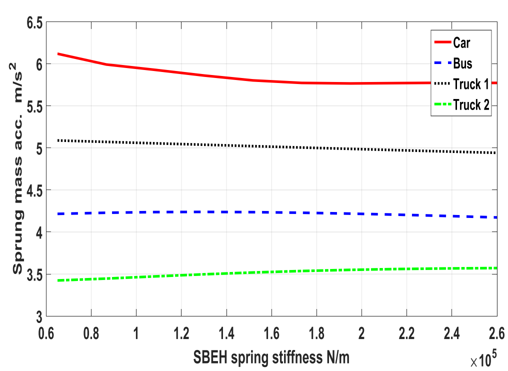

Fig. 9-c: Effect of **SBEH** stiffness on vehicle ride comfort

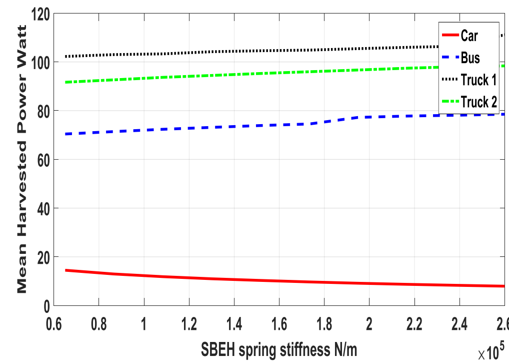

Fig.9-d: Effect of **SBEH** stiffness on Harvested power from **SBEH**

4.2.5. SBEH Spring Preload % effect:

In Fig.10, the effect of SBEH stiffness preloading is studied by changing its value from 5% to 40%. Similar to the stiffness effect, the preloading also has nearly no effect on performance or the harvesting of power.

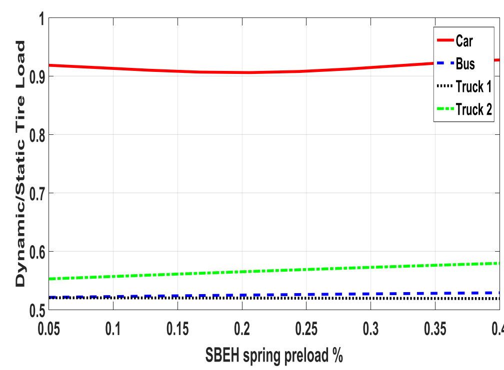

Fig.10-a: Effect of **SBEH** stiffness Preload % on vehicle road holding

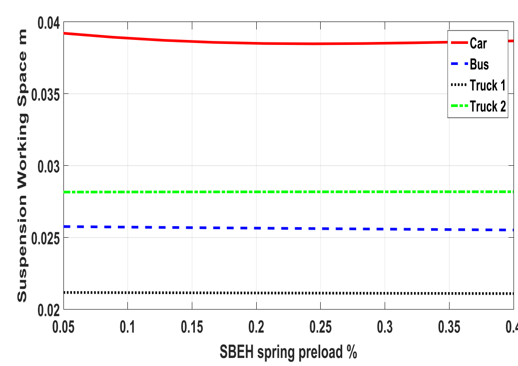

Fig. 10-b: Effect of **SBEH** stiffness Preload % on vehicle suspension working space

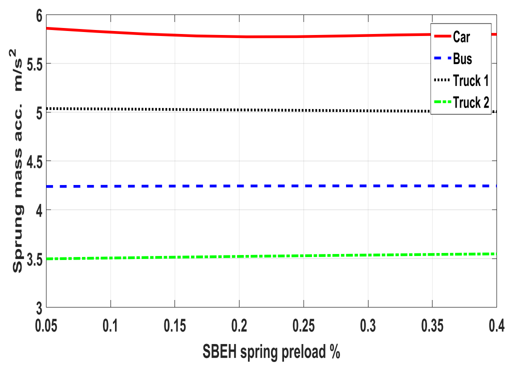

Fig.10-c: Effect of **SBEH** stiffness Preload % on vehicle ride comfort

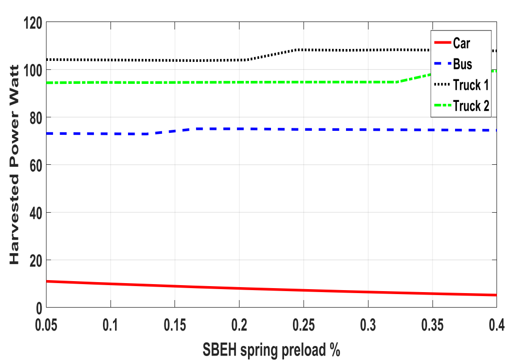

Fig. 10-d: Effect of **SBEH** stiffness Preload % on Harvested power from **SBEH**

4.2.6. SBEH Equivalent Damping effect:

Finally, the effect of SBEH equivalent damping is shown in Fig.11. Varying its value has almost no effect on road holding, ride comfort, or suspension working space. On the other hand, it has a significant effect on the harvested power which can be explained by equation 15.

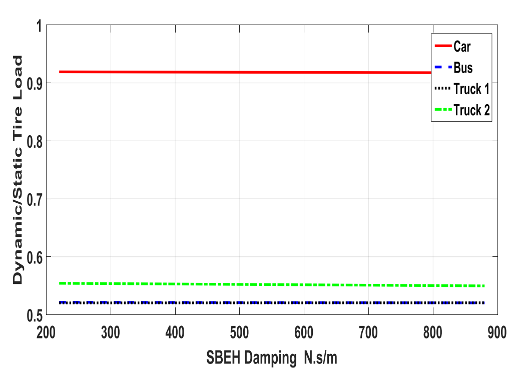

Fig.11-a: Effect of **SBEH** equivalent damping on vehicle road holding

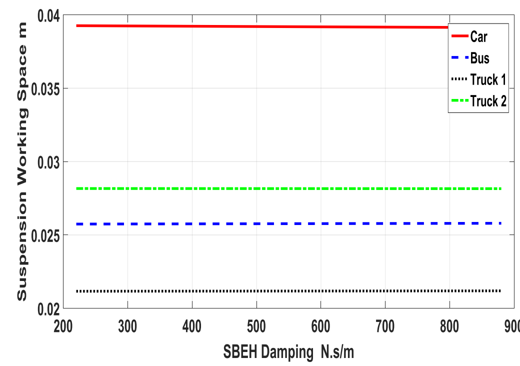

Fig. 11-b: Effect of **SBEH** equivalent damping on vehicle suspension working space

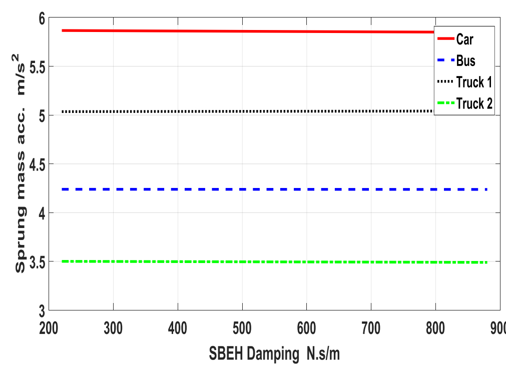

Fig. 11-c: Effect of **SBEH** equivalent damping on vehicle ride comfort

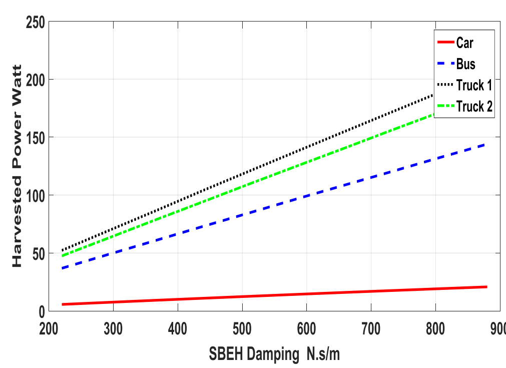

Fig.11-d: Effect of **SBEH** equivalent damping on Harvested power from **SBEH**

5. Optimization for Suspension Performance and Harvested Power:

From the previous parametric study, there are three effective design parameters in the SBEH system, SBEH mass M_b, SBEH equivalent damping C_b, and maximum displacement of SBEH. The SBEH mass can be varied by changing mass of the bump cover and the gear ratio in the SBEH model. The equivalent SBEH damping coefficient can be varied by changing the generator parameters, as described in Equation (6). And the maximum displacement of the SBEH can be varied by changing the stops position that limit the bump movement.

It can be seen from Figures 7-a and 8-a that the road handling can be optimized by properly designing the SBEH mass and SBEH maximum displacement. Based on Figures 7-c and 8-c, the ride comfort will be enhanced if we design a relatively small SBEH mass and choose a certain value of SBEH displacement. And from Figures 7-d, 8-d, and 11-d; it is clear that these three parameters have a significant effect on the available power to be harvested. In this section, we optimize the three parameters in SBEH to achieve the most energy harvesting first. Then, the overall suspension dynamics performance is optimized, considering the trade-off between the ride comfort, road handling, and energy harvesting.

As we can see from figures (6-11) that all vehicles models show nearly the same trend with different values. Hence, we selected the bus as a reference model in the optimization study considering it as an intermediate model between passenger car and trucks.

The statement of the optimization problem can be stated as follows:

Find the decision variables M_b, C_b, and x_{bmax} that minimize the objective function $f(M_b, C_b, x_{bmax})$ with no constraints. The objective function is formulated as follows:

$$f = f_{ride} + f_{holding} - f_{power} \qquad (16)$$

$$f_{ride} = rms(\ddot{x_s}) \qquad (17)$$

$$f_{holding} = rms(\mu) \qquad (18)$$

$$f_{power} = mean(power) \qquad (19)$$

Values of f_{ride}, $f_{holding}$, and f_{power} are scaled to give the three objectives the same importance.

Optimization algorithm parameters for GA are tabulated in Table 3. The lower and upper bounds for the SBEH mass, SBEH equivalent damping, and maximum displacement of SBEH are: $400\ Kg \le M_b \le 1600\ Kg$, $200\ \frac{N.s}{m} \le C_b \le 800\ \frac{N.s}{m}$, and $2\ cm \le x_{bmax} \le 8\ cm$.

Table 3 GA parameters

GA Parameter	**Value/Corresponding GA toolbox option**
Population size	100
Number of generations	100
Scaling function	Stochastic uniform
Selection function	Roulette
Mutation function	Constraint dependent default
Crossover function	Arithmetic
Function tolerance	$1e^{-6}$

GA optimization codes are executed for 10 runs and the best results obtained out of all 10 runs are shown in table 4.

Table 4 Best run results of GA

	M_b	C_b	x_{bmax}	f
GA Results	400 kg	800 $\frac{N.s}{m}$	5.75 cm	-0.525

Statistics of the optimization results are shown in table 5 which shows the best, worst, mean and standard deviation of the objective function obtained in each run in GA.

Table 5 Statistics of GA Calculations

	Best result	Worst result	Mean	Standard deviation
10 runs statistics	-0.5253	-0.4735	-0.509	0.0176

To check the validity of the optimization study results for the other vehicle models, their performances in case of optimized SBEH model is evaluated and improvement with respect to nominal SBEH are shown in table 6

Table 6 Improvement of Performance & Harvested Power

	Car	Bus	Truck1	Truck2
$rms(\ddot{x_s})$	5.64	3.85	4	3.24
%Improvement	3%	1.73 %	19.5 %	7.95 %
$rms(\mu)$	0.92	0.511	0.45	0.66
%Improvement	-1.01 %	8.4 %	12.5 %	-16.2 %
$mean(power)$	44.5	309.95	452.1	426.14
%Improvement	252.6 %	304 %	313.5 %	330.6%

It is clear from table 6 that the harvested power is well improved by 252.6 %, 304%, 313.5%, and 330.6% for passenger car, bus, truck1, and truck2 respectively.

6. Conclusion:

This paper studies the effect of speed bump energy harvester SBEH on different vehicles performance and the optimization of SBEH parameters. Vehicles were chosen from different sizes (passenger car-bus-truck1- truck2) and were modeled as a quarter car model. The SBEH is modeled as a trapezoidal bump with mass m based on 4 springs and an equivalent damper. The mean power in SBEH, RMS sprung mass acceleration (ride comfort), RMS suspension working space, and RMS dynamic to static force (road handling) are parameters to assess the model. Results from SBEH were compared with conventional bump for the various vehicles and at different speeds to assess the validity of SBEH model. Sensitivity studies of vehicle performances on SBEH parameters were illustrated graphically based on numeric calculation to show the significant SBEH parameters that affect vehicle performance and power harvesting. These significant parameters of SBEH were also optimized using GA for suspension performances and energy harvesting. The main conclusions may be stated as follow:

a- The comparison indicates that below a certain speed, the SBEH provide better performance than the conventional bump. And this speed depends on the vehicle size; i.e. it is 10, 25, 45 km/hr for passenger car, bus, and trucks respectively.

b- As the vehicle speed is increased, the harvested power is increased, on the other hand, ride comfort and road handling are deteriorated.

c- The vehicle size has a vital role in harvesting power from SBEH where; at a speed of 10 km/hr the available mean power for harvesting from SBEH are 12.5, 76.5, 100 watt for passenger car, bus, trucks respectively.

d- The mean power potential depends on the vehicle size, vehicle speed, SBEH maximum displacement, SBEH mass, and equivalent damping of SBEH. On the other hand, it is insensitive to the changes of SBEH stiffness, SBEH stiffness preloading.

e- At higher maximum stroke of SBEH $\mathbf{X_{bmax}}$ (performed by moving bump stops) the bump dissipates more power, or the regenerative SBEH system harvests more power; however, the road holding and ride comfort will become worse. In this sense, more power harvesting does not mean better road holding or better ride comfort.

f- Small SBEH mass is preferred for ride comfort and power potential, but it almost has no effect on the road holding.

g- Increasing the equivalent damping of SBEH improves the power harvesting significantly. However; no effect is detected on neither road holding nor ride comfort.

h- SBEH mass, equivalent damping, and the maximum displacement of SBEH are optimized for energy harvesting, ride comfort, and road holding using MATLAB Genetic Algorithm toolbox.

i- Optimization results show an increase in the harvesting mean power by 252.6 %, 304%, 313.5%, and 330.6% for passenger car, bus, truck1, and truck2 respectively. The ride comfort is also improved when the sprung mass is reduced by 3%, 1.73%, 19.5%, and 7.95% for passenger car, bus, truck1, and truck2 respectively. While road holding is enhanced in some vehicle model when the dynamic to static tire load is reduced by 8.4% and 12.5 % for bus and truck1, on the other hand it deteriorated by 1% and 16% for passenger car and truck2 respectively but the dynamic to static tire load still less than the unity which means that the tire still in contact with the ground.

References:

[1] T. A. A. a. O. S. Salau, "Vehicle speed control using road bumps," *Transport*, pp. 130-136, 2004.

[2] Aslan, S., Karcieglu, O., Katirci, Y., Kandis, H., Ezirmick, N., and Bilir, O.,, "Speed bump induced spinal column injury," *Journal of Emergency Medecine*, vol. 23, pp. 563-564, 2005.

[3] Dedovic V., and Sekulic D., "Effect of shock vibrations due to speed control humps to the health of city bus passengers using oscillatory model with six DOF," in *International Conference on Traffic and Transport Engineering*, Belgrade, 2012.

[4] G. A. Hassaan, "Car dynamics using quarter model and passive suspension, Part II: A novel simple harmonic hump," *Journal of Mechanical and Civil Engineering*, vol. 12, no. 1, pp. 93-100, 2015.

[5] Weber P., and Baraaksma J., "Towards a North American geometric standard for speed humps," *ITE journal*, pp. 30-40, 2000.

[6] Ansari Ardeh H., Shariatpanahi M., Nikkhah Bahrami M., "Shape optimization of speed humps," *Struct Multidisc Optim*, vol. 37, no. 2, pp. 203-214, 2008.

[7] M. H. A. M. B. F. J. A. V. a. S. U. Amin M., "Exergy analysis of a Combined Cooling, Heating and Power system integrated with wind turbine and compressed air energy storage system," *Energy Conversion and Management*, vol. 131, p. 69–78, 2017.

[8] B.S. Lee, W.J. Wu, W.P. Shih, Dejan Vasic, Francois Costa, "SCREEN-PRINTED PIEZOELECTRIC GENERATOR FOR HELICOPTER HEALTH AND USAGE MONITORING SYSTEMS," in *Proceedings of PowerMEMS 2008+ microEMS2008*, Sendai, Japan, November 9-12, (2008).

[9] Li Z., Brindak Z., and Zuo L., "Modeling of an Electromagnetic Vibration Energy Harvester With Motion," in *Proceedings of the ASME International Mechanical Engineering Congress and Exposition*, Denver, 2011.

[10] S. Andriopoulou, "A review on energy harvesting from roads," pp. 1-39, 2012.

[11] Todaria L., Wang A., Pandey J., O'Connor D., McAvoy T., Harrigan B., Chernow, and Zuo L., "Design, modeling and test of a novel speed bump energy harvester," in *Proc. of SPIE Vol. 9435, 943506*, 2015.

[12] Abdelhaleem A., and Crolla D., "Analysis and design of limited bandwidth active hydropneumatic Vehicle Suspension System," *SAE Technical paper*, pp. 01-1631, 2000.

[13] Elizer Jr., "Summary of a Proposed Recommended Practice Guidelines for the Design and Application," *ITE Journal*, pp. 11-15, 1993.

[14] Kashem S. B. A., Chowdhury M. A., Choudhury T. A., Shabrin N., Ektesabi M., and Nagarajah R., "Study and Comparison on Linear Electromagnetic Shock Absorbers among other Available Intelligent Vibration," *International Journal of Science and Research*, vol. 4, no. 6, pp. 2394-2401, 2015.