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COMPARISON OF THE IMPACT OF POWER BUMPS AND CONVENTIONAL BUMPS ON VEHICLES AND USERS

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ABSTRACT

Energy plays an important role in a country's development. Traffic energy is one of the alternative energies being investigated worldwide. Over the years, investigations are being carried out to improve the functionality and efficiency of various types of devices used in traffic energy harvesting. There are still questions on the possible impact these traffic energy harvesters impose on vehicles and users. However, there is a limited study on the impact of traffic energy harvesters on vehicles and users. A detailed investigation of the possible impact of traffic energy harvesters is necessary to identify and mitigate the challenges which would help promote this promising alternative energy in the future. In this paper, a MATLAB simulation was carried out to investigate the impact of a rack-and-pinion based speed bump on vehicles and users in comparison with that of a conventional speed bump, in terms of its fuel consumption rate, impact on vehicle suspension, and ride comfort. The investigation revealed that power bumps do have negative influences on vehicles' performance compared to that of conventional speed bumps.

Keywords: power bump, rack-and-pinion, traffic energy harvester, alternative renewable energy, wasted energy.

1. INTRODUCTION

The potential risks to the energy security and issues associated with global warming call for a reduction in the dependency of fossil fuels as primary energy sources. Researchers around the world are striving hard to explore various alternative energies including the utilization of wasted energies and renewable energies. Automobiles waste most of their rotational kinetic energy in the form of friction, thermal energy, and pressure, particularly when slowing down. This wasted energy could be put to use if tapped effectively. The traffic energy, despite a new form of renewable energy as compared to wind and solar etcetera, has many advantages such as economic and sustainable functionalities. Various traffic energy harvesters with simple installation and minimal obstruction for the facility operations are being investigated globally. The source of energy for the traffic energy harvester is the friction between the vehicles and the road surface when the vehicle slows down drastically at the bumps. In general, the Construction of energy-harvesting speed bumps (called power bumps) is simple, part of a matured technology and the maintenance is easy.

If a power bump uses the piezoelectric generator, then it can potentially sense the ambient vibrations which can be utilized to generate power even when a vehicle does not roll over the bump [1]. A lot of studies have been conducted on various methods possible for harnessing the traffic energy. In a study that monitors the bridge health by using a vibration harvesting system, Galchev [2] has proposed an electromagnetic inertial micro power generation system to harvest the vibration energy present on a bridge. There are many mechanisms available for energy harnessing in speed bumps such as rack-and-pinion mechanism, hydraulic mechanism [3], air compression mechanism [4], roller mechanism [5] and crank mechanism [6]. One of the most common methods uses the rack and pinion mechanism. The work of Fawade [7] describes the rack and pinion method along with the principle of a reciprocating air compressor. The whole mechanism was fixed underground exactly below the bump with the head of the piston rod at the road surface level. From the study conducted by Aniket Mishra *et al* [8], it can be found that when a 300kg vehicle passed through the rack-and-pinion based bump, an output power of 7.3575W was developed in one minute, which is 441.45W/h and 10.5948kW/day. The energy generated was able to light up four streets for the whole night. Todaria *et al*. [9] have suggested a novel power bump that could generate electricity up to a few hundred watts when cars pass over it. The rotary mechanism enables the up-and-down motion to turn the generator into a uni-direction, producing useful energy. This development offers the bump a new purpose other than just ensuring road safety [9]. It can be seen from the literature that in the future, power bumps with smart features or increased functionalities could play an active role in intelligent transportation systems [10-12]. However, additional research is required to get an insight into its challenges. Many studies have been conducted to show the relationship between the fuel consumption rate of a vehicle and its friction coefficient [13-15]. The road surface irregularities harm the vehicle's suspension system and also the vertical acceleration of the vehicle [16, 17].

A lot of research is ongoing globally on the traffic energy such as fuel consumption modeling [18], analysis of car suspension system using automatic dynamics of the mechanical system (ADAMS) [19], comparing the discomfort levels of occupants when different vehicles move over a speed bump [20], review of the different technologies used in existing traffic energy harvesting devices [21], modeling of an energy harnessing system using CATIA V5 PRIMER software and its design [22], a technical simulation based piezoelectric system to support the concept of generating energy from road traffic using piezoelectric materials validating and predicting real-time economic outcome [23], evaluating the energy output and mechanical failure of piezoelectric energy harvesters for roadway applications [24], a novel bridge transducer based on the cymbal design for energy harvesting from impact loading by vehicle-induced deformations on the pavement [25], optimizing the problem of power consumption of street lights [26], late review and analysis of an improved energy generation by using speed humps [27], a piezoelectric energy harvester that uses the energy to power self-powered sensors and vehicle indicators [28], using a piezoelectric energy harvester to charge a mobile phone [29], flexible Polyvinylidene Fluoride (PVDF) polymeric piezoelectric thin film as piezoelectric energy harvester [30], and mechanical energy harvesting devices for low frequency applications [31].

It can be found from the literature that most of the work carried out worldwide focus on establishing new design criteria, optimizing the design of speed bumps, and generating more energy. The investigation should also include analyzing the impact each energy harvester imposes on people, vehicles, and the environment to demonstrate its usability. However, there are little studies found on the comparison of these impacts on different types of speed bumps. This information gap brings in many questions about the practicability of traffic energy harnessing in real life. In this paper, an investigation has been carried out exploring the impact on vehicles and users that would help identify the potential challenges of this promising technology. To reduce the complexity, a rack-and-pinion based power bump and simplified two-mass quarter-car dynamics have been used in the investigation. Using MATLAB, the dynamics of the vehicle, power bump, and the conventional bump have been modeled and simulated. Figure-1 represents the conventional speed bump model and the power bump model used in the study. The material commonly used in a conventional bump is asphalt and it has a coefficient of friction of 0.7 when in contact with hard rubber surfaces such as vehicle tires. On the other hand, the cover of a power bump is generally made of steel or iron which has a coefficient of friction of 0.8. The simulation results for the vehicle performance in terms of its fuel consumption rate, the effect on vehicle suspension and ride comfort have been investigated and compared with that of a conventional speed bump. It is expected that this investigation will aid in the exploration of this new promoting future energy.

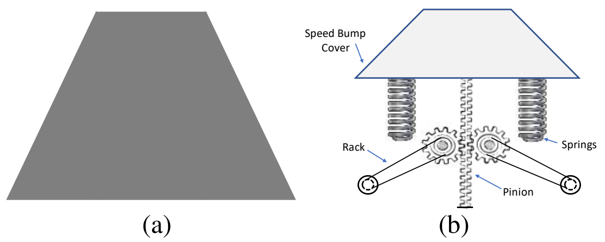

Figure-1. (a) Conventional bump and (b) Power bump.

2. FUEL CONSUMPTION RATE OF VEHICLE

The fuel consumption rate of vehicles which is one of the most crucial impacts depends on many factors. It is a small value when no engine power is applied. When engine power is required, the rate depends mostly on the engine speed and vehicle's demanded power. When more power is needed, engines function with a fuel-rich mixture to avoid overheating of the catalyst. The tire rolling resistance is another factor that influences the fuel rate of a vehicle. Although many of the factors which affect the rolling resistance are vehicle dependent, the road surface is also one of the most integral parts in determining the overall rolling resistance a vehicle needs to overcome. The vehicular rolling resistance is affected mostly by the road's surface texture, roughness, and stiffness. The vibration in tires and suspension systems caused by the road's surface texture and roughness are absorbed by shock absorbers, resulting in a loss of energy in the vehicular system. Furthermore, these vibrations will ultimately affect the fuel rate of vehicles. There are many studies conducted on the rolling resistance and they show that smooth road surfaces reduce the rolling resistance. The Missouri rehabilitation project shows that a reduction in the International Roughness Index (IRI) of pavement from 130 to 60 in/mile saves up to 2.46% of the fuel. Based on the road load model introduced for the tractive-energy requirements of vehicles driving the Environment Protection Agency schedules, the brake power depends on the tire rolling resistance coefficient, speed-correction to rolling resistance, air drag coefficient, vehicle speed, the mass of the vehicle, vehicle acceleration and the road grade. It is evident that the higher the acceleration rate of a vehicle, the more the brake power it requires. This relationship is consistent with Newton's 2nd Law of Motion, whereby the acceleration of an object is directly proportional to the net force acting upon it and inversely proportional to its mass.

2.1 Research Method

A MATLAB simulation has been carried out based on (1) to study how the power bump would affect the fuel consumption rate of vehicles [13, 15]. From (1), it can be seen that the fuel consumption rate (g/s), FR depends on the fuel/air ratio, Φ, the friction factor of the engine (kJ/rev), K, the engine speed, N, the engine indicated efficiency, Ƞ, the engine displacement volume (L), V, the tractive power (kW), Pb, the transmission and final drive efficiency, $Ƞ_t$, the power of accessories (kW), P_{acc}, and the lower heating value of the fuel (kJ/kg), LHV.

$$FR = \left\{\Phi\left[KNV + \left(\frac{P_b}{\eta_t} + P_{acc}\right)/\eta\right]\right\}/LHV \quad (1)$$

2.2 Simulation Results and Discussion

To observe how the fuel rate varies with the type of speed bumps, the fuel consumption rate of a vehicle has been calculated at different values of the friction coefficient (μ). Figure-2 depicts the changes in the fuel consumption rate and changes in the tractive power, Pb, of the vehicle for different values of the friction coefficient.

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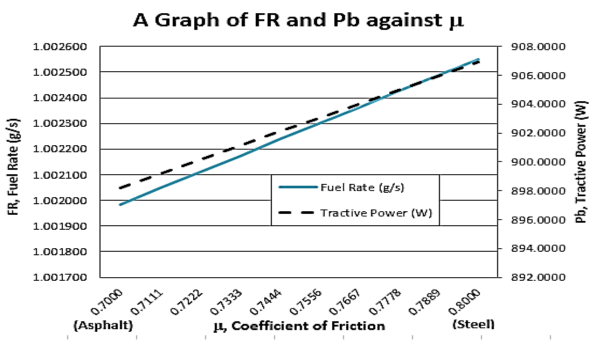

Figure-2. Comparison of fuel consumption rate and tractive power.

From the figure, it can be seen that both the tractive power and fuel consumption rate increase with the increase in the friction coefficient. At a friction coefficient of 0.7 (asphalt type conventional bump), the tractive power is 898.2082W whereas, at a coefficient of 0.8 (steel/iron type power bump), the tractive power is 906.9096W. A total amount of 8.7014W of extra power has been used by the vehicle to cross over the power bump, which is approximately 1% higher than that of the conventional bump. It can also be seen from the graph that the fuel consumption rate of the vehicle has gone up by 0.000565g/s which is 0.0565% when passing over the power bump compared with that of a conventional bump.

3. EFFECT ON VEHICLE SUSPENSION

Suspensions are used in vehicles to support the load and protect passengers from shocks coming mainly from tire-road interactions. They provide directional stability and yaw controls for vehicles. Usually, road surface irregularities and the dynamics of speed bumps act as the major source that stimulates the vibration of a vehicle's body through its suspension system. In a conventional speed bump, the ground excitation to the vehicle is fixed and time-invariant, whereas, in a power bump, the ground excitation is both bump profile based and time-dependent as the power bump is linearly movable. This scenario is similar to a moving boundary condition which is characterized by time-dependent boundaries. This section investigates the interaction between a rack-and-pinion based power bump and vehicles passing over them and reveals how it impacts the vehicle suspension system.

3.1 Research Method

To study how the power bump affects a vehicle's suspension, the simplified quarter-car dynamics with a rack-and-pinion based power bump has been modeled and simulated in Matlab. The quarter-car configuration represents a two-mass vibration system with a body mass, M_s and an unsprung mass, M_u. The power bump is conceptualized as a speed bump with a translational stroke-like motion which in turn, is converted to rotational motion using a rack-and-pinion gear system. This paper has used the modeling techniques and parameters adopted in [9] to study the impact of power pumps on the vehicle suspension system and the ride comfort of vehicle users. The vehicle model, the power bump model, and the combined model of the bump and the vehicle are shown in Figure-3.

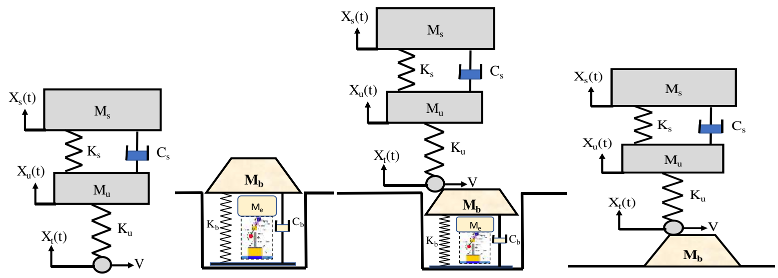

Figure-3. (a) Vehicle model (b) Power bump model (c) Combined model of vehicle and power bump (d) combined model of the vehicle and conventional bump.

The governing equations of the overall system when the vehicle and speed bump interact with each other are described below. The dynamics of the two-mass vibration system of the vehicle is given by (2), and (3).

$$M_s\ddot{x}_s + C_s(\dot{x}_s - \dot{x}_u) + K_s(x_s - x_u) = 0 \qquad (2)$$

$$M_u\ddot{x}_u + K_u(x_u - x_t) - C_s(\dot{x}_s - \dot{x}_u) - K_s(x_s - x_u) = 0 \qquad (3)$$

The interaction between the power bump and the vehicle is given by (4).

$$\left\{\begin{matrix} (M_b + M_e)\ddot{x}_b + C_b(\dot{x}_b) + K_b(x_b) - K_u(x_u - x_t) = F_K - F_V: & for x_b < x_{b,max} \\ (M_b)\ddot{x}_b + K_b(x_{b,max}) = F_K - F_V: & for x_b = x_{b,max} \end{matrix}\right\} \qquad (4)$$

The input to the tire of the vehicle is given by (5).

$$\dot{x}_t = V\tan\theta - \dot{x}_b \qquad (5)$$

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where, M_s, M_u, M_b, M_e are the sprung mass of the vehicle, the un-sprung mass of the vehicle, the mass of the bump cover and equivalent mass of the energy harvester, respectively in kg, x_s, $\dot{x}_s$, $\ddot{x}_s$ are the vertical displacement(m), velocity(m/s) and acceleration(m/s^2) of the sprung mass, respectively, x_u, $\dot{x}_u$, $\ddot{x}_u$ are the vertical displacement(m), velocity(m/s) and acceleration(m/s^2) of the un-sprung mass, respectively, x_b, $\dot{x}_b$, $\ddot{x}_b$ are the vertical stroke(m), velocity(m/s) and acceleration(m/s^2) of the power bump, respectively, x_t, $\dot{x}_t$ are the displacement(m) and velocity(m/s) inputs to the vehicle, respectively, C_s, C_b are the coefficients of the sprung mass damping and equivalent electrical damping of the power bump, respectively in (Ns/m), K_s, K_u, K_b are the stiffness coefficients of the sprung mass spring, un-sprung mass spring, and power bump spring, respectively in (N/m), F_K, F_V are the spring force of the bump and the force of the static vehicle load, respectively in N, θ is the pitch angle made by sprung body in degree.

The equivalent mass of the energy harvester, M_e, represents the combined inertial mass of the various rotating parts of the energy harvester such as pinion gears, coupling shaft, generator, etc. This inertial mass opposes the motion of the bump cover and hence has been added to the mass of the bump cover considering it to be placed at the end of the rack. The equivalent electrical damping of the power bump, C_b, comprises the mechanical damping caused by friction in the mechanical devices such as rack and pinion, coupling shaft, gearbox, and generator and the electrical damping caused by internal resistance and electrical load on the generator.

3.2 Simulation Results and Discussion

A vehicle suspension system sustains a great force when a vehicle accelerates, decelerates and brakes. There are no doubts that a speed bump harms the vehicle suspension system. A damper or shock absorber is responsible for dampening the springs' natural tendency to oscillate, especially when passing over hurdles, but when the force exceeds the amount it could handle, the shock absorbers could be damaged, compromising the suspension system's performance. To explore and compare how the road condition of power bumps and conventional speed bumps would affect a vehicle suspension system, the simplified quarter-car dynamics explained in section 3.1. has been analyzed using Matlab. Figure-4 and Table-1 show the comparison of the simulated results at 20km/h.

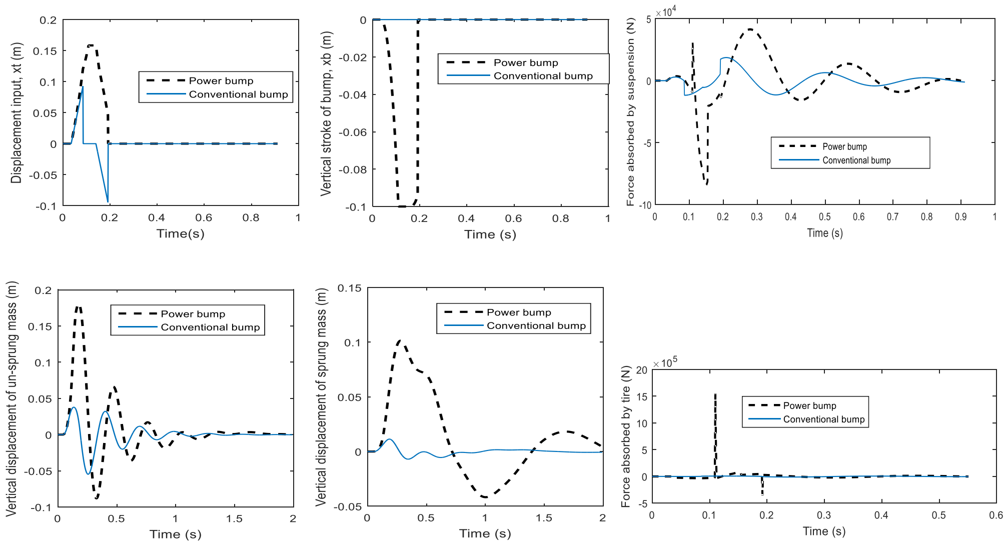

Figure-4. Comparison of the impact.

Table-1. Comparison of the impact.

Type of bump	Conventional bump	Power bump
Displacement input, x_t (m)	0.0926	0.1584
Vertical stroke, x_b (m)	0	0.1
Force absorbed by suspension (N)	1.857×10^4	4.139×10^4
Vertical displacement of un-sprung mass (m)	0.0378	0.1805
Vertical displacement of sprung mass (m)	0.0112	0.1013
Force absorbed by the tire (N)	6143	1.548×10^6

From the figure and table, it can be observed that the peak value of the displacement input to the tires, x_t, has increased by 0.0658m which is about 71%, the vertical displacement of the un-sprung mass has increased by

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0.143m which is about 3.7 times higher, the vertical displacement of the sprung mass by 0.0901m which is about 8 times higher, and the force absorbed by the suspension system by 22820N which is about 3.5 times higher, whereas, the force absorbed by tires has increased drastically when the vehicle was passing over the power bump compared to that of the conventional bump.

4. RIDE CONFORT

The ride comfort is predominantly influenced by the vibration behavior to which a vehicle is subjected. A soft vehicle suspension system is expected to insulate its passengers from any car body vibrations and provide the ride comfort. The vertical acceleration is a direct measure of the ride comfort. The influence of the suspension damping upon ride comfort has been evaluated by the RMS acceleration of the vehicle which reflects the vehicle's ability to maintain vibrations within acceptable or comfortable limits.

4.1 Research Method

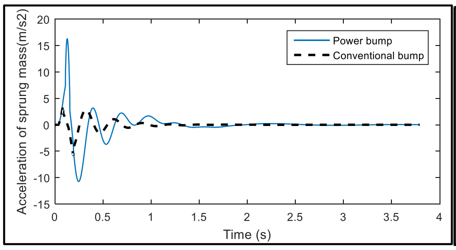
A MATLAB simulation of the system described in section 3.1. has been carried out to determine the RMS acceleration of the vehicle given by (6) and hence the ride comfort level.

$$a_{RMS} = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} a^2\right)} \tag{6}$$

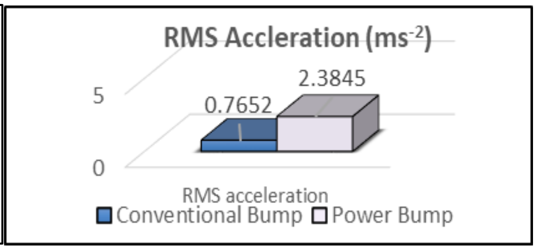
where a_{RMS}, is the RMS acceleration of the vehicle (ms^{-2}), a is the vertical acceleration of the vehicle (ms^{-2}) and N is the number of data points.

4.2 Simulation Results and Discussion

The acceleration of the vehicle, $\ddot{x}_S$ when passing over the two types of speed bumps has been simulated separately and has been plotted against time. Figure-5(a) shows the comparison of the vehicle's acceleration. It can be seen from the figure that the acceleration of the vehicle increases when passing over the power bumps. The rise in the acceleration has increased the vibration of the car body which affects the ride comfort. The RMS acceleration of the vehicle with different bumps is shown in Figure-5(b).



(a)



(b)

Figure-5. (a) Comparison of the vehicle's acceleration, and (b) Comparison of the RMS acceleration.

The RMS acceleration is desired to be as low as possible to obtain the best comfort level. By analyzing the results based on Lima *et al*, it can be seen that the passengers of the car will have a middling uncomfortable experience when passing over conventional bumps while the passengers will have a highly/extremely uncomfortable experience when passing over the power bumps. Therefore, it can be proved that power bumps will bring more discomfort to users than conventional speed bumps. The result of the investigation is consistent with the findings given in reference [20].

5. CONCLUSIONS

As a conclusion, based on the MATLAB simulation carried out on the rack-and-pinion based power bump with quarter-car vehicle dynamics, it can be observed that power bumps do affect the fuel consumption rate, vehicle suspension system and the ride comfort when compared with that of conventional bumps. The fuel consumption rate has gone up by 0.000565g/s which is about 0.05% and the tractive power by 8.7014W per bump which is approx. 1% but, could be considered as insignificant due to the benefits rendered by power bumps. The study has also revealed that there is a significant increase in the displacement input to tires, vertical displacement of the vehicle, force absorbed by the suspension system and the force absorbed by tires. Furthermore, the study clearly shows that the ride comfort is affected significantly which is an important concern of drivers which has to be addressed convincingly. Further studies on techniques to enhance ride comfort is mandatory to increase the functionality of power bumps. Since the major factors contributing to the impact such as coefficient of friction, fuel consumption rate, displacement input to vehicle tires and force exerted by the bump have increased, it can be concluded that power bumps do affect a vehicle's overall efficiency. However, an overall impact study with all relevant factors of power bumps is essential in different perspectives to uncover the facts about power bumps and hence to find remedial measures to overcome the potential issues.

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