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Vibration Energy Harvesting in Automotive Suspension System: A Detailed Review

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Abstract:

Hydraulic shock absorbers have come into widespread use in vehicle suspensions since decades ago to effectively reduce the acceleration of vehicle bodies and maintain good contact between tires and ground under road irregularities. Although energy efficiency has been a major concern in the automotive industry since the mass production in the 1900s, researchers realized that the energy dissipated in traditional hydraulic shock absorbers is worthy of being recovered only in the middle of 1990s. Since then, many different types of energy harvesting based shock absorbers were conceptualized and prototyped. Unlike traditional suspension systems which suppress the vibrations by dissipating the vibration energy into waste heat, the regenerative suspension with energy harvesting shock absorbers can convert the traditionally wasted energy into electricity. This paper is a comprehensive review on energy harvesting based vehicle suspensions. Specifically, it focuses on an analytical and statistical study of the vehicle regenerative suspensions and reviewing the concepts, designs, simulations, test rig experiments and vehicle road tests. The most common energy harvesting systems in vehicle suspensions are compared in terms of advantages and limitations. In addition, the challenging issues and research gaps that remain unresolved are addressed and some recommendations regarding such challenges are stated for further research.

Keywords:

Energy harvesting; Vehicle suspension; Regenerative dampers; Electromagnetic harvesters; Vibration.

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Highlights:

1. State-of-the-art of the energy harvesting based vehicle suspension is introduced.
2. Different electromagnetic harvesting-based dampers are presented and compared.
3. The challenging issues and research gaps that remain unresolved are addressed.
4. The given synthesis to regenerative suspensions is helpful for future research.

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1. Introduction

Traveling on roads, vehicles are subjected to different disturbances such as road irregularities, braking forces, acceleration forces, and centrifugal forces on a curved road which cause discomfort to the driver and passengers and influence maneuverability. Passive suspensions, composed of viscous hydraulic shock absorbers and springs in parallel, have been widely used to suppress the vibration by dissipating the undesired mechanical energy into heat waste. The active and semi-active suspensions have been investigated extensively in the past 40 years showing improved vehicle dynamic performances at the cost of complexity and additional energy consumption [1-3]. However, the passive suspension system is still dominating in the automotive industry because of its simple structure, high reliability, and low cost.

Reducing vehicle energy losses is necessary for improving fuel economy, reducing emissions, and supplying other systems power demand [4-6]. In addition to improving engine and powertrain efficiency, we may also harvest the energy wasted in vehicles including the recovery of wasted heat

energy [7-9], regenerative braking energy [10-12], and vibrational energy on shock absorbers [13, 14]. Regenerative suspensions with the energy harvesting shock absorber have gained tremendous attention in the past two decades as promising directions in vehicle research because of its potential to enable the suspension system not only providing enhanced dynamic performance but also converting the wasted vibration energy to electricity. After the early trial in the middle of 1990s [15-17], the number of publications per year on regenerative energy suspensions has been exponentially increased over the last decade, as illustrated in Fig. 1.

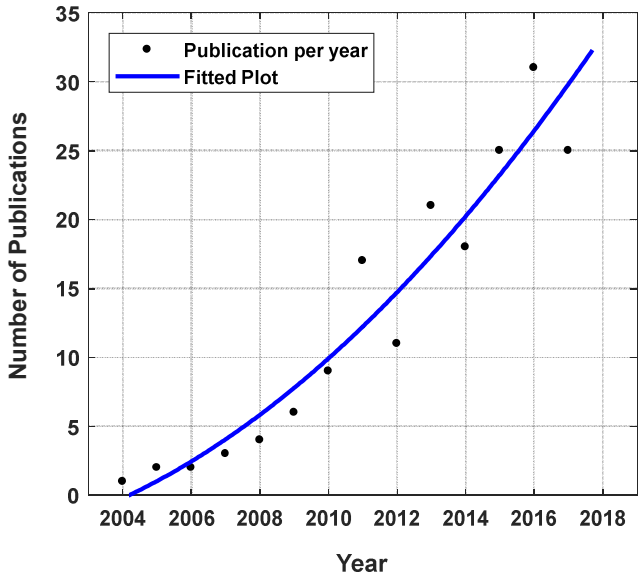


Fig. 1. Publication profile over the last decade regarding energy regenerative suspension. [Drawn according to the literature survey].

Energy harvesting potential based vehicle suspensions and its effect on fuel saving have been estimated extensively by several scholars. Zuo and Zhang [18] demonstrated that the potential energy of a typical passenger car is between 100-400 W considering that the car is traveling on good and average roads with a 97 km/h approximately. Consequently, for an energy conversion efficiency of 75%, 300 W of electrical power can be achieved which corresponds to 3% fuel efficiency improvement according to BMW's data on the electricity need in typical passenger cars [19]. Levant Power engineers [20] also emphasized such a positive effect on the fuel saving if such a power loss is partially recovered in which an average power of 1 kW could be captured from a 3-axle truck on a highway which is

possibly enough to replace the high-power alternator from heavy-duty trucks or military vehicles. Additionally, Audi Automotive Group (Audi AG.) [21] reported the possibility of reducing carbon dioxide (CO_2) for hybrid vehicles with energy harvesting based suspension in which a 3 g/km of CO_2 emission reduction could be achieved for a hybrid passenger automobile traveled on German roads. Moreover, Audi AG. engineers expected that harvesting this otherwise dissipated energy could improve the fuel economy by 0.7 liters per 100 kilometers. Fig. 2 and Fig. 3 summarize the energy harvesting potentials and fuel efficiency benefits for different vehicles. The power capacity is related to the vibration intensity levels meaning that the aggressive vibrations can collect more power and save more fuel which manifested obviously in case of heavy trucks and off-road vehicles. For example, as for the fuel cost saving, harvesting the otherwise dissipated energy from small road bumps in Wal-Mart trucks could save $13 million a year [22]. In addition to fuel-saving, several studies have been carried out for achieving better ride quality and road handling using the energy harvesting absorbers through different strategies such as tunable damping and variable inerter [23-25].

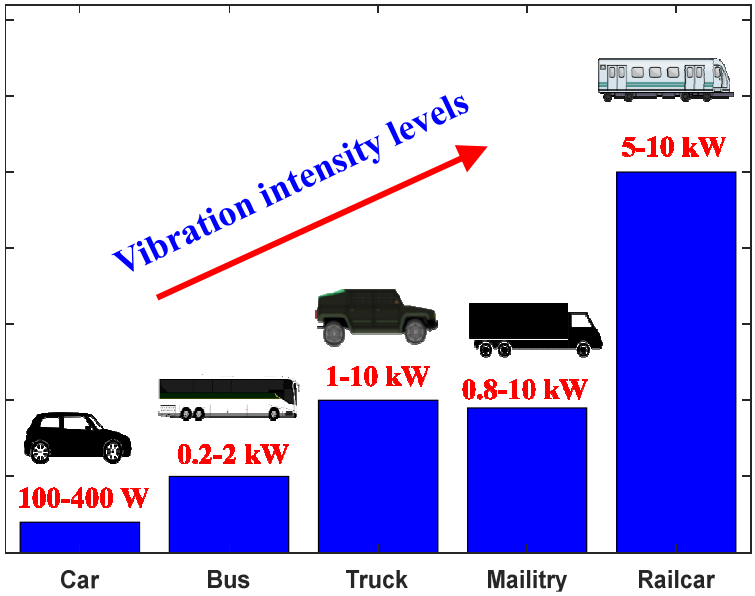


Fig. 2. Energy harvesting potentiality for different kinds of vehicles. [Reproduced and drawn with permission from Ref. [26]]

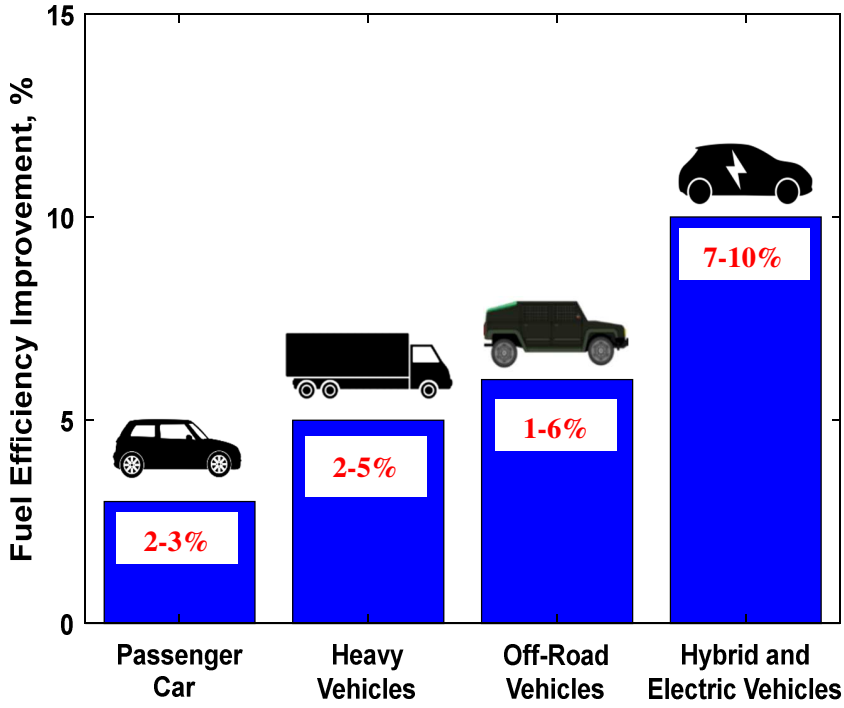


Fig. 3. Fuel efficiency potentiality using regenerative energy shock absorbers. [Reproduced and drawn with permission from Ref. [7] Copyright (2017) Elsevier]

Different strategies of regenerative suspension systems have been investigated and proposed to recover the otherwise dissipated energy in vehicle suspension. The energy harvesting mechanisms for suspension systems have also been investigated with an aim to improve the fuel efficiency and thus reduce energy consumption [27-30]. Practically, the harvested energy from suspension vibrations could be used for charging batteries and supplying electrical loads as a supplement to the vehicle alternator [31, 32]. Otherwise, it may have the potentiality to provide the energy demand of the semi-active or active suspensions as a self-powered controllable damper to achieve better ride quality and road handling [33-35].

The regenerative based shock absorbers can be classified based on how the perpendicular vibrations are translated into electricity. Among various vibration energy harvesting structures, the electromagnetic harvesters have gained popularity in vehicle regenerative based suspensions because of the high-energy conversion efficiency, quick response, strong controllability, and capability in energy recovery [36-38].

The electromagnetic motors were first proposed to be used as energy harvesting dampers two decades ago since then the electromagnetic shock absorbers have been the main interest of many scholars. Mainly, the energy harvesting suspension mechanisms can be classified as linear electromagnetic harvesters [39, 40] and rotary electromagnetic harvesters [41-43]. The linear electromagnetic harvester converts the energy potential of vertical oscillations directly into electricity based on electromagnetic induction with a simple structure. While the rotary electromagnetic harvester translates the linear vertical vibration into rotational oscillation of the generator and produces electrical energy based on linear-to-rotary transmission mechanisms. The rotary electromagnetic harvesters can be more compact and have high energy density than linear harvesters [44].

In rotary based electromagnetic harvesters, there are two common kinds of linear-to-rotary motion transmissions, the mechanical based transmission and the hydraulic based transmission. The mechanical transmission based harvester has been developed rapidly because of its simple construction, greater efficiency, and considerable average power [45]. Many proposed designs of the mechanical regenerative shock absorber have been introduced including ball screw mechanism [46, 47], rack-pinion mechanism [48, 49] and other mechanisms [50, 51]. The second category of the rotary electromagnetic harvesters is the hydraulic regenerative shock absorbers which harvest the vibration energy by employing oscillatory motion from hydraulic absorbers to drive the generator. Many researchers have implemented the hydraulic energy harvesters in vehicle suspensions and studied their performances theoretically and experimentally [52, 53].

This review tends to provide updates and state-of-the-art concerning energy harvesting from vehicle suspension as a large-scale vibration source. The energy harvesting potentiality from vehicle suspensions is addressed in this review paper to answer the question of how much energy is available for being harvested in vehicle suspensions. The principal motivation of this study focuses on reviewing the energy harvesting based suspension technologies and exploring the concept, structure and properties of the different harvesters as regenerative dampers. This state-of-the-art also presents a

comprehensive, analytical and statistical survey on the vehicle energy harvesting suspension systems including the conducted theoretical simulations, experimental bench tests, and real road tests. Further, a technical comparison between the most popular vibration energy harvesting schemes used in automotive suspensions is given. The research gaps that remain unresolved are addressed and some recommendations regarding such challenges are stated for further research and real scale applications.

2. General aspects of the power dissipation in vehicle suspension

Energy is considered an essential key worldwide. Energy could be found in several forms like electrical energy, chemical, thermal, mechanical (potential and kinetic). When something is capable of producing energy, it is called potential energy like water. While the kinetic energy is defined when energy is produced through motion such as vehicle crosses on a real road where the vibration energy through the suspension is generated out of both the potential and kinetic energy. Despite the widespread of vibrational energy harvesting applications in small electronic applications, the energy harvesting mechanisms attracted wide attention recently in automobile suspension. In automobile suspensions, the vibration harvesting mechanism implemented as a subsystem in which the power recycling is not the sole purpose but it should provide a satisfied dynamic behavior. The research on harvesting the wasted energy has become the major research aspect for different countries, commercial institutions and researchers as a green energy source [13, 21].

Basically, it is well known that energy could be converted from one sort to another as described in Fig. 4. In this manner, the piezoelectric and electromagnetic technologies are adopted for mechanical-to-electrical energy transformation. The piezoelectric style is mainly used in case of small-scale vibration harvesting as in micro-watt and milli-watt harvesters such as harvesting electricity from human body movement [54, 55]. Whereas, the electromagnetic harvesters are utilized for large-scale vibration-to-electricity harvesting like vehicle electromagnetic regenerative absorbers.

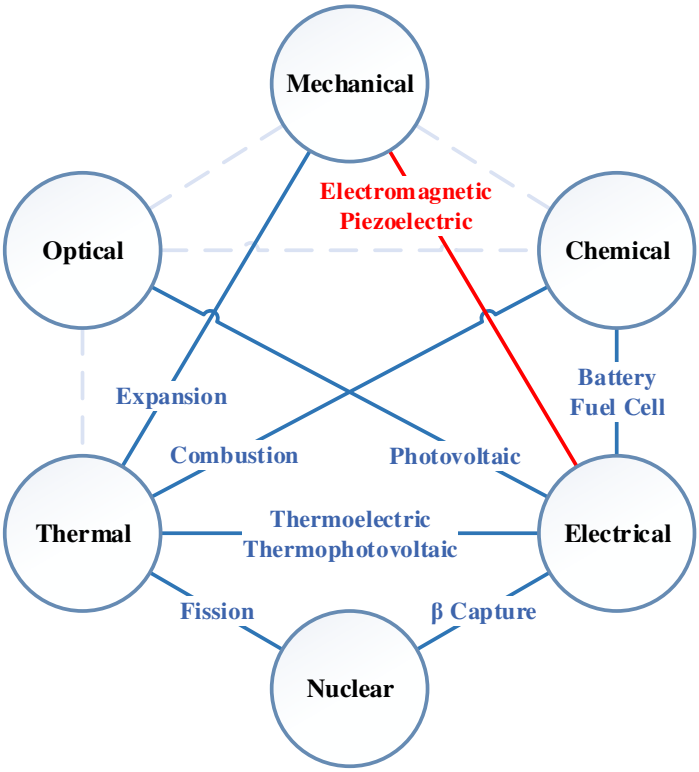


Fig. 4. Energy types and the transformation mechanisms among them. [Reproduced and Reprinted (adapted) with permission from Ref. [56] Copyright (2014) Springer]

Cao and Li [57] reported a comparison of the general energy harvesting methods stating that the energy source of machine vibration has a considerable overall efficiency between 20-40% compared to other energy sources (e.g., solar, wind, thermal, and other ambient energy sources). Thus, the application of energy harvesting technologies in the automotive sector is a very promising track based on the power potential capacity per damper. In terms of vibration energy harvesting, the regenerative shock absorbers have been developed and proposed as harvesting transducers to convert the kinetic energy of the undesired irregular vibrations into electricity and reduce the vibration as well. The earliest harvester based shock absorber with a linear electromagnetic motor was proposed and validated by suda and Shiiba [58], Karnopp [59] and Fodor and Redfield [60]. Based on the literature survey, the potential energy of the harvestable power is summarized in a very broad range from 46 to 7500 W for different vehicle categories and operation conditions. It might be that there are discrepancies between the laboratory and theoretical harvested energy results and the results for a real drive cycle on a real

field. This may be due to the differences between the testing conditions and assumptions and the real operational conditions for a vehicle under normal driving conditions [61, 62].

2.1. How much energy is dissipated in vehicle suspension?

In terms of ground vehicles, the majority of the produced energy is lost in the powertrain operations including the engine and drivetrain and overcoming resistances such as rolling resistance and aerodynamic drag [63-65]. Reducing the vehicle energy losses is necessary for improving fuel economy, reducing emissions, and supplying other systems with the saved energy like active suspension [66]. The vehicle consumes about 20-30% of the fuel energy in the car moving on roads. Considering the vehicle energy balance, suspension energy dissipation regrettably is not clearly quantified out of the fuel consumption, but it is only considered in the rolling resistance (Fig. 5) ranging from 3-12% of the fuel energy consumption [67-70]. Nevertheless, in a world where energy becomes rare and expensive, even the small quantities of such otherwise dissipated energy are worth of being harvested such as the energy lost in car suspension.

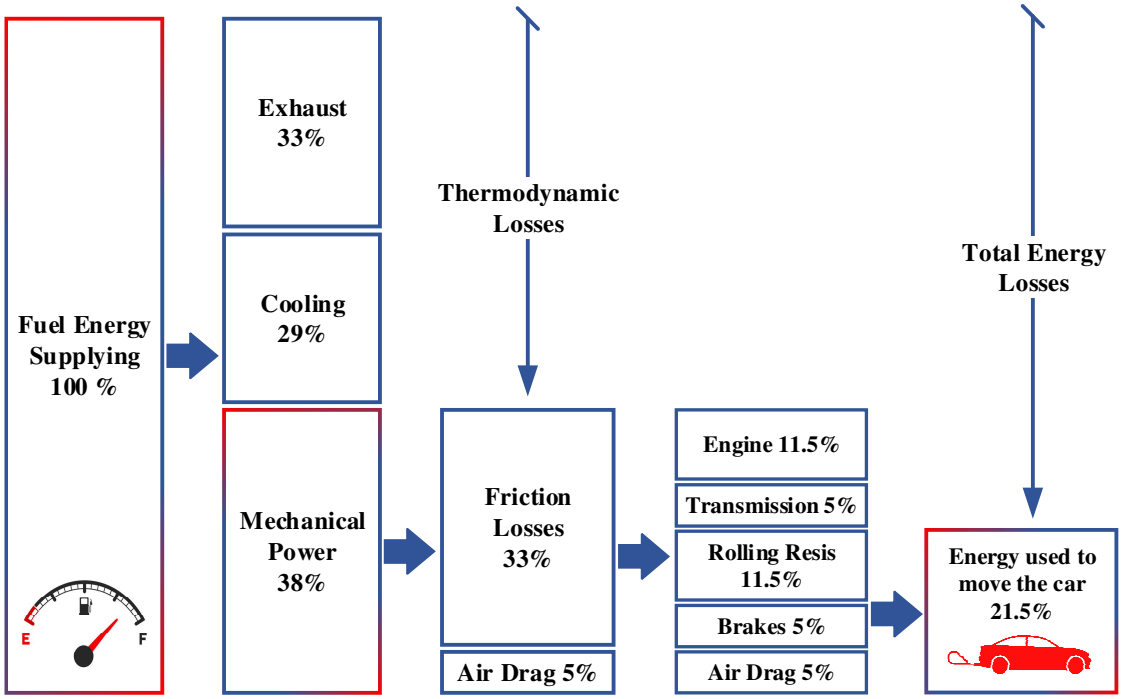


Fig. 5. Vehicle energy losses. [Reproduced and Reprinted (adapted) with permission from Ref. [67] Copyright (2012) Nature]

To calculate the power dissipation by the traditional viscous damper, the instant potential power is calculated as the damping force times the suspension relative velocity. Therefore, the instant and the average power dissipation are defined as appended below according to Ref. [71]:

$$P_i(t) = F_d * \left(\dot{Z}_s(t) - \dot{Z}_u(t)\right) = C * \left(\dot{Z}_s(t) - \dot{Z}_u(t)\right)^2 \quad (1)$$

$$P_{avg} = C * \left(\frac{1}{n} * \sum_{ii=1}^{n} \left(\dot{Z}_s(t) - \dot{Z}_u(t)\right)^2\right) \quad (2)$$

where P_i is the instant power, F_d is the damping force, C is the damping coefficient and $\left(\dot{Z}_s - \dot{Z}_u\right)$ is the suspension velocity. While P_{avg} is the average potential power value per damper.

Table 1 surveys the power dissipation from vehicle suspension accounting the theoretical and experimental conducted investigations. Notably, it is observed from the literature that the area of measuring the dissipated energy through the vehicle suspension need further investigations and a typical data for a passenger car is needed in correspondence with the dissipated energy. According to

the predicted power results in [72], the energy dissipation from the vehicle damper was predicted for various road profiles and vehicle velocities. Under city driving velocities, each damper in the vehicle dissipated energy with an average rate of 20 W while a 35 W under highway velocities was dissipated per absorber. Thus, as for the whole vehicle, the average dissipated power was predicted to be 80 W and 140 W at city and highway velocities, respectively, because of the high-speed effect corresponding to the highway roads.

Considering the on-field test for a middle-sized car (Fig. 6), Zuo and Zhang [18] stated that the root mean square (RMS) of the dissipated power for one damper was 5 W for a class B road (good road), 15 W for a class C road (average road) and 37 W for class D (poor road). In addition, more harvestable power could be collected for different tire stiffness at the expense of the ride comfort and road handling. In the same investigation, the theoretical potential power of a typical passenger car was between 100-400 W for good and average roads when the car speed was about 97 km/h. Whilst, Khoshnoud et al. [73] indicated that the theoretical maximum recovered power at a sweep input of 20 Hz considering 3 different quarter car models (bounce, pitch, and roll) were 1.1 kW, 0.88 kW, and 0.97 kW, respectively. In Ref. [74], the authors calculated theoretically the dissipated power in the suspension system depending on 2-DOF quarter model and 4-DOF half car model for a sine wave input of 10 Hz frequency and 5 mm amplitude. Results showed that the energy harvesting potentiality per damper increased from 280 W for a quarter model to be 305 W for a half car model. Despite the considerable number of conducted studies in the dissipated power based vehicle suspension, a measured data for a typical passenger car were not found considering the four suspension sets. In an interesting on-field based study, Zuo and Zhang [18] measured the dissipated power of the left rear shock absorber mounted in Miles ZX40S (2007) with a speed of 40 km/h on-campus road of Stony Brook University in which the study showed that a power of about 15 W per damper.

Fig. 7 extensively compares the potential power for different vehicles over different driving circumstances. As for a driving velocity of 30 m/s (108 km/h or 67.1 mph), the car, bus, truck and off-

road vehicles dissipated an average power of 108, 559, 892, and 192 W, respectively, for ISO road class of D. This concludes that the overloaded trucks can collect 8 times power higher than the passenger car due to high vibration capacity in case of trucks and off-road cars. As reported in [71], in the regards of standard driving schedules, the vehicle can collect a potential power capacity up to 420 W per damper for different driving trips including NEDC (New European Driving Cycle), WLTP (Worldwide harmonized Light Vehicles Test Procedure), HWFET (Highway Fuel Economy Test), and FTP (Federal Test Procedure). Abdelkareem et al. [75] investigated the conflict of the ride confront, road handling and the energy harvesting potential stating that even in case of the best ride comfort, the absorber still dissipates a considerable potential power that is worthy of being harvested.

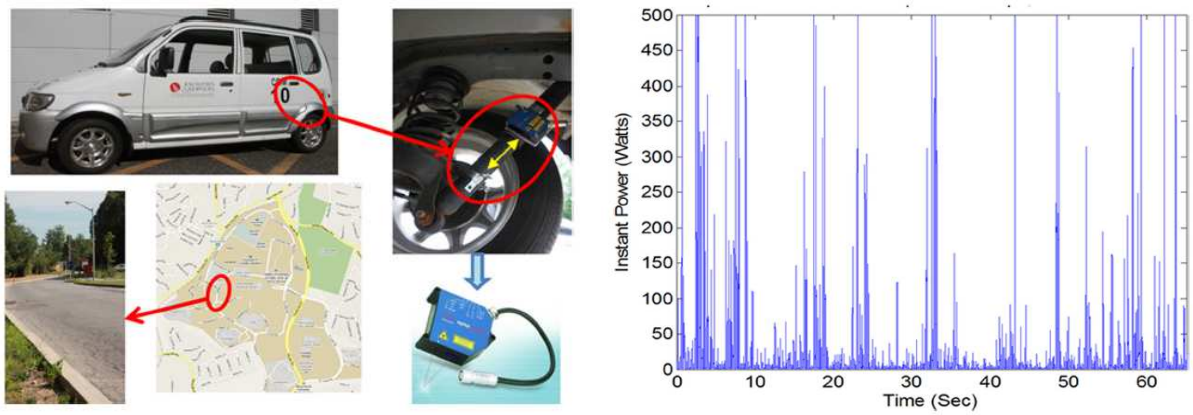


Fig. 6. Road test of a super compact car on Stony Brook campus and the dissipated power of the rear-left absorber at 25 mph. [Reprinted with permission from Ref. [18] Copyright (2013) ASME]

Observably, looking at Fig. 8, the power dissipation during the damping process correlates strongly to the driving speed, road roughness, and tire stiffness in which the aggressive vibrations have a considerable capacity of the energy harvesting potential.

In summary, considering the simulation environment using an uneven road surface, the power dissipated by one shock absorber in a 2-DOF quarter model varied widely from 20-1600 W for different driving circumstances (Table 1). In the case of heavy and off-road vehicles, the dissipated power potentiality is significantly higher than the passenger cars which requires consideration of regeneration and utilization of this power losses. In practical, it seems that the amount of power dissipated per

absorber is different and lower than the theoretical one, however, recapturing such wasted power in the transportation sector across the whole country will save millions of dollars [22].

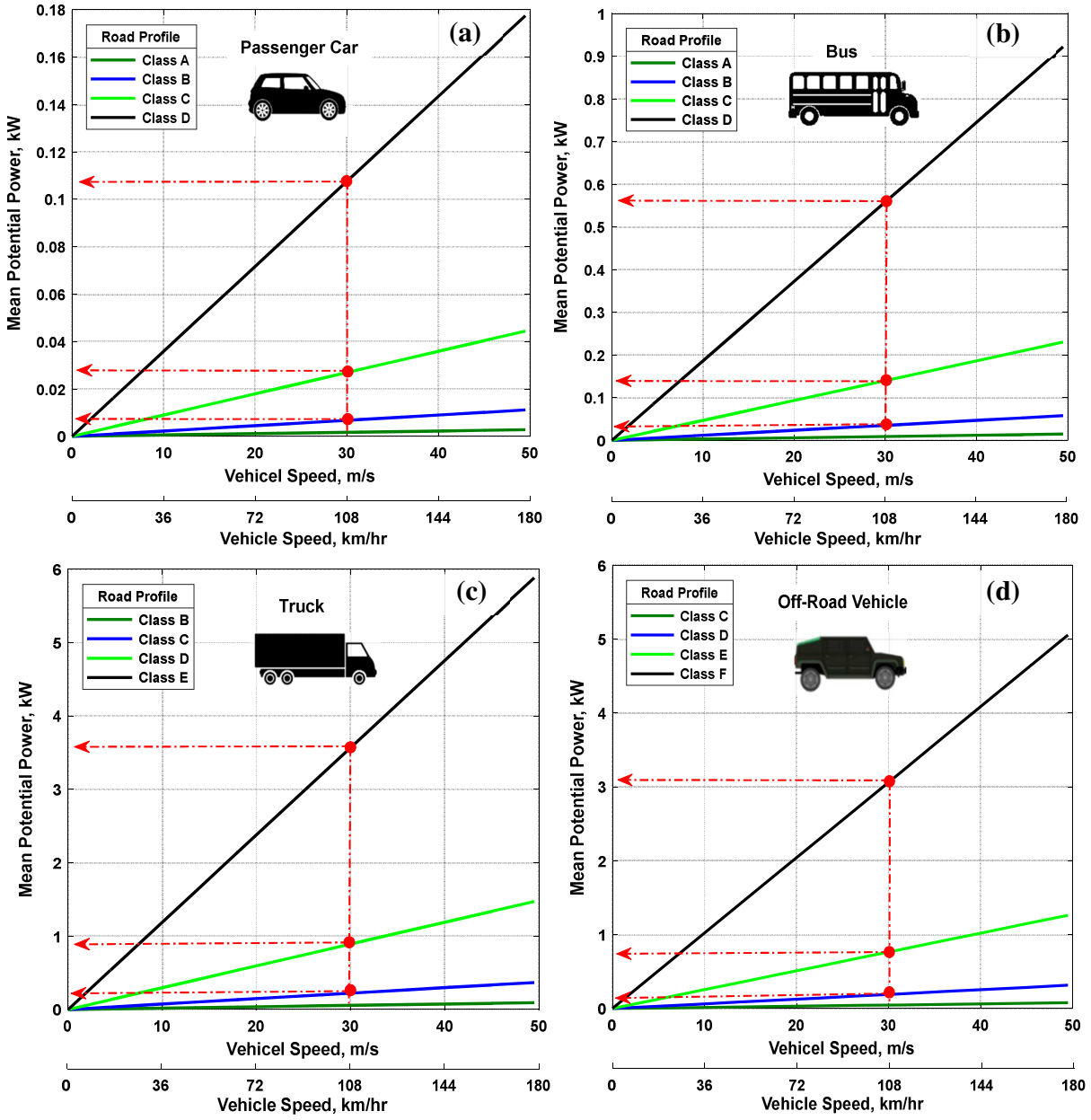


Fig. 7. Average potential power results for different vehicle types traveling under different ISO road levels. [Reprinted (adapted) with permission from Ref. [71] Copyright (2018) Elsevier]

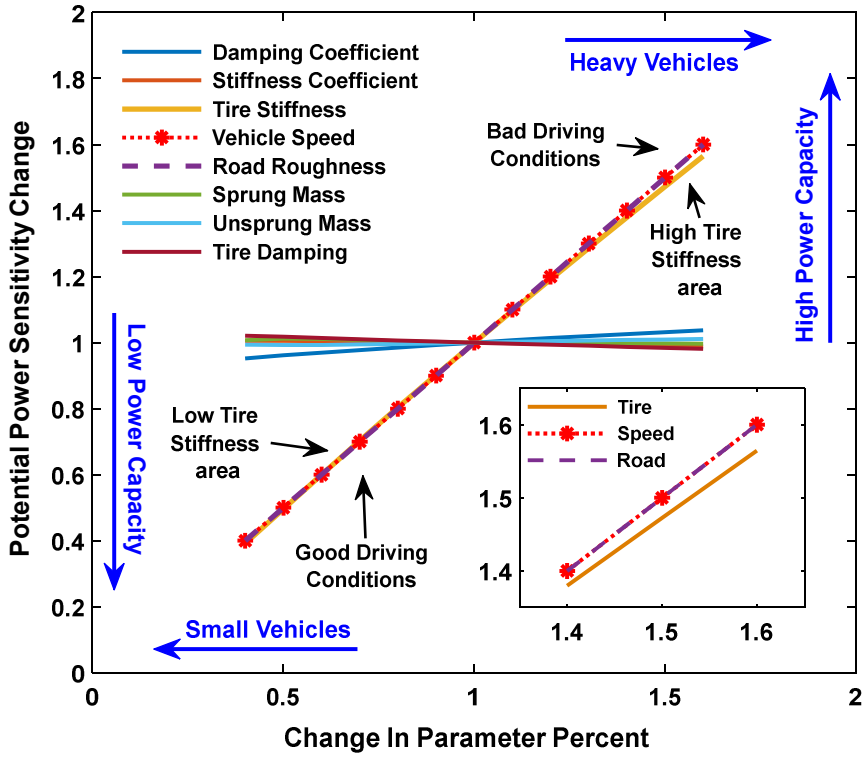


Fig. 8. Parametrical sensitivity analysis of the potential power based vehicle suspension. (Reproduced and drawn with permission from Ref. [71] Copyright (2018) Elsevier)

Vehicle tires are also dissipating some power in which the vibration capacity inside a tire has the potential to collect electricity using piezoelectric based harvesters [76, 77]. Despite the small power capacity that can be harvested from vehicle tires, it can be utilized in the field of self-powered sensor systems for intelligent tires such as self-powered wireless sensors [78, 79] and remote sensing of car tire pressure [80]. Lafarge et al. [74] explored theoretically the potential power dissipated by vehicle tire for a stimulus magnitude of 5 mm and frequency of 25 Hz showing that the dissipation power was 5 W for smaller tire damping of 10 Ns/m and up to 45 W wasted power corresponds to a damping factor of 100 Ns/m. Considering a piezoelectric ring harvester, Xie and Wang [81] developed a dual-mass model of a piezoelectric ring tire harvester and explored the theoretical harvested power from vehicle tires vibration showing that 42.08 W can be utilized for rough roads (Class C) and 40 m/s speed.

Table 1. Survey of the energy harvesting potentiality of vehicle suspensions.

	No.	References (Published Work)	Model Type	Road Conditioning	Velocity (km/h)	Dissipated power per damper (W)
Simulation Investigations Survey	**1.**	Zuo and Zhang [18]	2 DOF Quarter Model	Class B ($G_d = 16 * 10^{-6}$ m^3/rad) Class C ($G_d = 64 * 10^{-6}$ m^3/rad)	40, 96.5	10, 25 40, 100
	2.	Zhang et al. [7]	2 DOF Quarter Model (Passenger Car) 2 DOF Quarter Model (Off-Road Car) 2 DOF Quarter Model (Bus)	Class B, Class C	60	30-105 285-384 402, 1152
	3.	Wei and Taghavifar [82]	4 DOF Half Model	Harmonic Excitation (2 Hz frequency and 10 mm amplitude) Smooth Highway (N_d = 2.1, C_{SP} = 4.4 *10^{-7}) Highway with gravels (N_d = 2.1, C_{SP} = 4.4 *10^{-6})	20 20	64 [a] 40 [b] 37 (average) 357 (average)
	4.	Liu et al. [83]	2 DOF Quarter Model	Class B-D	72	27-1626
	5.	Múčka [84]	9 DOF Full Car Model 2 DOF Quarter Model	Real Road Profiles (PCC and AC)	60, 90	~ 5 - ~ 12 ~ 6 - ~ 15
	6.	Lafarge et al. [74]	2 DOF Quarter Model 4 DOF Half Model	Sine Wave (10 Hz, 5 mm)	20 ~ 120	~ 280 (mean) ~ 305 (mean)
	7.	Khoshnoud et al. [73]	2 DOF Bounce Model 2 DOF Pitch Model 2 DOF Roll Model	Sweep Excitation (0.5-20 Hz, 10 mm)	-	1106 (average) 880.5 (average) 970.5 (average)
	8.	Nakano and Suda [85]	6 DOF Half Truck Model	-	-	55.39 (average)
	9.	Pham et al. [86]	7 DOF Full Car Model	Random Road Excitation	-	120 (average)
	10.	Singh and Satpute [62]	2 DOF Quarter Model	Random Road Excitation	35	15 (average)
	11.	Segel and Xiao [87]	2 DOF Quarter Model	-	48.24	50
	12.	Zou et al. [88]	2 DOF Quarter Model	Class A-D	-	3-107
	13.	Abdelkareem et al. [75]	2 DOF Quarter Model	Class A-D	72	2-33 (RMS) 1-19 (average) 12-190 (peak)

	14.	Abdelkareem et al. [71]	7 DOF Full Car Model	Bounce, Pitch, Roll input modes (Class C)	36 72 108	49, 48, 55 97, 95, 109 146, 143, 164
Experimental Investigations Survey	**1.**	Khoshnoud et al. [73]	2 DOF Bounce Model 2 DOF Pitch Model 2 DOF Roll Model	Sweep Excitation (0.5-20 Hz, 10 mm)	-	984 (average) 741 (average) 786 (average)
	2.	Shi et al. [35]	2 DOF Quarter Test Bench	Random Excitation Input	-	321.16
	3.	Browne and Hamburg [89]	-	Typical City Road	48.24	60
	4.	Zuo and Zhang [18]	2007 Miles ZX40S electrical low-speed car (1088 kg curb mass)	Campus road of Stony Brook University	40	15 (RMS) [c]
	5.	Gill et al. [90]	2005 Toyota Hilux SR5 (curb mass of 1800 kg, gross vehicle mass of 2810 kg, leaf springs.)	Suburban	~ 36	~ 14
					~ 60	~ 20
					~ 33	~ 21
					~ 49	~ 33
					73	~ 36
				Rural	~ 58	~ 33
					~ 48	~ 90
					~ 50	~ 95
				Suburban (Highway)	~ 60	~ 20
					~ 37	~ 30
			1997 Freightliner FL112 flatbed hauling vehicle (gross vehicle mass of 26600 kg, air springs.)	Suburban	~ 25	~ 12
					~ 41	~ 27
				Suburban (Highway)	~ 52	~ 34
					~ 53	~ 40
					~ 60	~ 53
					~ 68	~ 65
					~ 50	~ 129
					~ 40	~ 162

a: the instantaneous power of the front suspension. **b**: the instantaneous power of the rear suspension. **c**: power result of the rear-left absorber mounted at an angle of 30o to the vertical direction.

2.2. Energy flow in vehicle suspension

Fundamentally, road irregular roughness and excitation vibrate the automobile suspensions giving rise to an undesirable disturbance onto the automobile chassis and body. The overall architecture of the regenerative shock absorber, which is implemented to recover the wasted vibration energy, as shown in Fig. 9, has four main junctures: (1) vehicle suspension excitation, (2) vibration power generation by means of a suspension damper, (3) energy conversion and modulation, and (4) power storage units. Accordingly, the vibration energy flows into the suspension making the damper moves vertically up and down sequentially. The electrical power could be generated out of these perpendicular oscillations directly by the linear electromagnetic harvesters or indirectly by the rotary electromagnetic harvesters. In the linear electromagnetic harvester, the perpendicular vibrations are used to generate electricity directly using linear generators and power modulation without any motion transmissions [91, 92].

In the rotary electromagnetic harvester, the vertical displacement is translated into a rotational motion via a transmission mechanism for driving an electrical rotary generator in which a power converter circuit is attached to the generation loop before storing the harvested power to be used for many applications. The transmission mechanism converts the vertical displacement to a bi-directional rotation which diminishes the energy recovery efficiency. Motion rectifiers are implemented by different researchers [93, 94] to overcome such shortcomings that can rectify the bi-directional motion to unidirectional rotation motion to enhance the mechanical reliability and the conversion efficiency. Li et al. [95] developed a mechanical motion rectifier (MMR) and thereafter investigated the influence of using an energy harvester damper based MMR on the energy harvesting efficiency. Notably, considering MMR modulators showed a stupendous improvement in the efficiency ranging from 30-62% at the higher frequency. Whilst, Fang et al. [96] proposed a hydraulic rectifier based on four hydraulic check valves combined together with a rectifying efficiency of 83.5% at 10 Hz so the fluid drives the hydraulic motor in one direction even if the damper is in the extension or in the compression stroke. However, MMRs are used on account of their capability to promote the power conversion efficiency, their influences on automobile dynamics were rarely investigated.

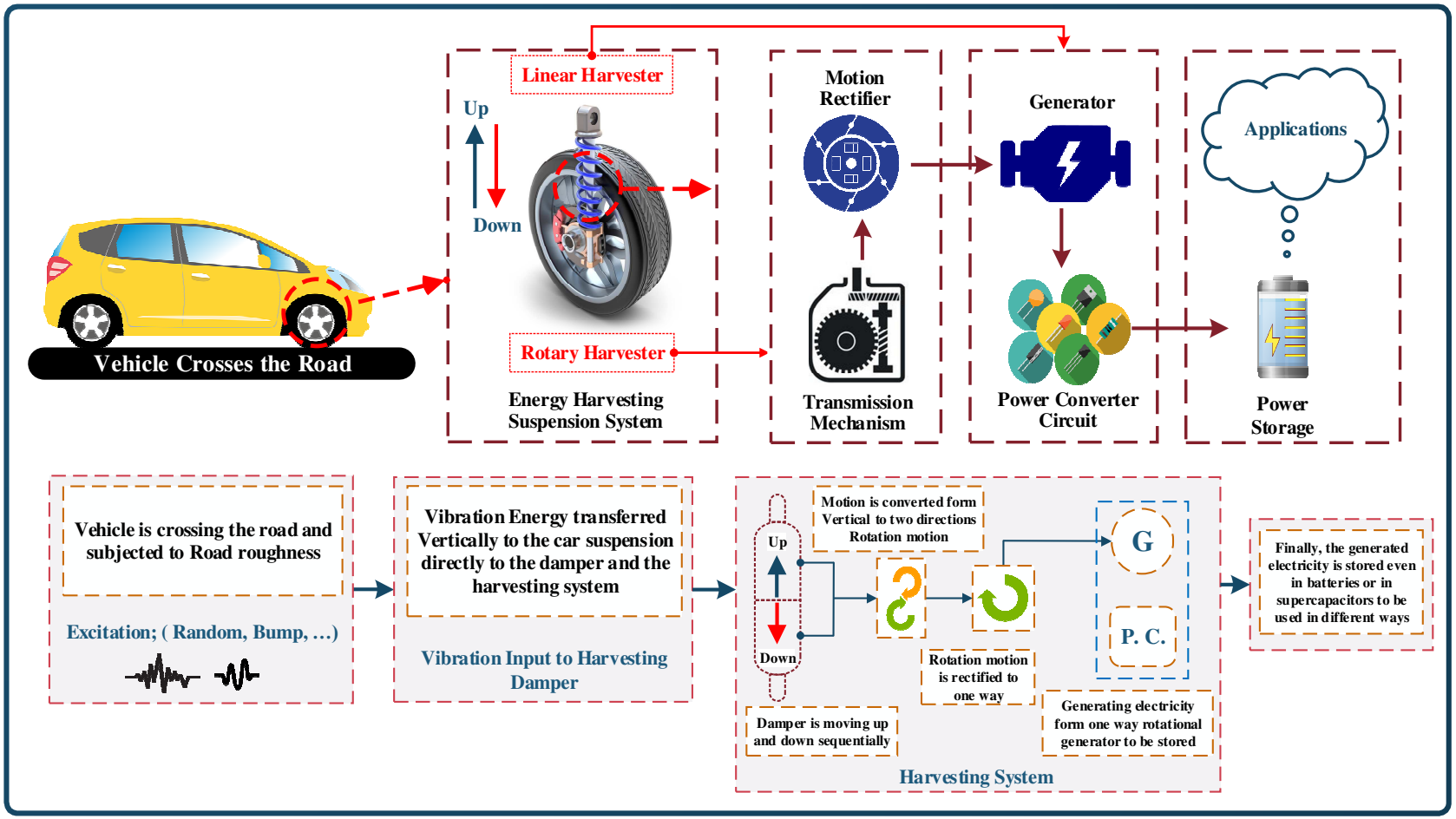


Fig. 9. Scheme of the vehicle energy harvesting suspension system layout.

3. Regenerative energy conversion mechanisms based vehicle suspensions

Ordinarily, the vehicle rolls on uneven roads in which the harvesting-based damper can convert the linear oscillation of the suspension into electricity based on an electromagnetic circuit. Regenerative suspension based on electromagnetic harvesting method is one of the most popular harvesting technologies used in automotive energy harvesting suspension as issued in the literature. The electromagnetic based harvester has been put forward and become increasingly attractive because of its high-energy conversion efficiency, design simplicity, quick response, strong controllability and capability in energy recovery [97, 98]. As previously mentioned in the literature, the energy harvesting mechanisms are categorized based on how the perpendicular vibrations are translated into electricity. According to the electromagnetic motor modulator, the harvesting mechanisms can be categorized into linear electromagnetic harvesters (direct energy harvesters) and rotary electromagnetic harvesters (indirect energy harvesters). Both the linear and rotary electromagnetic based energy harvesting suspensions were investigated by many scholars.

This section presents the implemented energy regenerative absorber configurations and their working principles and mechanisms. Besides, a comparison of the findings with those of other studies conducted on energy harvesting shock absorbers is addressed.

3.1.Electromagnetic linear harvesting shock absorbers

The electromagnetic motors (EM) were first proposed to be used as energy regenerative dampers two decades ago since then the electromagnetic shock absorbers have been the main interest of many researchers. Basically, the linear-based electromagnetic damper transforms the kinetic energy of vertical oscillations directly into electricity by electromagnetic induction with a simplistic structure. Unlike the rotary electromagnetic harvester which depends on a transmission-based system to provide the rotary generator with a unidirectional motion, in the linear motor-based system, there is no need for a transmission mechanism in which the electricity is generated directly

from the vertical displacement. In this regard, the linear-based electromagnetic harvester offers a high capacity of the regenerated power as the power losses by the transmissions are saved.

The transmitted vibration from the base excitation due to the ambient environment causes a relative translational movement of the magnet in relation to the coil. This relative oscillating motion causes a variation in the magnetic flux inside the coil where the voltage induced in the coil can be determined as in Eq. (3) according to the Faraday's law [99].

$$\varepsilon_v = -\frac{d\phi_B}{dt} \tag{3}$$

where ε_v is the induced voltage and ϕ_B is the magnetic flux.

Based on the linear electrodynamic motors, Suda et al. [58] developed an active suspension combined with an energy harvesting system with a linear DC generator to achieve good performance of vibration suppression with less energy consumption. In [59], the first mechanical damper with adjustable damping considering a linear permanent magnet motor was proposed.

Considering the linear generator concept, Zuo et al. [91] prototyped a linear generator based harvesting damper in which the vibrational kinetic energy of the vehicle wheel/body could be converted into electricity. The proposed linear electromagnetic harvester (Fig. 10b) has two main parts which are the magnet assembly and the coil assembly. The magnet arrangement composed of ring-shaped permanent magnets and ring-shaped high magnetically permeable spacers stacked on a rod of high reluctance material [91]. In another study conducted by Sapinski and Krupa [92], two linear generator structures were proposed as a vibration-based power harvester for a linear MR damper (Fig. 11). The first generator structure exhibited in Fig. 11a in which it was constructed with two neodymium-boron magnet assemblies (four magnets in each), three ferromagnetic spacers and a one-section coil. In Fig. 11b, the second generator was built with three neodymium-boron magnet assemblies, four ferromagnetic spacers and a coil winding with two sections.

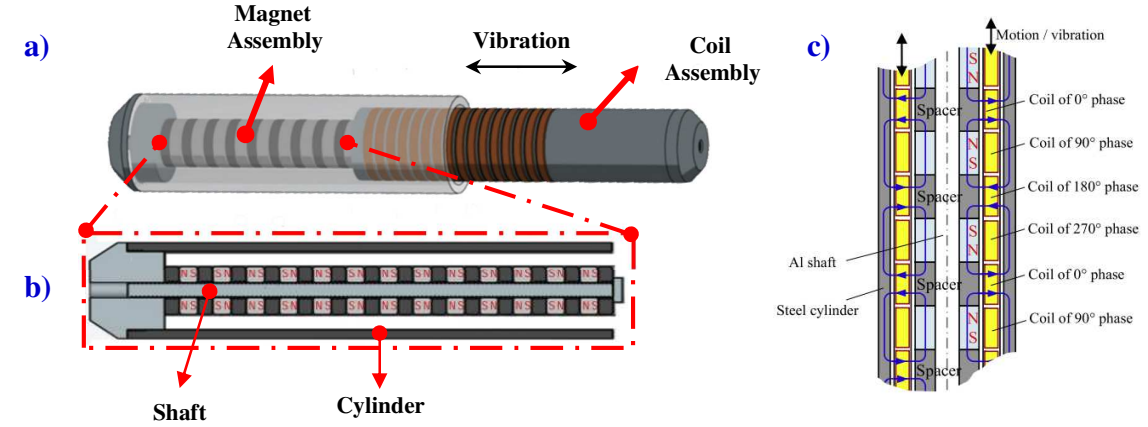


Fig. 10. Linear electromagnetic based energy harvesting shock absorber; (a) 3D model of the linear motor-based damper; (b) cross-section of the magnet assembly; (c) diagram of the four-phase generator. [Reprinted (adapted) with permission from Ref. [91] Copyright (2010) IOP]

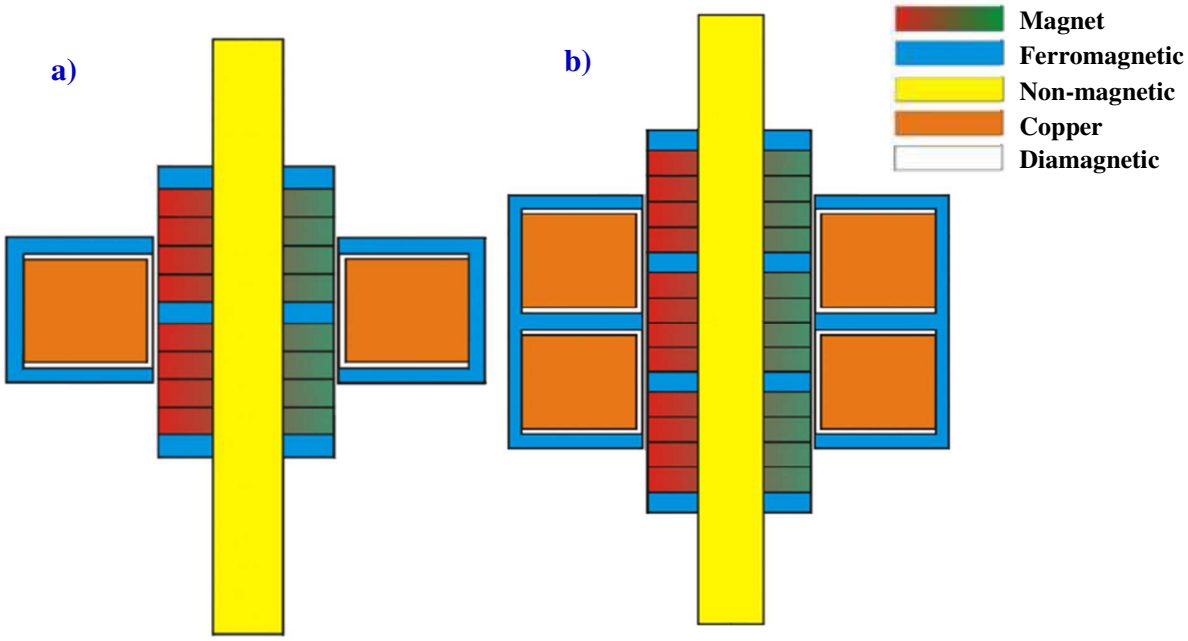


Fig. 11. A sectional view for two linear generator structures; (a) linear generator with two neodymium-boron magnets and three ferromagnetic spacers assembly; (b) linear generator with three neodymium-boron magnet systems and four ferromagnetic spacers assembly. [Reprinted (adapted) with permission from Ref. [92] Copyright (2013) IOP]

Meanwhile, self-powered actuation recognizing energy harvesting out of ambient vibrations has risen as a prominent research topic [100-102]. These results indicated that this electromagnetic

suspension system can significantly improve both comfort and handling with minimal power requirements between 150-300 W overall power consumption for the full vehicle depending on road conditions and objectives [28]. In General, the electromagnetic generators have high energy density with the ability to be fabricated without difficulties. Unlike the piezoelectric and electrostatic generators, the electromagnetic generators require neither smart materials nor external voltage supplier [103].

One advantage of the linear electromagnetic harvesters is that being easily and reliably integrated into most existing vibration systems without the requirement for transmission mechanisms. Another advantage is that they are commonly used for active and semi-active suspensions due to their good controllability properties. However, there are certain drawbacks associated with the use of linear electromagnetic harvesters in vehicle suspensions as stated in Table 2. As an example of the drawbacks, the linear harvester has a high production cost which requires accurate system design to make the magnetic hold the excitation force. In addition, their size is still large because of the relatively low vibration velocity.

3.2. Electromagnetic rotary harvesting shock absorbers

In terms of electromagnetic rotary harvesters, the kinetic energy represented by the perpendicular vibration of the car suspension is harvested to electrical energy using a rotary electromagnetic motor. The perpendicular vibration is translated into a rotational motion through a transmission mechanism to drive the rotary motor. Based on the electromagnetic rotary harvesters, different linear-to-rotary motion transmissions have been prototyped and developed with different mechanisms and structures. As mentioned in the literature, there are mainly two common linear-to-rotary motion transmissions which are the mechanical transmission based electromagnetic rotary harvesters and the hydraulic transmission based electromagnetic rotary harvesters.

3.2.1. Mechanical transmission based electromagnetic rotary harvesting shock absorbers

Mechanical based transmission rotary harvesters could be one of the most common designs among various energy harvesting structures which are developed early due to simple construction and high conversion efficiency. Different strategies of regenerative suspension systems based on mechanical concept have been conceptualized, prototyped and studied extensively. There are numerous categories of energy regenerative suspensions considering mechanical styles like ball-screw mechanism [104-106], rack-pinion mechanism [107, 108], algebraic screw mechanism [109], pullies-cables assembly and other mechanical based systems [110]. Graves et al. [111] stated that the rotary electromagnetic dampers provided the potential of mechanical amplification of damping and regeneration due to the transmission gear ratio. Whereas the rotating inertia of the transmission mechanism affected the suspension system, a solution to this problem was proposed by adding extra dynamic elements in series with the rotating damper. Fig. 12 presents the structural design of the rack and pinion assembly and ball screw mechanism as a harvesting shock absorber. As illustrated in Fig. 12a, the linear vibration created when the vehicle rolling on an uneven road is translated into a rotational motion via a rack-pinion assembly and thus, it is transmitted to the generation motor through a small differential with two perpendicular bevel gears. While in Fig. 12b, the input torque for the motor is created through a ball-screw assembled with a small ball nut and coupler.

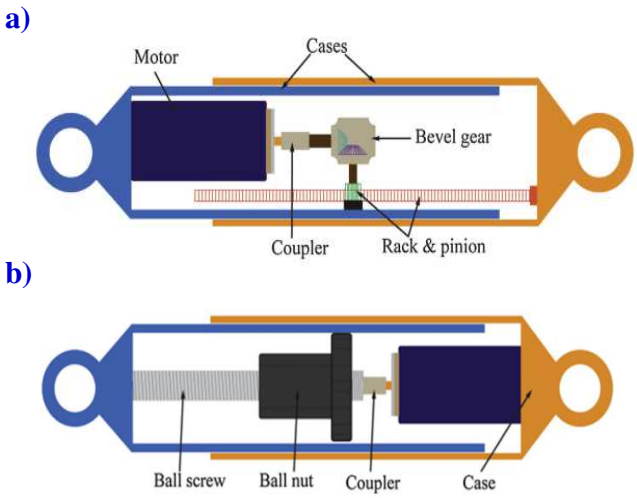
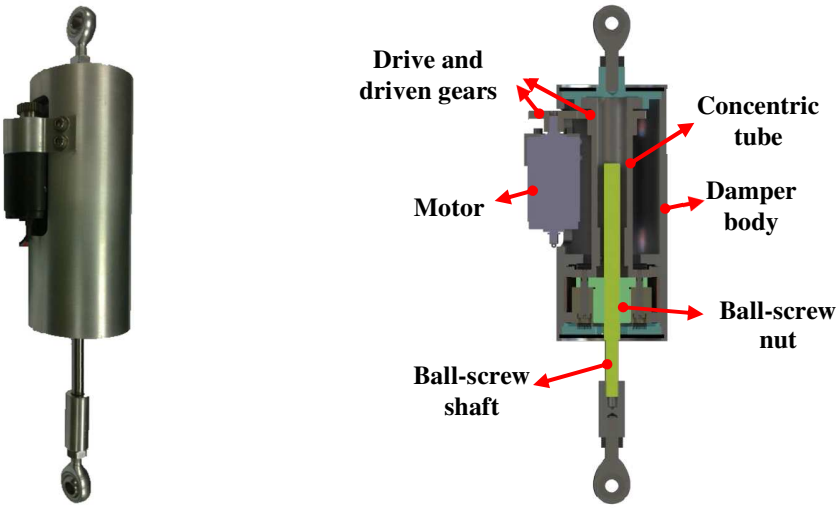
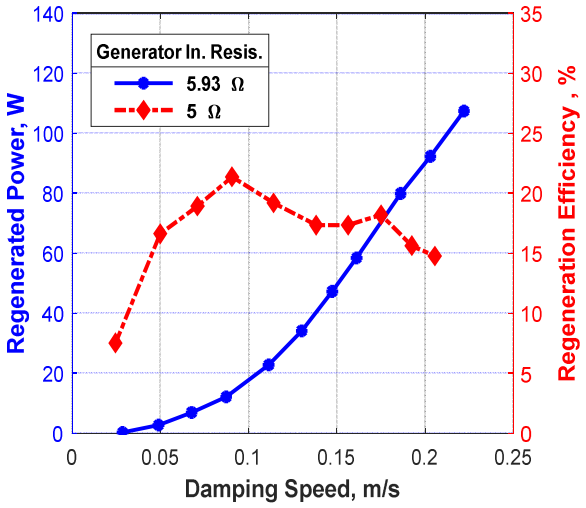


Fig. 12. (a) Rack-pinion energy regeneration mechanism, (b) Ball-screw energy regeneration mechanism. [Reprinted (adapted) with permission from Ref. [112] Copyright (2016) Elsevier]

Zhang et al. [113] proposed a regenerative damper prototype based on a ball-screw mechanism, thereafter they validated it experimentally on a full vehicle via Road-Lab four post rig considering a sinusoidal excitation of 3 and 11 Hz frequency and 5 and 10 mm amplitude. The proposed prototype produced 12 W harvested power per damper. The proposed damper gave a poor ride behavior when considering high frequencies excitation, while a good ride performance was achieved for low frequencies excitation because of the high produced inertia moment of the ball screw at high frequencies bandwidth. Song et al. [114, 115] patented a shock absorber harvester with ball-screw mechanisms which achieved a considerable power conversion density, however bad ride comfort was found at high frequencies bandwidth above 7 Hz which compatible with [113]. In [116], a ball-screw assembly was prototyped in a regenerative damper in which the energy harvesting performances was illustrated as displayed in Fig. 13. It can be seen from Fig. 13c that an electrical regenerated power of 107 W was observed at a damping speed of 0.22 ms^{-1} and a generator internal resistance of 5.93 Ω during rebound case. While the generation efficiency reached a percent of about 21.3% for damping speed of 0.09 ms^{-1} and an internal resistance of 5 Ω.



(a) (b)



(c)

Fig. 13. Regenerative shock absorber with ball screw shaft; (a) proposed prototype; (b) CAD model sectional view with major components; (c) power generation performance for the proposed prototype during rebound stage. [Reproduced and drawn (adapted) with permission from Ref. [116] Copyright (2013) National University of Singapore]

Xie et al. [117, 118] proposed an energy harvesting absorber with ball-screw transmissions and multiple controlled generators (Fig. 14) to recover the kinetic energy dissipated during the damping process and continuously adjust the damping coefficient according to road conditions. The proposed harvester recaptured an average electrical power of 32 W at a displacement input of a 3 Hz frequency and 20 mm amplitude.

In 2010, Zuo at al. [119] patented a prototype of a harvesting damper considering rack and pinion assembly that had a high energy density. Li et al. [120] conducted both laboratory testing analysis and real road field test for a new design of a retrofit rack-pinion harvester which attained a total power conversion efficiency of about 56% for an excitation of 30 mm amplitude and 0.5 Hz vibration frequency. Additionally, an average power of 19.2 W can be recovered from one energy-harvesting unit when the vehicle speed was about 48 km/h on a smooth real road. With a view to enhance the power conversion efficiency at high frequencies bandwidth, Li et al. [95] proposed a mechanical motion rectifier attached with a rack-pinion damper (Fig. 15) to convert the irregular bi-directional motion to unidirectional rotational motion which offered a small impact forces caused by backlash to promote the reliability significantly leading to enhance the conversion efficiency by decreasing the friction effectiveness. As the demand for alternative power sources of a railway, Zhang et al. [121] developed a portable track vibration-based energy harvesting unit depending on a mechanical transmission of rack-pinion motion converter in which the motion is rectified using one-way bearings. A considerable efficiency of about 55.5% was calculated based on experimental fulfillment for a vibration excitation of 2 Hz frequency and an amplitude of 6 mm.

Another regenerative energy damper based on a mechanical concept (Fig. 16) was presented by Maravandi and Moallem [50] that depended on a two-leg mechanism with a view to convert the vertical motion due to vibrations into rotary motion. The prototype of the two-leg based regenerative damper was capable of recovering energy with an average mechanical efficiency of 78%. However, there is a difficulty in applying this type practically in vehicle suspension which it was fabricated with a view of power harvesting in a way that overwhelms the damping properties.

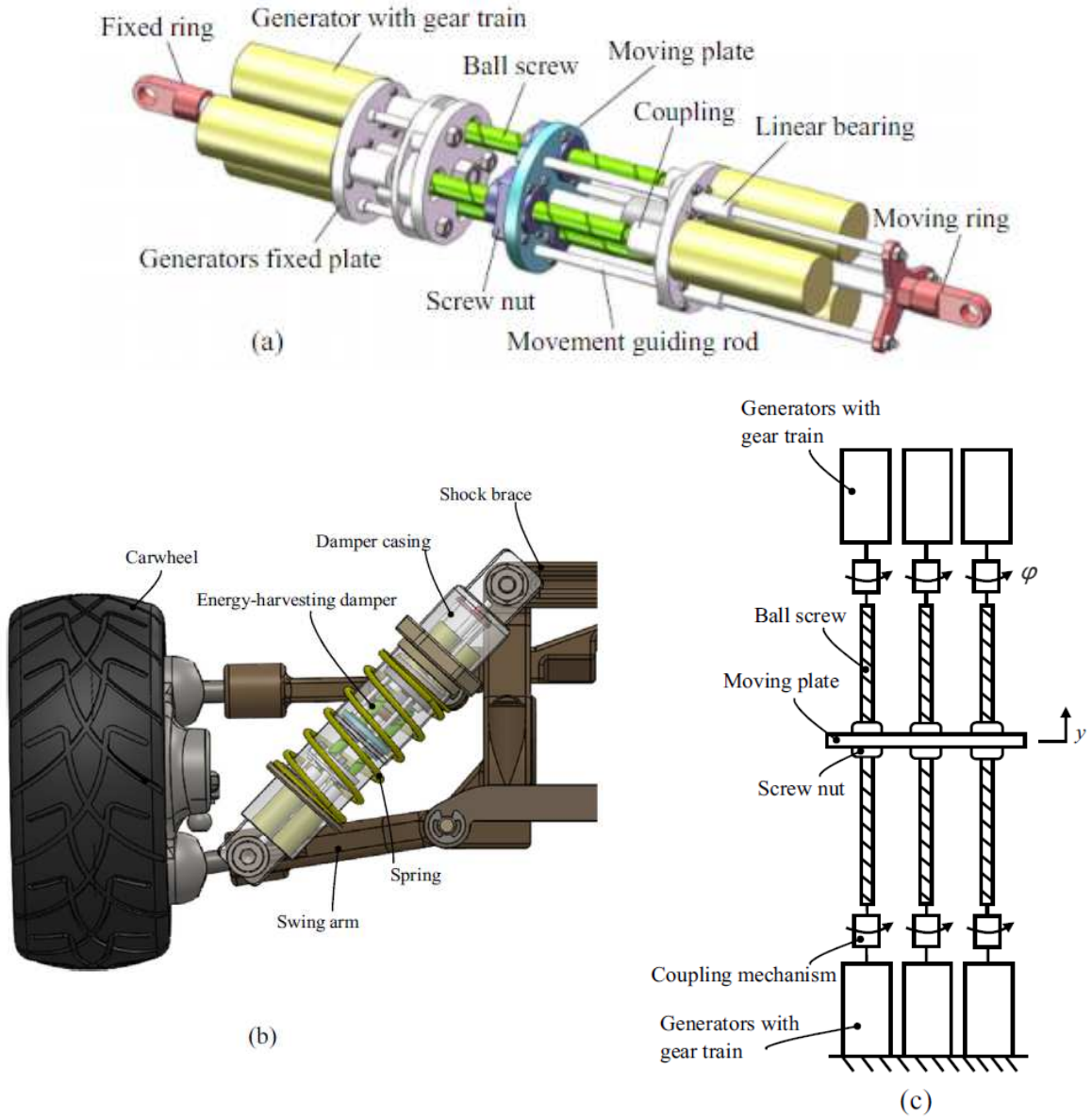


Fig. 14. Ball-screw transmission-based energy-harvesting damper; (a) 3D model, (b) the damper in suspension, (c) diagram of the transmission mechanism. [Reprinted (adapted) with permission from Ref. [117] Copyright (2017) Elsevier]

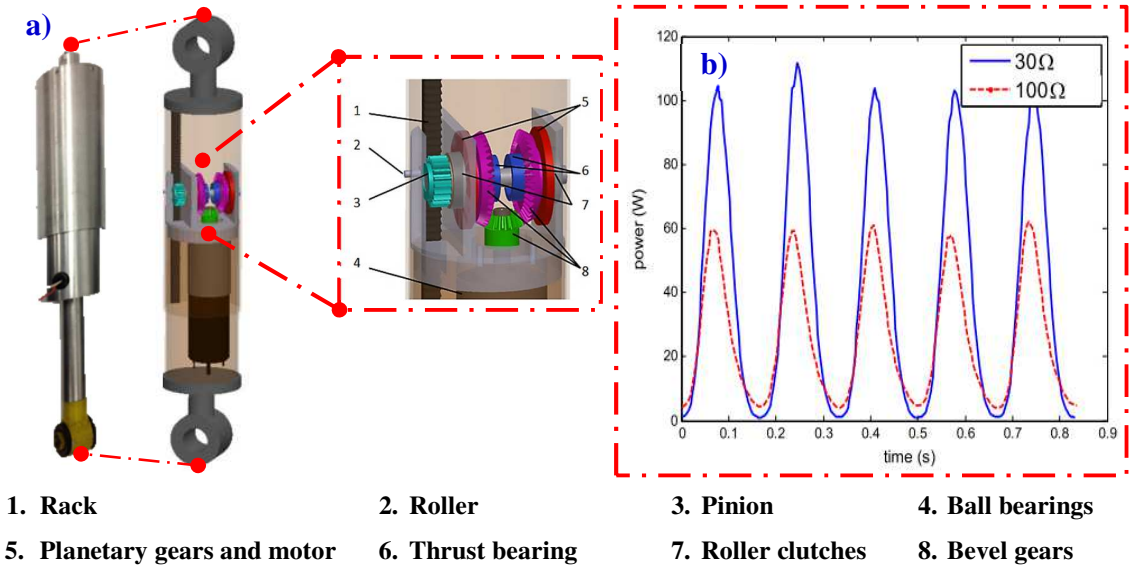


Fig. 15. Regenerative shock absorber based on rack and pinion mechanism with MMR; (a) 3D model and actual prototype; (b) power generation performance at 3 Hz input frequency and 5 mm amplitude. [Reprinted (adapted) with permission from Ref. [95] Copyright (2013) IOP]

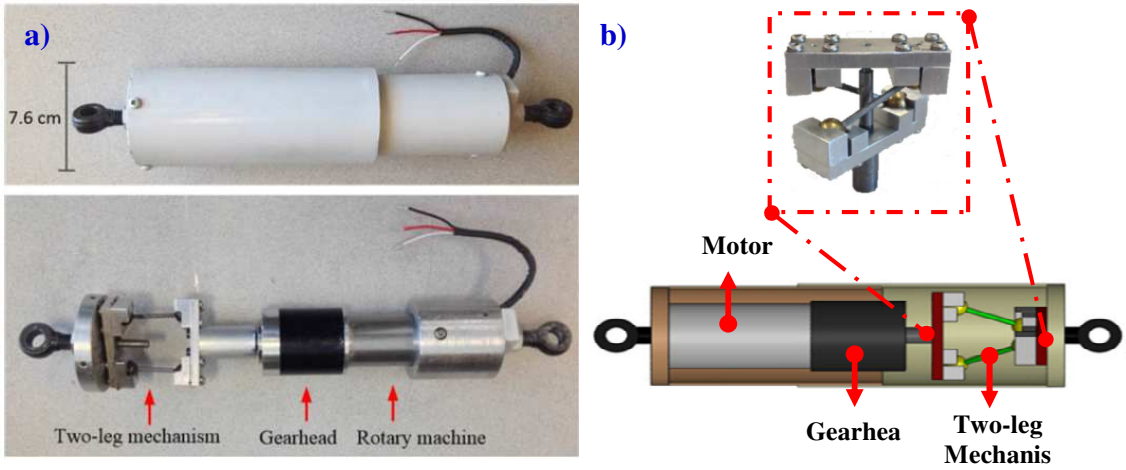


Fig. 16. Regenerative shock absorber based on the two-leg mechanism; (a) prototype of the two-leg mechanism-based damper; (b) CAD assembly of the proposed prototype. [Reprinted (adapted) with permission from Ref. [50] Copyright (2015) IEEE]

In Fig. 17, another indirect drive based mechanical transmission rotary electromagnetic energy harvesting based damper is given which is called Cable-Dynamics Energy Harvesting Shock Absorber (CD-EHSA) [122]. The CD-EHSA's prototype is shown in Fig. 17a in which the linear oscillations of the shock absorber are converted to rotational motion using cables, two main pullies

(generator pulley and driven pulley), tensors and end stops, see Fig. 17b. Looking at the power results of the CD-EHSA's prototype, the total output electrical power (4 CD-EHSA in a full car suspension model) reached a mean square power of 105 W for a driven speed span of 20-30 km/h.

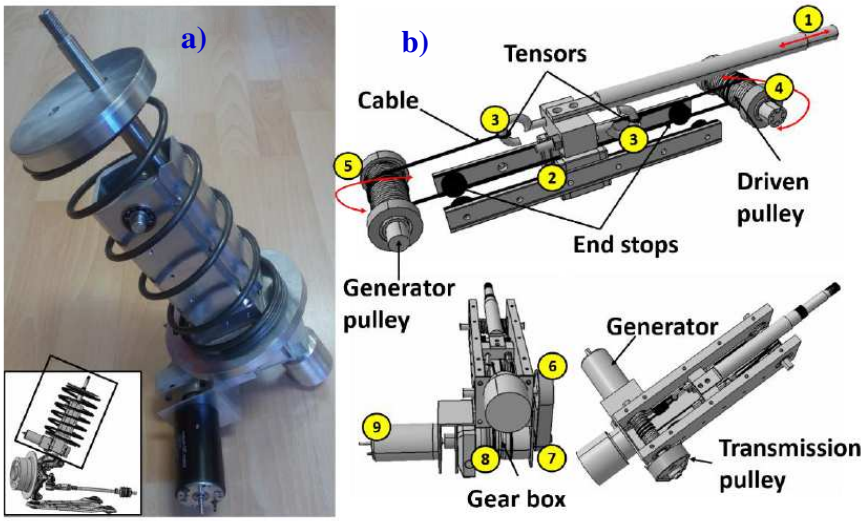


Fig. 17. Cable/pullies transmission based rotary electromagnetic regenerative shock absorber; (a) prototype assembly of the CD-EHSA; (b) CAD assembly, structure and components of the CD-EHSA. [Reprinted from Ref. [122] Copyright (2018) Universidad Antonio de Nebrija]

In another major study, Audi AG. technical developers [21] prototyped an electromechanical rotary damper called "eROT" which had a quick response with a minimal inertia and an interesting geometry. The horizontal electric motors attached to the rear axle replacing the upright traditional telescopic dampers with a possibility of saving an additional space in the luggage cubicle. As in Fig. 18, a lever arm compounded with a series of gears to an electric motor in which it absorbs the movement of the carrier for the purpose of translating the kinetic capacity during the jounce stroke and rebound stroke into electricity.

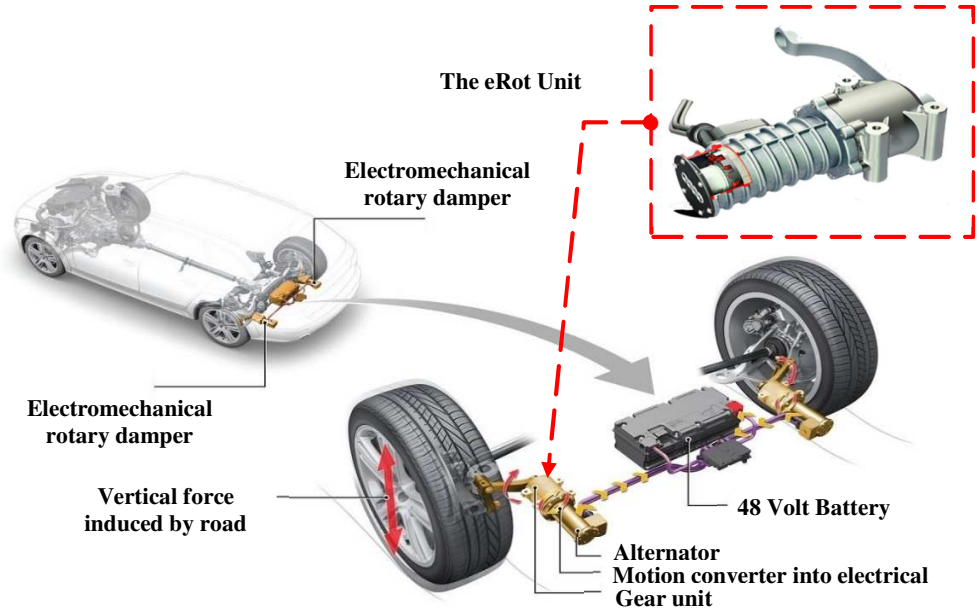


Fig. 18. The innovative eROT based on a horizontally arranged electromechanical rotary damper. [Reprinted (adapted) with permission from Ref. [21] Copyright (2016) Audi AG.]

The generalizability of mechanical based harvesting system observations given in the current section is subject to certain limitations however the mechanical based system has higher conversion capacity than others. For instance, increasing the prospect of system damage particularly (short life operation cycle) in regards to automotive suspension because of the repeated vibration shocks as of the solid mechanical parts counter to the hydraulic-based system which accumulates the input shocks through the hydraulic loop [123]. Despite its simplicity and efficacy, another drawback of the mechanical based system is poor controllability of the mechanical parts in the case of active or semi-active systems. There is abundant room for further progress in determining possible ways for overcoming these drawbacks in which good durability, compactness and enhanced dynamics behavior should be developed in the mechanical transmission based electromagnetic rotatory energy harvesting absorbers [13, 14].

3.2.2. Hydraulic transmission based electromagnetic rotary harvesting shock absorbers

One of the promising energy harvesting suspension systems is the hydraulic transmission-based energy harvester despite its relatively high cost compared to other systems. Hydraulic-based

harvesting shock absorber depends mainly on the hydraulic fluid to transfer the up-down displacement of the cylinder to the hydraulic pump/motor that is attached to an electrical generation circuit for power extraction out of the translated rotational motion. In order to achieve stability in the hydraulic regenerative based damper performance, some necessary components are used in the system such as gas accumulators and hydraulic check valves as motion rectifiers [124-126]. Fang et al. [96, 127] prototyped a hydraulic electromagnetic shock absorber compacted with hydraulic rectifier and internal accumulator in which the regeneration efficiency of the proposed system was 16% (Fig. 19). Li et al. [128] developed a hydraulic-based regenerative damper (Fig. 20) and then developed a hydraulic motion rectifier (HMR) (Fig. 21) depending on four sets of check valves to rectify the hydraulic motor direction of rotation. The equivalent schematic layout of the proposed hydraulic energy conversion assembly with the HMR is exposed in Fig. 21b.

According to the experimental investigation by Li et al. [128], the hydraulic regenerative suspension based on HMR offered a maximum recovered power of 248.8 W and a mean value of 114.1 W with a maximum conversion efficiency of 39% approximately for a harmonic excitation of 8 mm and 2 Hz. Zhang et al. [129] used the genetic algorithm (GA) optimization method to detect optimal regeneration power trends of a hydraulic pumping regenerative suspension with HMR. The average harvested power by such a structure was 33.4 W for a simulated sinusoidal input of 1.67 Hz frequency and 50 mm amplitude and the theoretical hydraulic efficiency was between 70-73%. In a recent cross-sectional study, Demetgul and Guney [130] proposed a hybrid regenerative energy harvesting absorber containing hydraulic and electromagnetic damper mechanisms to produce electricity out of the linear motion. The concept of developing a hybrid energy harvesting suspension, combination of both direct and indirect drive energy harvesters, is a promising direction that can achieve the balance among the all energy harvesting mechanisms [131-133].

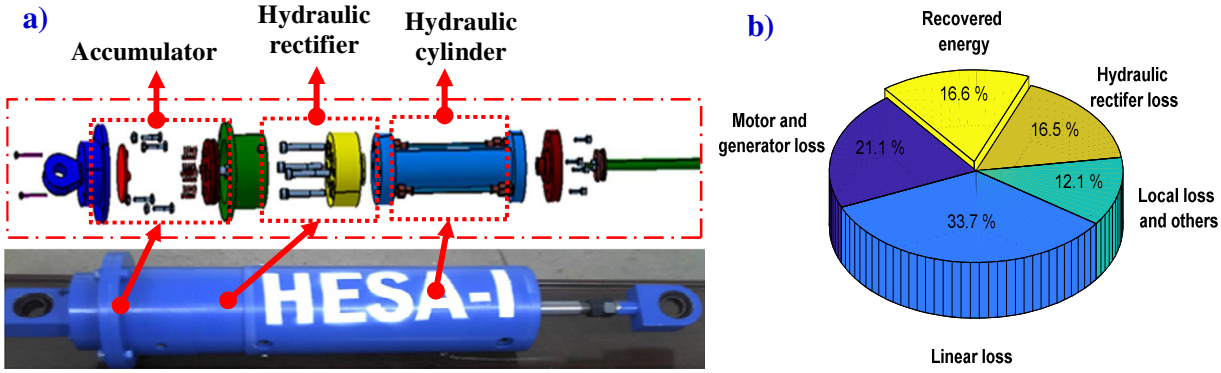


Fig. 19. Hydraulic harvesting absorber with HMR; (a) HESA prototype; (b) Energy distribution of the HESA. [Reproduced (adapted) with permission from Ref. [96] Copyright (2013)]

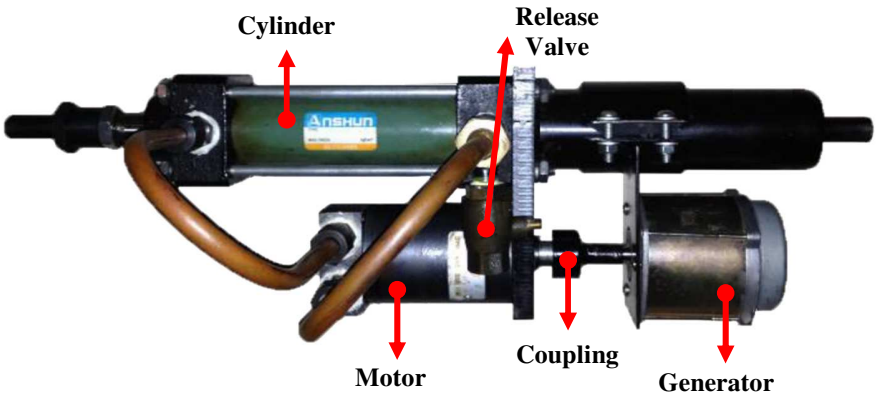


Fig. 20. A full-scale prototype of a hydraulic regenerative based shock absorber without HMR. [Reprinted (adapted) with permission from Ref. [52] Copyright (2013) IOP]

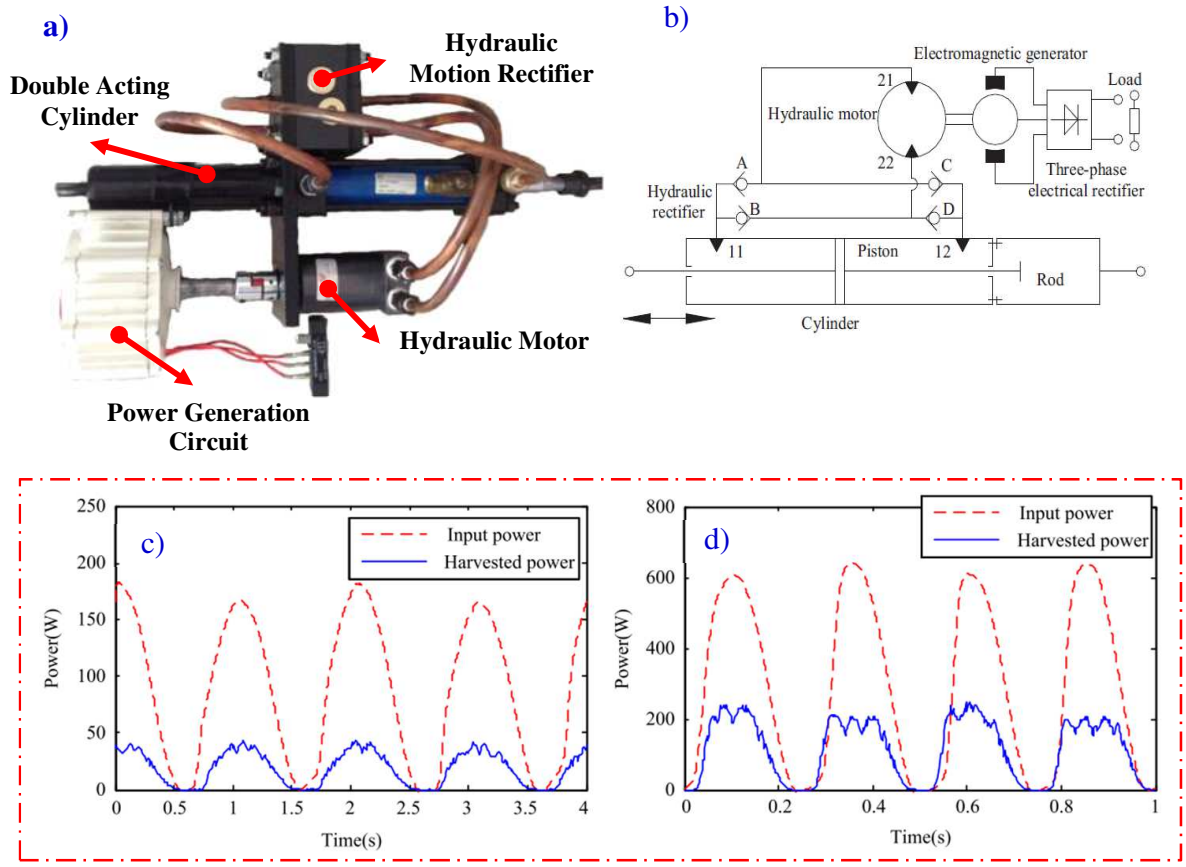


Fig. 21. A full-scale prototype of a hydraulic transmission based regenerative shock absorber; (a) prototype with the HMR; (b) schematic diagram of the system; (c) and (d) comparison of the input and harvested power under excitations 0.015sin πt and 0.008sin 4πt, respectively. [Reprinted (adapted) with permission from Ref. [128] Copyright (2014) Elsevier]

In another innovative energy harvesting devices considering the hydraulic based transmission, power bumps can recover the energy wasted by vehicle brakes in the decelerating lanes [134]. Hence, the theoretical average output power was 2.2 kW which harvested from the strike of one wheel at a vehicle speed of 40 km/h.

It has been conclusively shown that the hydraulic transmission based rotary electromagnetic harvesting damper could practically harvest a power of 310 W out of an input power of 840 W with a conversion ratio of 37% approximately [135]. In [136], the authors prototyped a hydraulic electromagnetic shock absorber (HESA) combined with a horizontal linear generator which

operated by a mechanical linkage mechanism. The proposed system regenerated a peak power of 75-227 W for a range of velocity between 0.1-0.4 m/sec with a conversion ratio of about 20%.

In 2008, MIT engineers developed a hydraulic transmission based electromagnetic rotary harvester and then it was installed in a heavy-duty military truck as in Fig. 22 to harvest the vibration wasted energy [137]. In their testing, it was stated that an average harvested power up to 1 kW could be achieved for each shock absorber on a standard road. The regenerated electricity is enough to completely replace the alternator load in heavy and military vehicles and in some cases even run accessory instruments such as the refrigeration units of the hybrid trailer.

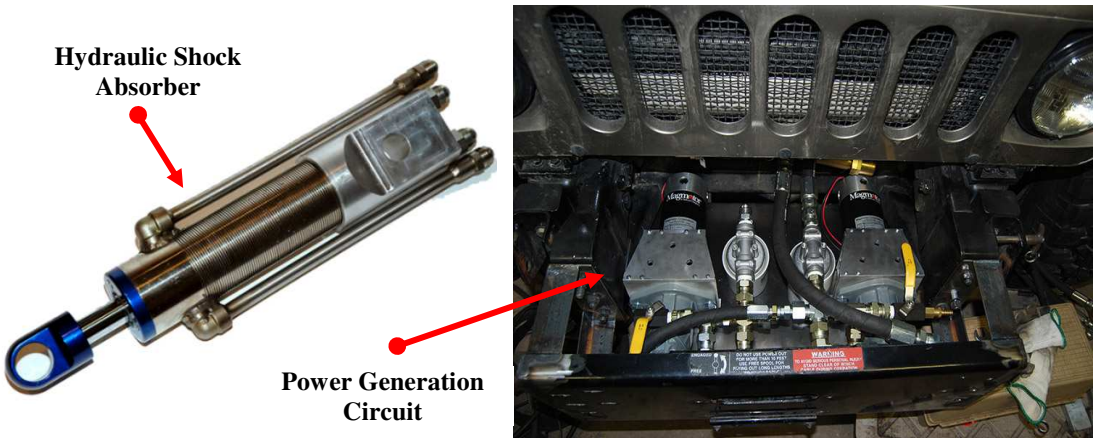


Fig. 22. Hydraulic transmission based energy-harvesting damper; (a) modified version of the traditional hydraulic damper; (b) hydraulic transmission and power generation circuit. [Reprinted [137] Copyright (2009) MIT]

Levant Power Corp. has been developing a controllable fully active energy-harvesting suspension called GenShock (Fig. 23), a commercial active suspension with vibration energy harvesting function considering a hydraulic-based transmission [20, 138]. The heart of the gen-shock device is called Activalve which consists of a hydraulic pump and an electrical generator driven by an integrated electronic control unit. The Activalve is utilized to route and regulate the fluid inside a standard hydraulic absorber. Besides the energy harvesting purpose, the GenShock

was proposed as a fully active suspension where an active force can be applied to push and pull the wheels leading to significantly enhanced ride comfort, handling and driving experience [139].

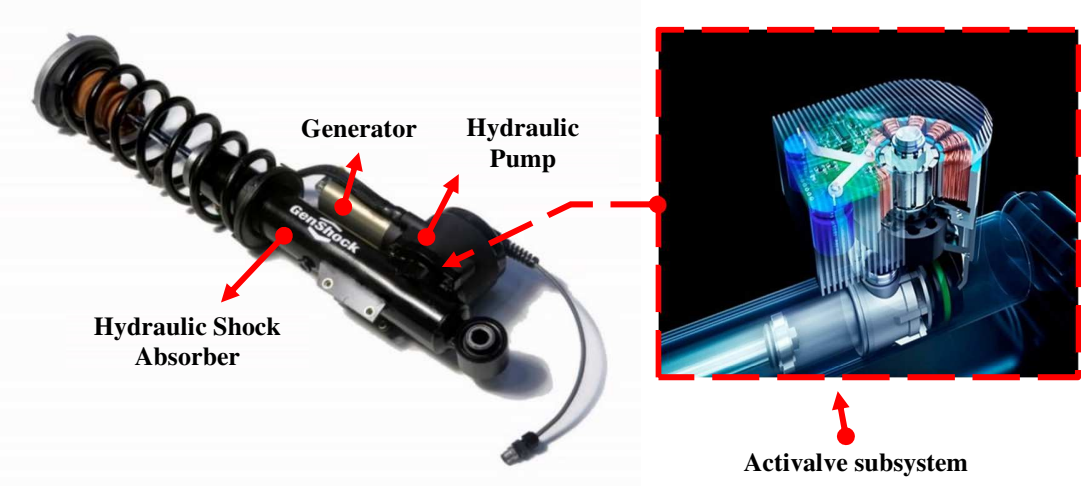


Fig. 23. Compacted hydraulic transmission based energy-harvesting damper. [Reprinted Copyright Levant Power]

As in Ref. [71], the authors provided expectations of the harvested energy based on a $ 1,000 HESA prototype as plotted in Fig. 24. It is obvious that such a harvesting function-based damper provides a high capacity of the regenerative power per damper in the case of overloaded trucks and military vehicles owing to their bad driving circumstances.

A Comparison of the findings with the most popular energy harvesting systems in automotive suspension is given in Table 2. Moreover, the advantages and limitations of these energy harvesting systems are highlighted in Table 2. Based on the comparison, the hydraulic-based system can satisfactorily provide an acceptable energy conversion performance for a full vehicle despite its lower conversion efficiency and high-power losses especially in case of heavy and off-road vehicles. The total power losses for an implemented hydraulic based harvesting system for a full vehicle (4-sets of suspension) can be suppressed in which one common power generation circuit could be recognized for all vehicle suspensions. In addition, using a controlled hydraulic suspension can improve significantly the vehicle dynamics due to its good controllability which

facilitates the control of the displacement and the force using the hydraulic suspension. Therefore, the hydraulic transmission based electromagnetic rotary energy-harvesting suspension should be more investigated as a promising direction in terms of vibration energy-harvesting and vehicle dynamic behavior.

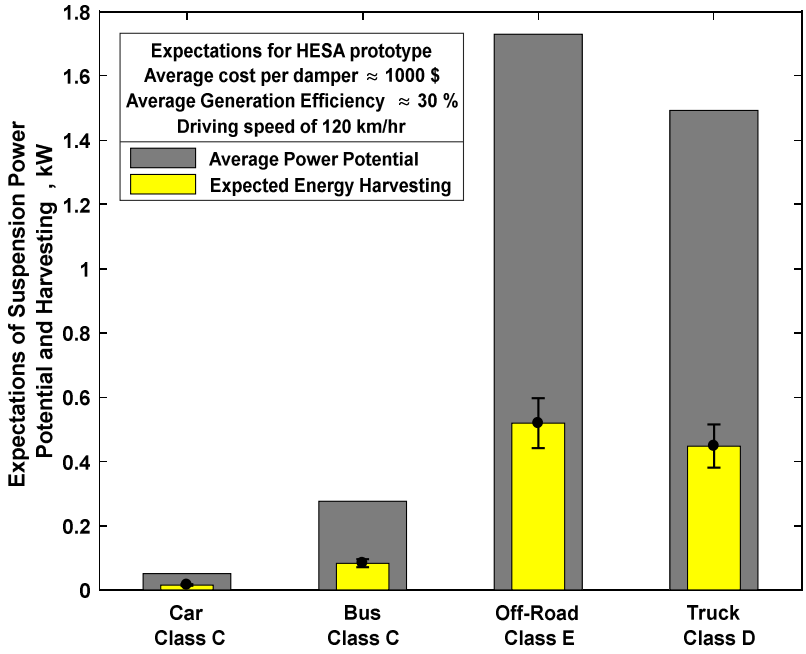


Fig. 24. Expectations of the energy harvesting with respect to the HESA prototype. [Reprinted (adapted) with permission from Ref. [71] Copyright (2018) Elsevier]

Table 2. Comparison of the most popular energy conversion mechanisms in automotive suspension.

No.	Energy Conversion System	Advantages	Limitations
1.	Rack-Pinion transmission based electromagnetic rotary energy harvesting damper (indirect-drive based electromagnetic rotary energy-harvesting damper)	Has a considerable potential energy and power density	Requires accurate system design and torque transmission capability limited by the gear module
		Having the highest energy conversion efficiency	Input and output axis perpendicular to each other and limited for the large space designs
		High assembly accuracy achievable and the stroke depends on the rack length	Short operation life cycle for small designs due to easily damage and hard to offer a good lubrication for the mechanical meshing parts
		Has the ability of motion and force magnification	Hard to control MMR mechanism for an ununiform input because of its nonlinearity
2.	Ball-Screw transmission based electromagnetic rotary energy harvesting damper (indirect-drive based electromagnetic rotary energy-harvesting damper)	Easy to be designed with simple construction with quiet and smooth operation	Relative lower conversion efficiency than the rack-pinion
		High mechanical advantages and high mechanical efficiency with lower power consumption and power losses	High relative cost compared to the rack-pinion mechanism
		High positional accuracy and smooth operation and have good durability properties comparing to rack-pinion	Risk of buckling in the region between supports
		Can hold a large force comparing to the rack-pinion damper which could be used for large-scale systems	Requires more parts for ball recirculating system
3.	Hydraulic transmission based electromagnetic rotary energy harvesting damper (indirect-drive based electromagnetic rotary energy-harvesting damper)	High potential power and high-power density with high sensitivity for the small stroke changes	Low power conversion efficiency
		High controllability and durability properties and very effective in motion and force control	High power losses during the hydraulic loop
		Can be implemented in a vehicle with four sets of suspension with one common power generation modulator	Big size with a high production cost and complex manufacturing production
		Can hold a huge force and can absorb force impacts effectively which Can be used for large-scale energy harvesting systems (e.g. Trucks)	Oil leakage problems
		Has the longest operation life cycle without damage comparing to other systems	Increased volume of the suspension
4.	Linear electromagnetic based energy harvesting damper (direct-drive based electromagnetic energy-harvesting damper)	Being easily and reliably integrated into most existing vibration systems without the requirement of the transmission mechanisms	Low conversion efficiency due to the continuous changing in the motor direction leading to a high inertia power loss
		Can generate power in compression and rebound stroke and can get the power for the small velocities	High production cost which requires accurate system design to make the magnetic hold the excitation force
		More applicable to a real vehicle and easy to be fabricated and used as a self-power controllable damper	Low power density for small-scale units and the magnetic field affected by surroundings
		The best choice for achieving good vehicle dynamics behavior as a semi-active or active suspension (easy to be controlled)	Their size is still large because of the relatively low vibration velocity

4. Simulation, Test Bench, and Real Road Test Survey

In this section, statistical analysis is given for the published work concerning the energy harvesting based vehicle suspension based on the conducted simulation, test bench, and real road test investigations (Sections 4.1, 4.2, and 4.3). Table 3 gives a comprehensive statistical view based on the previously published simulation work on the vehicle regenerative suspension. Whereas Table 4 reviews the conducted experimental investigations for different regenerative suspension configurations including the test excitation parameters and conversion efficiency. In Table 5, the real road investigations of the energy-harvesting based suspension are presented. Whereas, Table 6 compares inclusively the harvesting energy performances of both the linear and rotary electromagnetic energy harvesting shock absorbers.

4.1. Theoretical Based Investigations

Observably, the majority of the conducted simulation studies were performed depending on a 2-DOF quarter suspension vehicle model as stated in Table 3. However, the researchers should extensively investigate the dynamic behavior of the regenerative suspension considering not only the vertical acceleration but also pitch and roll accelerations (full vehicle suspension model) which were scarcely studied.

Mapelli et al. [140] carried out a thermotical study investigating the regenerated power considering a 2-DOF quarter model of an electromagnetic vibration-driven generator (EGDV) which depended on a linear permanent magnet alternator. The simulation was executed on different roads including a typical main road, average and poor roads according to road classifications of ISO 8606 when the vehicle speed was between 20-140 km/h. It was found that an average power of 50 W for the good roads and 100 W for the poor roads could be recovered from their proposed harvesting suspension. Li and Zuo [93] obtained theoretically an average harvested power of 78-86 W considering rack-pinion based harvesting rotational damper when the vehicle traveled on an average road with a speed of 108 km/h.

What's more, in some investigations [25, 74], half car suspension model considering harvestable dampers were used while a full car model was considered in [84, 141]. Peng et al. [142] investigated the regenerative power of a hydraulic electromagnetic damper based on a 7-DOF full car model for an average road and 70 km/h speed showing that a proximate RMS power of 340 W could be recovered that was considerably greater than that of the quarter model. This is due to the presence of the pitch acceleration which affects the vibration intensity levels per damper compared to that is existed in a quarter model. Another reported investigation was conducted by Nakano and Suda [85] in which the averages regenerated and absorbed power of a self-powered active damper based energy harvesting function (Fig. 25) were 31.63 W and 55.39W, respectively, with a generation efficiency of 36%.

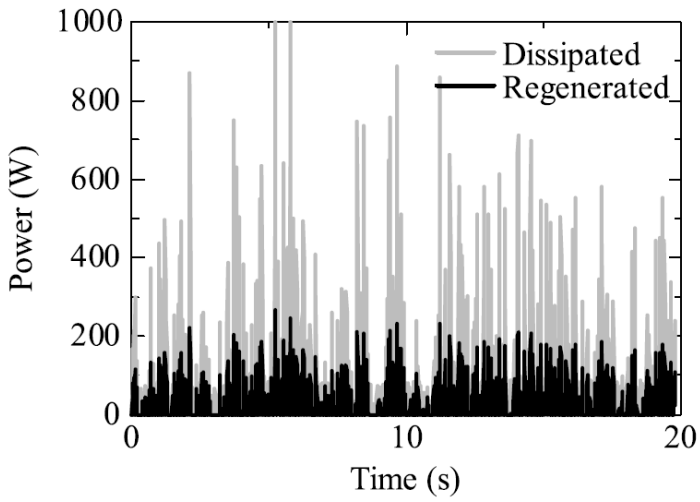


Fig. 25. Regenerated and absorbed power of an energy regenerative damper based self-powered active suspension. [Reprinted with permission from Ref. [85]. Copyright (2004) Taylor & Francis]

It can be summarized that the driving speed parameter significantly affects the harvested power from vehicle shock absorber. The effects of vehicle velocities on the RMS of the electric power generated on a road level C are revealed in Fig. 26 which is plotted based on the statistical results of the previously conducted investigations in Table 3. To be noticed, the harvested power is proportional to the vehicle speed since the speed is considered as a critical parameter in the road roughness formation that makes the road level is the most important parameter affecting the recovered power [66, 143]. As in Fig. 27, when the vehicle speed is 120 km/h, the influences of the road roughness index is not as

strong as its influences at the speed of 80 km/h. If the car speed decreases, the car body will be able to partially follow the road variations while if the speed increase, the wheel inertia will filter the movement. Fig. 28 analyzed graphically the influence of damping ratio and frequency on the harvested power of a regenerative force actuator [144]. This concludes that the power content is related to both the damping rate and the vibration content meaning that more power is available considering aggressive vibrations and high damping rates. The harvested power trend (RMS) with respect to the damping rate for a single degree of freedom (SDOF) model is displayed in Fig. 29 for different driving speeds. Looking at the harvested power trend, it is obvious that the speed effect is higher than the damping ratio effect what makes the high-power capacity is strongly related to high-speed driving conditions.

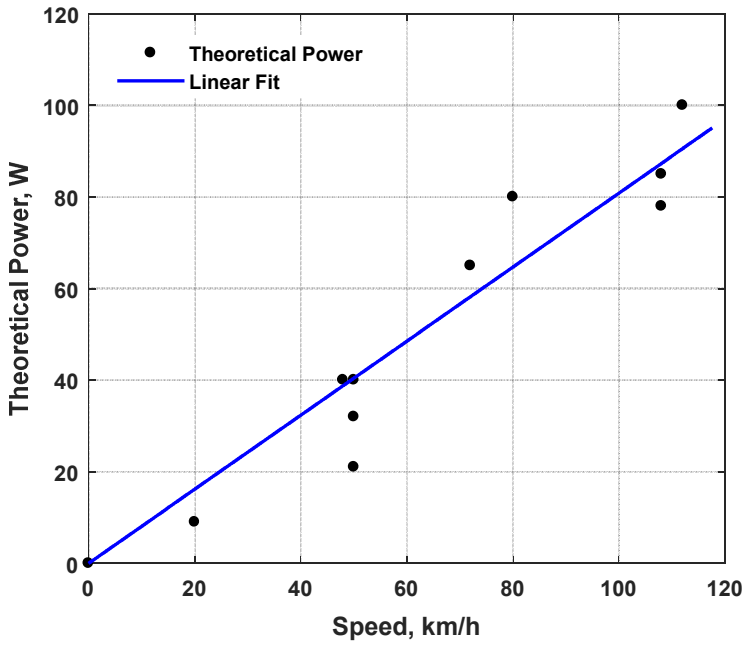


Fig. 26. The driving speed influence on the theoretical regenerated power per damper for ISO-based road of class C. [Drawn according to the statistical survey data in Table 3]

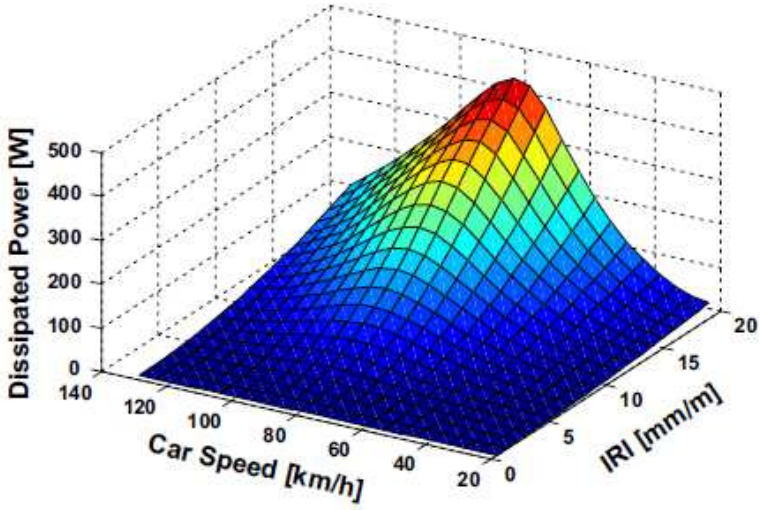


Fig. 27. Damper dissipated power as a function of the car speed and roughness index (IRI). [Reprinted (adapted) with permission from Ref. [74]. Copyright (2016) Springer]

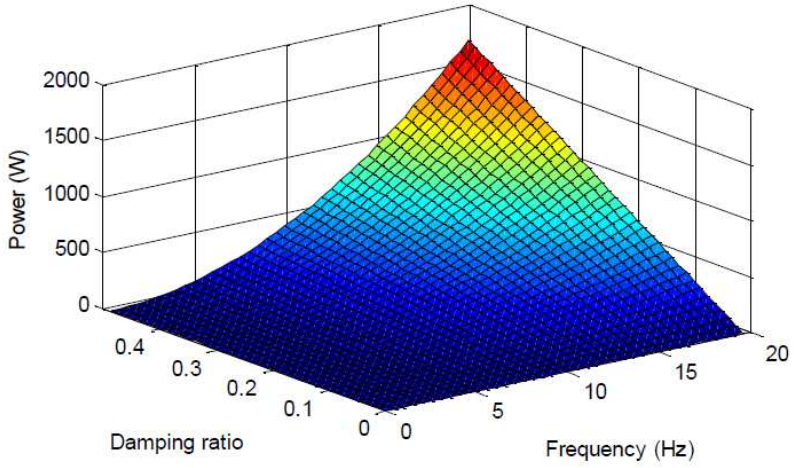


Fig. 28. Harvested power based suspension system versus frequency and damping ratio. [Reprinted (adapted) with permission from Ref. [144]. Copyright (2013) Inderscience]

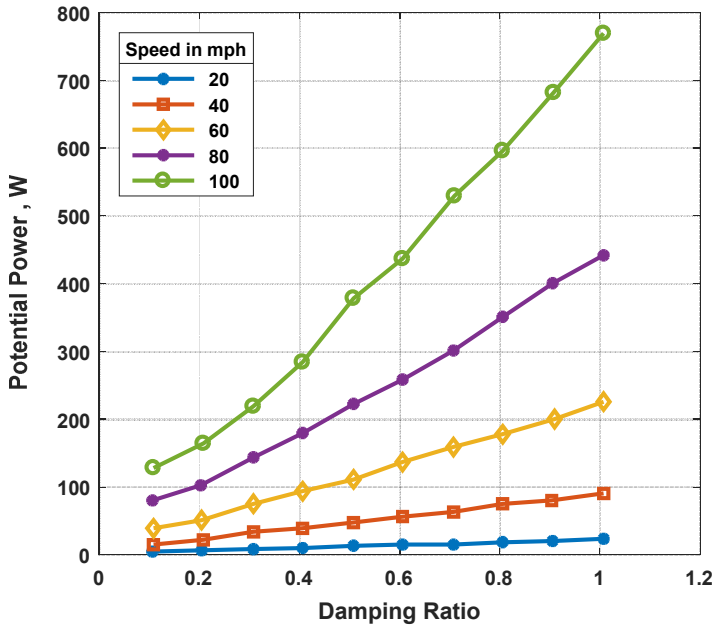


Fig. 29. RMS trend of the recoverable power in SDOF with various damping ratios and driving speeds. [Reproduced and redraw with permission from Ref. [135]. Copyright (2016) University of Huddersfield Repository]

Another observation has already been drawn attention in [39] is that the output power is proportional to the excitation frequency square while the damping force is proportional directly to the frequency. Furthermore, according to Fig. 30, it is indicated that the increase in the generation circuit load resistance was accompanied by a decrease in the harvested power after a certain frequency value for a hydraulic-based regenerative damper [52]. The same attitude has been confirmed by another investigation for a speed bumper equipped by a hybridized nano-generator, while the voltage trend was proportional to the applied resistance till a certain frequency then the out voltage stabilized [101].

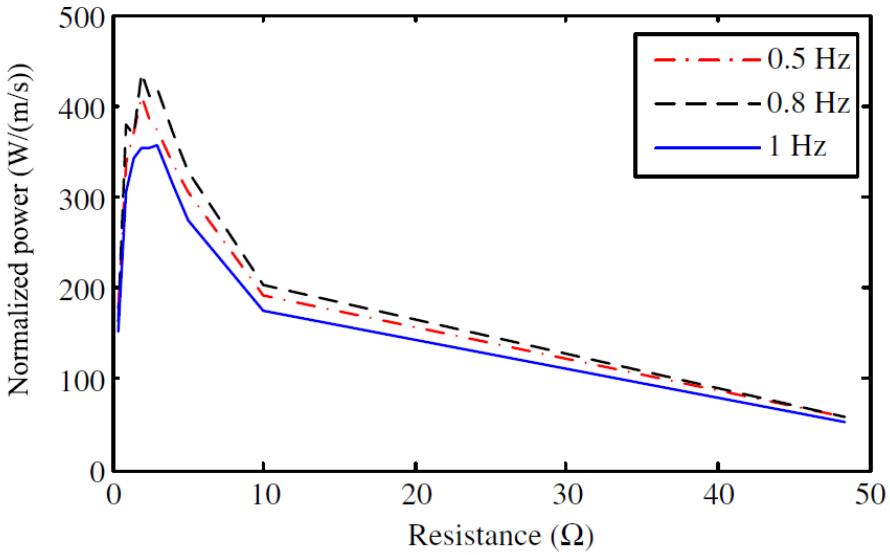


Fig. 30. Comparison of normalized power for different loads at different excitations. [Reprinted (adapted) with permission from Ref. [52] Copyright (2013) IOP]

Statistically, according to Table 3, it can be observed that the harvested power varies in the range from 15-2000 W for one harvestable damper considering different vehicles and operation conditions. Whereas, an unreasonable harvested power value of 1.1 kW was estimated for a full truck model excited with a sinusoidal signal input with 4Hz/50mm. However, a significant harvested power was captured per damper for high-frequency excitations in [73, 141] which did not realistically simulate the case of a real car traveling on a real road. The purpose of that was to indicate the maximum recovered power and discuss the influence of heavy-duty excitations on the power conversion. Hence, it is strongly suggested for future investigations that researchers should focus on the real on-filed based test for a full-scale prototype of the energy-harvesting based dampers, so as the recorded results will be reliable, reasonable, and persuasive. Observably the previously conducted simulation works used simplified models without considering parameter uncertainties and system losses. Therefore, as a future direction, comprehensive simulation investigations using a full-car suspension model depending on a measured data are needed for more reliable prediction of the energy conversion performances.

Table 3. Survey of the conducted simulation-based investigations in terms of energy harvesting based shock absorbers.

No.	References (Published Work)	Energy Harvesting Technology	DOF Model	Road Conditioning		Velocity (km/h)	Regenerated Power per damper (W)
				$G_q(n_0)(10^{-6}m^3)$ $n_0 = 0.1$	Road Class		
1.	Guo et al. [48]	NonMMR-EHSA and MMR-EHSA	2 DOF Quarter Car 2 DOF Quarter Bus 2 DOF Quarter Truck 1 2 DOF Quarter Truck 2	256	Class C (Average)	97	~29 - 30 ~13 - 160 ~280 - 320 ~300 - 400
2.	Huang et al. [145]	Regenerative Suspension Based on Ball Screw Mechanism	SDOF Quarter Model	1 4 16 64	Class A (Highway I) Class B (Highway II) Class C (City Road) Class D (Off-Road)	120 90 50 30	~9 ~9.5 ~21 ~24
3.	Xie and Wang [66]	Piezoelectric Bar Harvester	2 DOF Quarter Model	4 16 64	Class B Class C Class D	126	738
4.	Ataei et al. [146]	Hybrid Electromagnetic Suspension	2 DOF Quarter Model	64	Class C	50	32
5.	Mapelli et al. [140]	Electromagnetic Vibration Driven Generator (EVDG)	2 DOF Quarter Model	32 64 128	Class B (Good) Class C (Average) Class D (Poor)	80 - 140 60 - 100 20 - 60	3.1 - 5.5 6.3 - 15.9 12.7 - 37.9
6.	Sultoni et al. [147]	Linear Electromagnetic Suspension	2 DOF Quarter Model	5 (f_0 = 0.1 Hz)	Class C	50	45
7.	Li and Zuo [93]	Electromagnetic Damper Based on Rack-pinion with MMR	2 DOF Quarter Model	(100*254*94 mm) 64	Road Bump Class C (Average)	7.2 108	- 78 - 86
8.	Satpute et al. [148]	Hybrid Electromagnetic Hydraulic Shock Absorber	2 DOF Quarter Model	Not Mentioned		-	~ 51
9.	Kim et al. [47]	Regenerative Suspension Ball-Screw Mechanism	2 DOF Quarter Model	Sine Wave (0.01 m)		-	~ 5.5 – ~ 12.5
10.	Peng et al. [142]	Hydraulic Electromagnetic Energy Regenerative damper	2 DOF Quarter Model 7 DOF Full Model	64 256	Class B (Good) Class C (Average)	30 70	~ 42 ~ 340
11.	Guo et al. [141]	Hydraulic Interconnected Suspension System with Hydraulic Electromagnetic Shock Absorber	Full Car Model [a]	Sinusoidal Excitation (1-4 Hz, 3-50mm)		-	~ 36 - ~11750
12.	Yu et al. [25]	Rotational Energy-Harvesting Shock Absorber with MMR	7 DOF Half Car Model	64	Class C	50	~ 15

13.	Obeid et al. [134]	Electromagnetic Hydraulic Power Hump Harvester	Multi-Stage Coordinates of a Speed Hump Harvester	Bumpy Road (Half Sine Wave Input)		30 - 50	2000
14.	Shi et al. [149]	Electromagnetic Energy Harvesting suspension with a Linear Generator	7 DOF Full Car Model	32 128	Class B Class C	80	~ 85 [b]
15.	Xu et al. [150]	HESA with Hydraulic Electric Rectifier Shock Absorber	2 DOF Quarter Model	46 256	Class B Class C	20, 30	300
16.	Casavola et al. [151]	Electromechanical Regenerative Suspension with Linear Electrical Motor	2 DOF Quarter Model	Road Bump (15*150 mm)		50	Not Mentioned
				256	Class C	50	~ 40 - ~ 160
			Full Car Model [a]	256	Class C	70	~ 48 - ~ 98
				1024	Class D	18	~ 124 - ~ 308
17.	Montazeri-Gh et al. [152]	Active Suspension Energy Regeneration (Ball-Screw)	7 DOF Full Car Model	Combined Road-Traffic Disturbance [c]	Condition	~ 6	~ 9
						~ 23	~ 167
						~ 32	~ 225
						~ 55	~ 286
18.	Li and Zuo [23]	Rotational Electromagnetic Regenerative Damper with Mechanical Motion Rectifier	2 DOF Quarter Model	256	Class C	36	~ 25
						72	~ 65
						108	~ 85
						144	~ 123
19.	Yin et al. [153]	AERS [d] based on Electromagnetic Actuator	2 DOF Quarter Model	--	Class B	~120	46
				--	Class D	108	
20.	Li et al. [154]	Regenerative damper with Rack-Pinion based on Dual Overrunning Clutches	Not Mentioned	--	A - Class [e]	54	44.73 (Peak) 22.34 (Average)
21.	Mi et al. [155]	Hydraulic Electromagnetic Energy-Regenerative Shock Absorber	Quarter Train Model (Vertical and Lateral)	Sine Wave (7.6 Hz, 4.7 mm)		60	300 - 500
				Sine Wave (13.91 Hz, 10.9 mm)		120	
				Sine Wave (20.52 Hz, 13.2 mm)		180	
22.	Nakano and Suda [85]	Electromagnetic Damper with Ball-Screw	6 DOF Half Truck Model	Not Mentioned			31.63
23.	Choi et al. [156]	Electrorheological Shock Absorber with Rack and Pinion Mechanism	2 DOF Quarter Model	Sinusoidal Excitation (0.4 - 3.4 Hz, 20 mm)		500 (rpm)	~ 5
						1000 (rpm)	~ 17
						1500 (rpm)	~ 36
						5000 (rpm)	~ 220
24.	Zhang et al. [129]	Hydraulic Pumping Regenerative Suspension with HMR	--	Sinusoidal Displacement (1.67 Hz, 50 mm)		--	33.4

25.	Liu et al. [157]	Hybrid Motorbike Suspension System with Linear PM Generator	Linearized Small-Signal Model	peak-to-peak amplitude of 10 n fluctuates sinusoidally at a frequency of 5 Hz.	--	10
26.	Shi et al. [35]	Semi-Active Energy Regenerative Suspension with a Linear Motor	2 DOF Quarter Model	-- Class C	80	46.57
27.	Cooley [158]	Electromagnetic Vibration Energy Harvesting Devices	Adjacent Proof Masses 2 DOF Horizontal Model	Sinusoidal Base Excitation (2 Hz and 2.5 Hz)	--	66 37.8
28.	Tang et al. [159]	Linear Electromagnetic Transducers (LETs)	2 DOF Quarter Model	Harmonic Excitation (10 Hz, 2.54 mm)	--	26, 33
29.	Nagode [160]	Electromagnetic Energy Harvesting based Ball-Screw Mechanism	--	Sine Wave (1 Hz, 19.05 mm)	--	40 (Average)
30.	Tarantini [161]	Electromagnetic Damper with Ball-Screw-Nut Mechanism	2 DOF Quarter Model	-- Class C	36	~26 (Average)
31.	Bao et al. [162]	Hydraulic Energy Regenerative Suspension (HERS)	2 DOF Quarter Model	-- Class C	72	42.5
32.	Zhang et al. [40]	Rack and pinion based electromagnetic harvester with speed doubling mechanism	2 DOF Quarter Model	Harmonic Excitation (10 Hz, 2.54 mm)	--	54 (maximum)

a: The DOF of the full car model is not mentioned. b: The generated power in this case is calculated in Watt unit from 98 kJ and simulation time of 1150 s.
c: a measured road profile was regulated according to the various traffic conditions of the TEH_CAR driving pattern that comprised of four traffic conditions including congested, urban, extra urban, and highway. d: Active and Energy Regenerative Suspension. e: A-class hatchback and a hot blacktop pavement model.

4.2. Laboratory Based Experimental Investigations

As mentioned before, the scope of experimental investigations of the energy regenerative suspensions is recently considered as a research track including improving both conversion efficiency and vehicle dynamic performances. Table 4 summarizes the conducted laboratory-based experimental investigations for both the linear and rotary electromagnetic based energy-harvesting dampers including the testing parameters and power regeneration efficiency. The conversion efficiency is a major evaluation criterion for the energy harvesting devices which is simply calculated as the output electrical power divided by the mechanical input power as it is seen Eq. (4).

$$\eta_c = W_{Out}/W_{In} \quad (4)$$

where W_{In} is the input power of the excitation source and W_{Out} is the output harvested electrical power.

Zhu et al. [39] investigated theoretically and experimentally the damping behavior, energy conversion efficiency and output power of a linear-based electromagnetic energy-harvesting damper with four representative circuits; (a) open circuit, (b) circuit with constant resistor, (c) circuit with rectifier and supercapacitor, (d) circuit with rectifier and rechargeable battery. The proposed linear EM damper was examined with excitation frequencies of 2 and 6 Hz and amplitudes of 3, 6, and 11 mm. In these tests, the conversion efficiency varied from nearly 14% to 25% for a 2 Hz input frequency, while when a 6 Hz input frequency was applied, the conversion efficiency was 33% for an amplitude of 11 mm. Wang et al. [163] achieved a power conversion efficiency of 40% for a hydraulic transmission based regenerative shock absorber for an excitation frequency and amplitude of 1 Hz and 25 mm, respectively. Considering MMR, Li et al. [29] improved the harvesting efficiency of a rack-pinion-based electromagnetic rotary regenerative damper to be about 62% for a harmonic excitation of 3 Hz and 5 mm. While, for an energy regenerative damper with a hydraulic rectifier, Li et al. [128] showed that an enhanced conversion efficiency of about 39% was measured at 2 Hz and 8 mm. A considerable conversion efficiency of 68% was measured experimentally for a linear electromagnetic energy harvesting absorber at 11.35 mm and 10 Hz [164]. Zhang et al. [31, 165] conducted an

experimental investigation for two energy harvesting dampers named MMR-based electromagnetic rotary regenerative damper and dual-overrunning clutches based energy-harvesting damper showing that the achieved conversion efficiency was between 54-63%. As can be seen in Fig. 31 that the harvested power efficiency is increased progressively with the excitation frequency increase as the high observed output power is relevant to the higher frequencies. This is due to the high vibration intensity levels corresponds to the high frequencies which increase both the input power and the damper relative velocity which helps the generator to work in its high-efficiency area leading to more harvestable power and conversion efficiency. In [166], a regenerative suspension system with piecewise springs based on ball-screw mechanism was prototyped and experimentally investigated using a harmonic sinusoidal excitation of 2-6 Hz frequency and 7 mm amplitude. According to Fig. 32, the results showed that the mechanical efficiency maintained at a percent around 50% and the electrical efficiency ranged from 66-93%. While the recoverable power efficiency was in the range of 33-46% and the highest efficiency was approximately obtained at 6 Hz. It is observed that both of the electrical efficiency and power conversion efficiency increased with the increase of the excitation frequency up to a certain level of frequency counter to the mechanical efficiency of a ball-screw damper [166].

Considering the average output power when subjected to a harmonic excitation, the effect of input frequency and amplitude on the harvested power trend is clearly illustrated in Fig. 33a and b. It is clear that the power is from the relative movement of the body-wheel assembly in which the strong movement can effectively collect more power. Hence, the excitation parameters (frequency and amplitude) positively affect both the harvested power trend and efficiency because of the aggressively generated vibrations along with the aggressive input parameters leading to more harvestable power and a high rotation speed of the generator. In [39], it was predicted that the optimal output power of a linear based electromagnetic energy-harvesting damper was proportional to the frequency square. Nevertheless, the conversion capacity decreased against the high frequencies and amplitudes since the power losses are increased in terms of high inertia of the moving parts.

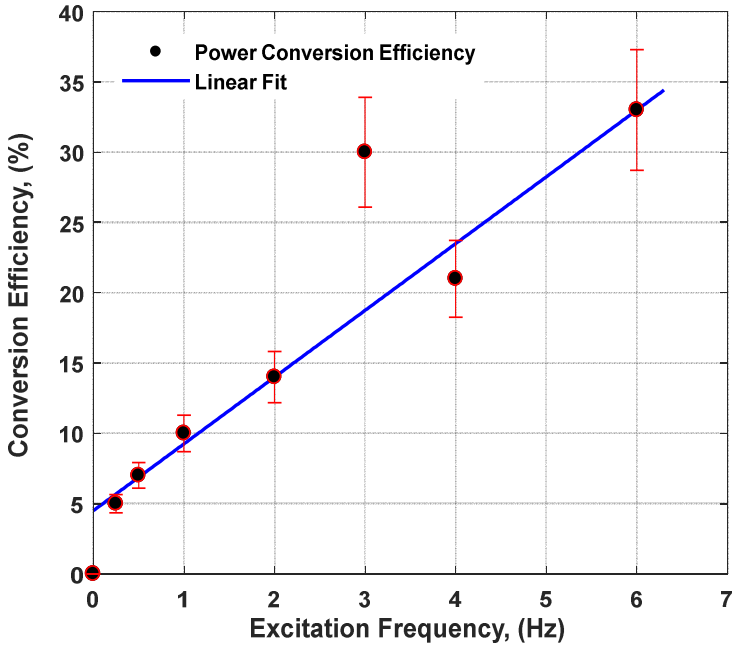


Fig. 31. Power conversion efficiency with respect to the input frequency in correspondence with experimental investigations. [Drawn according to the statistical survey data in Table 4]

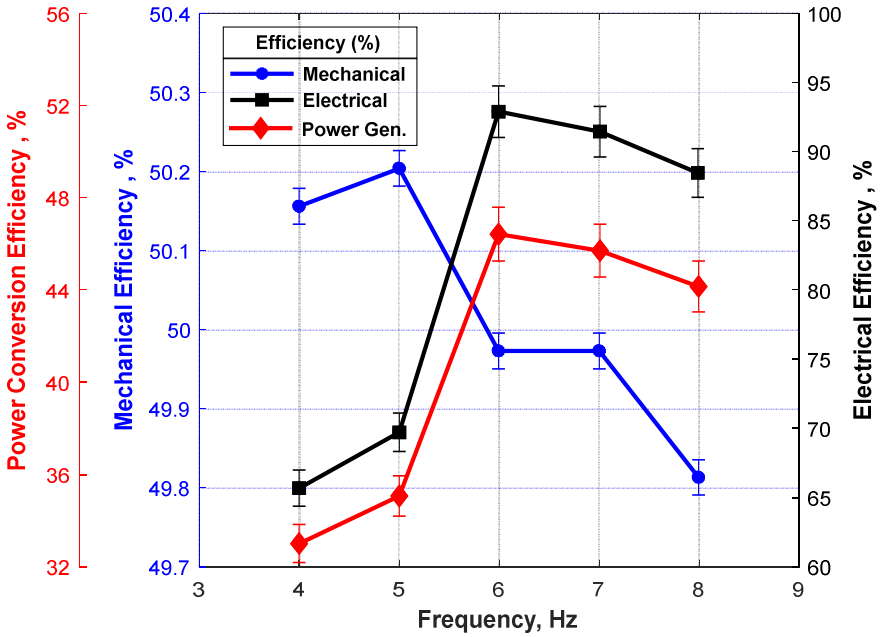


Fig. 32. Experimental comparison of mechanical, electrical, and power generation overall efficiency of ball-screw transmission based regenerative suspension. [Reproduced and redrawn with permission from Ref. [166] Copyright (2016) Huang]

In Fig. 34, a comparison is carried out between the different energy-harvesting based dampers including both the harvested power and conversion efficiency. All in all, it is observed that the electric power generated for each harvesting mechanism could fairly reach an average power value of 350 W

for different operation conditions. Whereas, there is a significant variation in the generation efficiency of each system according to the statistical survey and data analysis in Tables 3-6. The mechanical based transmissions energy-harvesting absorber has a considerable conversion efficiency varied from 5-75 % for different case studies. It seems possible that these results are due to the lack of energy lost in the mechanical based transmission and it is also because of the direct contact and bonding between the mechanical parts. Conversely, the other regenerative mechanisms could provide a lower conversion efficiency up to 40% because of the large power loss during these systems. This does not give great preferences to the mechanical transmission based harvesters comparing to the others because the mechanical based system has drawbacks in some applications as the vehicle suspension as discussed in Section **2.2**. However, the mechanical transmission based harvesters are considered the most suitable solution in some applications such as wave energy harvesting since it is used only for the function of recapturing the vibration energy. Whilst in other applications as in automobiles, the vibration harvesting system is considered as a subsystem in which the power recycling is not the sole purpose but it should provide acceptable dynamic performances (road holding, and ride quality) comparing to the traditional suspensions.

Observably, the majority of the experimental investigations were conducted on damper characterization test rig while some investigations were performed on road simulator test bench. In general, according to the statistics in Table 4, it can be seen that the energy conversion efficiency varies between 10-70% approximately considering different excitation frequencies and amplitudes, notwithstanding it might be unconformity match with a real vehicle travels on standard roads. Moreover, the research on energy harvesting based vehicle suspension and it's influences on the vehicle dynamics are still in the initial stage [7, 13, 66]. Further work is needed even academically or industrial in terms of real applicability of the energy-harvesting based suspension in real vehicles. Therefore, the future investigations should study and explore the suspension energy conversion mechanisms and its damping characteristics, in addition to improve its dynamic behavior including ride comfort and road

holding considering reliable simulation environment; full-car suspension models and measured data of the road and the suspension displacement and velocity. Furthermore, the conversion efficiency should be enhanced at high-frequency and high-amplitude vibrations. Comprehensively, Table 6 presents a comparison of the implemented energy-harvesting based dampers including the observed range of the power-harvesting trends in accordance with the literature.

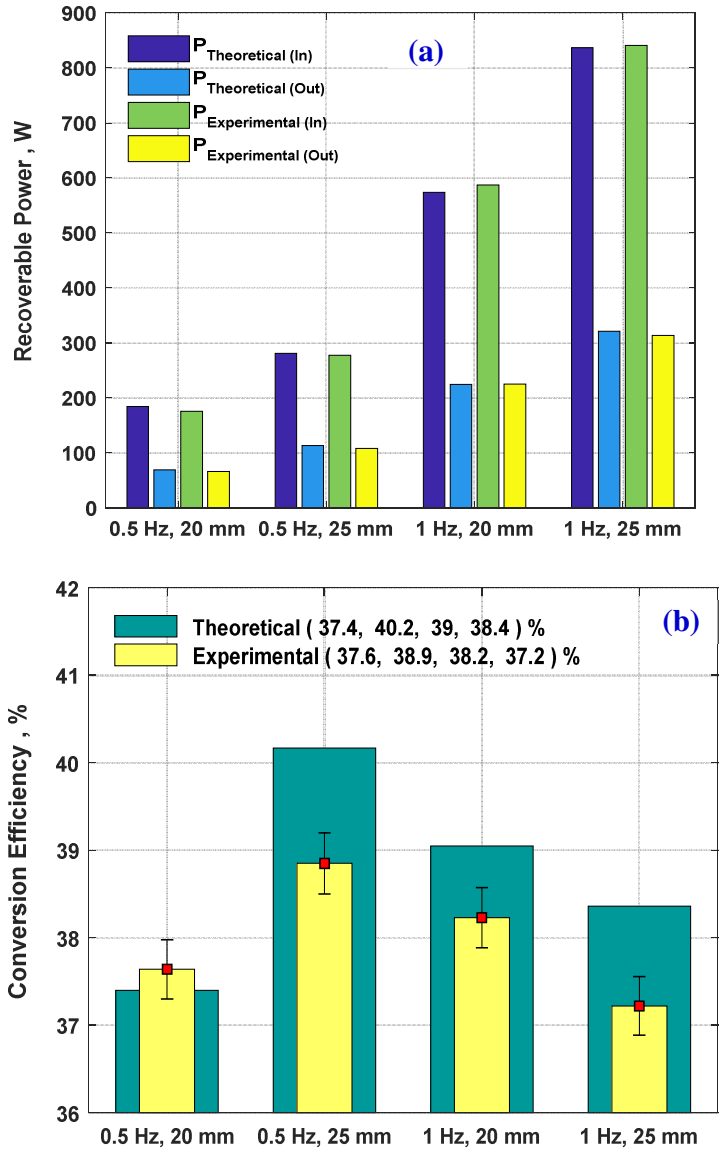


Fig. 33. Predicted and measured energy harvesting performance of a hydraulic transmission based energy-harvesting shock absorber at various harmonic excitations; (a) recoverable power, (b) conversion efficiency. [Drawn according to the data stated in [135] Copyright (2016) University of Huddersfield Repository]

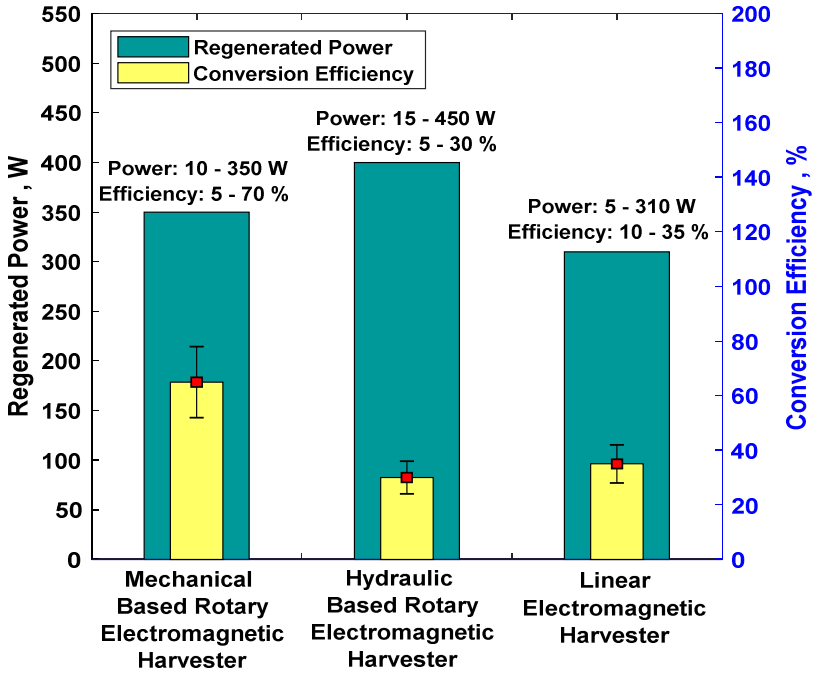


Fig. 34. Comparison of the harvested power accompanied by the conversion efficiency for different regenerative suspension mechanisms. [Drawn based on the statistical survey in Tables 3-6]

Table 4. Survey of the measured energy-conversion efficiency of vehicle regenerative based shock absorbers.

No.	References	Energy Harvesting Technology	Excitation parameters		Power conversion efficiency (%)
			Frequency (Hz)	Amplitude (mm)	
1.	Zhu et al. [39]	Linear Motion Electromagnetic Damper	2	3, 6, 11	14.4 % - 25.9 %
			6	3, 6, 11	23.2 % - 33.1 %
2.	Wang et al. [163]	Regenerative Hydraulic Shock Absorber System	1	25	40 %
3.	Li et al. [29]	Energy-Harvesting Shock Absorber with a Mechanical Motion Rectifier (Rack-Pinion)	1.5, 3	5	62 %
4.	Fang et al. [96]	Hydraulic Electromagnetic Shock Absorber with a Hydraulic Rectifier	10	3	16.6 %
5.	Li et al. [167]	Electromagnetic Vibration Energy Harvester with Motion Magnification (Rack-Pinion)	0.25	100	44 %
6.	Maravandi and Moallem [50]	Regenerative Shock Absorber Using a Two-Leg Motion Conversion Mechanism	1	5	59 %
7.	Scully et al. [164]	Linear Electromagnetic Shock Absorber	10	11.35	56 % - 68 %
8.	Shi et al. [35]	Semi-Active Energy Regenerative Suspension System with a Linear Motor Harvester	Random Road Excitations (Class C)		21.86 %
9.	Xu et al. [168]	Hybrid Piezoelectric Electromagnetic Energy Harvester	Not Mentioned		26 %
10.	Sabzehgar et al. [109]	Regenerative Suspension Using an Algebraic Screw Linkage Mechanism	5.6	3.05	56 %
11.	Cho et al. [169]	Electromagnetic Shock Absorber with a Hydraulic Motor and a DC Generator.	0.25, 0.5, 1	100	5 % - 10 %
12.	Satpute et al. [136]	Hydraulic Electromagnetic Shock Absorber with a Linear Generator	4	11.2	19.25 %
13.	Singh and Satpute [62]	Energy-Harvesting Shock Absorber with Fluid Damping and a Linear Generator	8	22.6	12.99 %
14.	Satpute et al. [170]	Hybrid Electromagnetic Shock Absorber with a Linear Generator	4	11	21.4 %
15.	Wang et al. [171]	Hydraulic Regenerative Shock Absorber System	1	20	18.49 %
			0.5	25	26.86 %
16.	Guo et al. [172]	Hydraulic Electromagnetic Shock Absorber	3	5	30 %

17.	Zhang et al. [165]	Regenerative Shock Absorber with a Mechanical Motion Rectifier (Rack-Pinion)	1 - 6	5	25 % - 63.46 %
18.	Li et al. [128]	Energy-Harvesting Shock Absorber Based on a Hydraulic Rectifier	2	8	38.81 %
19.	Zhang et al. [31]	Energy Regenerative Shock Absorber Based on Dual-Overrunning Clutches	2.5	7.5	54.98 %
20.	Li et al. [154]	Energy-Regenerative Shock Absorber based on Dual Overrunning Clutches (Rack-Pinion)	0.5	50	59.77 %
			1	15	69.19 %
21.	Nagode et al. [173]	Electromagnetic Energy Harvesting Systems Based on Ball-Screw Mechanism	1	19.05	51.5 %
22.	Zhang et al. [121]	Portable High-Efficiency Electromagnetic Energy Harvesting System Based on Rack-Pinion Mechanism	2	6	55.5 %
23.	Nagode [160]	Electromagnetic Energy Harvesting System Based on Ball-Screw Mechanism	1	6.35, 12.7, 19.05	(34 % - 45 %) [a]
					(15 % - 25 %) [b]
24.	Liu [61]	Ball-screw-based MMR shock absorber	2	2	42 %
			1 - 5	2	36 % - 52 %
25.	Huang [166]	Regenerative Suspension System Based on Ball-Screw Mechanism with Piecewise Springs	2 - 10	7	33 % - 46 %
26.	Hoo [116]	Regenerative Suspension System Based on Ball-Screw Mechanism	0.067 (m/s) [c]		22 % [d]

a: Corresponding to fastest input. **b**: Corresponding to slowest input. **c:** Testing damping speed. **d:** Rebound efficiency of the regenerative damper.

4.3. Real Road Based Experimental Investigations

Apparently, the real field testing is considering more factual and beneficial than the lab testing in providing a real and an actual driving cycle that can give an accurate judgment about the research point. However, the actual driving trip testing requires special mobile measuring instrumentations as well as it requires special tracks and roads with an average length between 20 to 40 km. In addition, there are some difficulties could be found in the real road investigation such as fixing the main parameters which representing the case study like vehicle speed. Hereinafter according to the literature review, a statistical survey of the published work regarding real road experimental studies in terms of the energy-harvesting based vehicle suspension is given in Table 5. The majority of the road field measurements were recorded for the left side of the vehicle rear axle and the squandered power was calculated considering the measured relative motion of the damper.

Li et al. [95] installed a rack-pinion based energy-harvesting damper with MMR on the left rear suspension of a Chevrolet Suburban car in order to perform a real road investigation of the actually recovered power in the vehicle suspension in a road driving trip. The power per damper was 16 W when the car made a trip on the campus road of the University of New York with 24 km/h speed. Considering the same testing vehicle and a rack-pinion-based electromagnetic regenerative shock absorber, see Fig. 35, Li et al. [27] captured an approximate power of 35 W when the vehicle speed was 65 km/h on the campus road of Stony Brook University while 41 W was recaptured when the vehicle traveled with a speed of 96 km/h on a highway road (Long Island Expressway). In Fig. 35, the peak voltage acquired at 48 and 32 km/h was over 40 V for an external load of 30 Ω, while the peak power was 67.5-58.2 W. Whereas in another study carried out by Mossberg et al. [174], a prototype of a GenShock system was attached in 2010 Freightliner Cascadia tractor (gross vehicle mass of 25,670 kg) considering a traveling track length of 32 km on U.S. Highway I-75 (mixed roughness). From the recorded results, it was found that a mean power of 79 W was harvested when

the damper installed in the front suspension while 43 W was harvested when the damper was in the rear suspension. MIT students [137] conducted a road test on a heavy-duty military truck (Humvee) prepared with 6-shocks of a hydraulic electromagnetic rotary harvester showing that an average harvestable-power of up to 1 kW could be accomplished on standard roads.

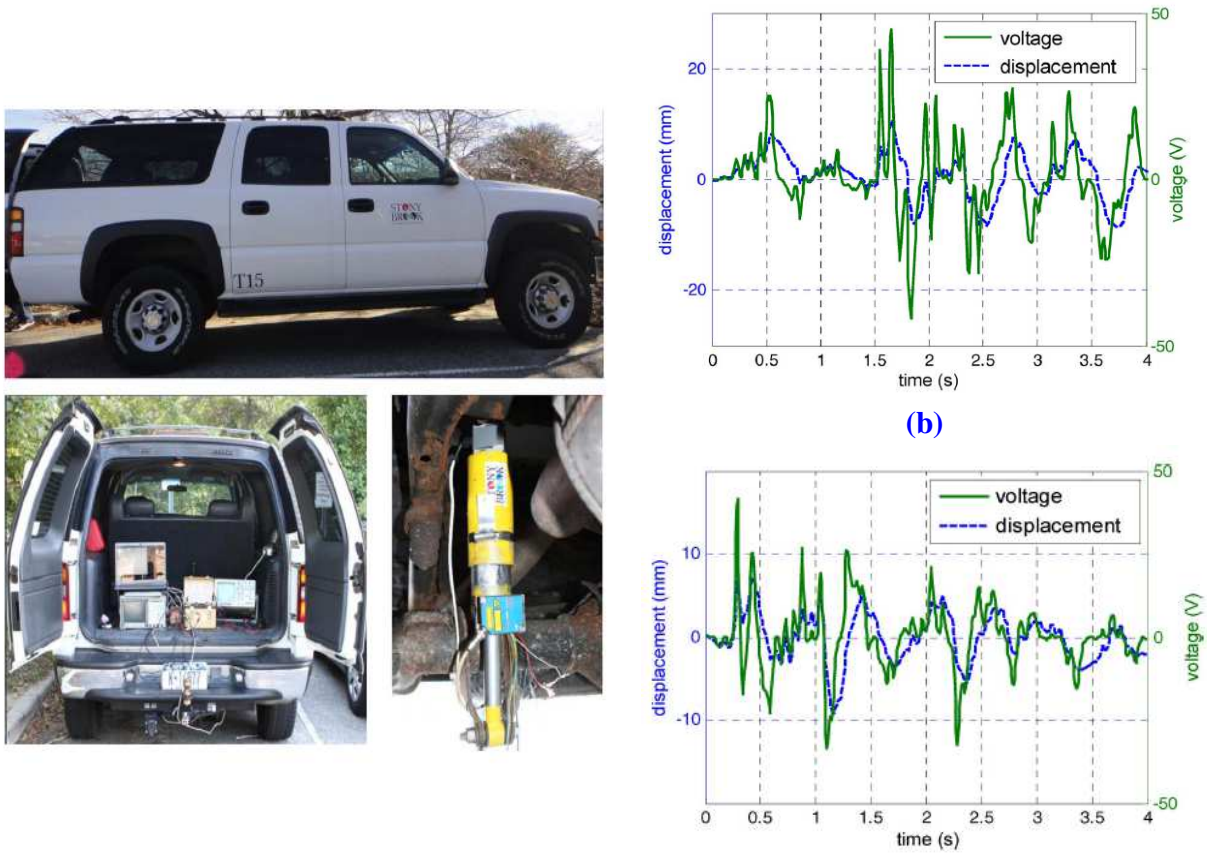


Fig. 35. On-field based test of a rack-pinion-based electromagnetic regenerative shock absorber; (a) setup of the road tests, (b and c) acquired displacement and voltage at driving speed of 48 km/h and 36 km/h respectively, on a paved campus road. [Reprinted from Ref. [27]. Copyright (2013) IEEE]

As known that the implementation of the vibration energy harvesting mechanisms is not limited to vehicle suspensions but it could be also used in regenerative based speed bumpers [101], railway energy harvesting [175, 176] and ocean wave energy conversion [177-179]. Zhang et al. [32] carried out a field investigation using Volkswagen TUREG SUV (body mass of 2255 kg) with a speed of 20

and 40 km/h on a road tunnel with 4 speed bumps for measuring the harvestable power from a proposed regenerative based speed bumper to be used for self-powered traffic monitoring.

Practically, the actual regenerative based damper cannot permanently harvest the wasted vibration energy with a desired conversion efficiency as it depends on several factors changed continuously while the vehicle traveling on roads such the road condition, vehicle velocity what makes the generator works sometimes out of its normal and high- efficiency area. Noteworthy that the area of energy-harvesting based vehicle suspension and power potentiality in heavy and off-road vehicles per damper were rarely established and need further investigations especially for a real road investigation. Furthermore, a data for a typical passenger car was not found [84]. The future real road investigations should measure the characteristics of road roughness as well as the position of the regenerative energy damper should be taken into account as a parameter.

Table 5. Survey of the conducted real road based experimental investigations for measuring the harvested power in vehicle suspension.

No.	References	Technology	Vehicle Details	Trip Conditioning		Harvested power per damper (W)
				Road Type	Velocity (km/h)	
1.	Li et al. [95]	Rack-pinion energy-harvesting shock absorber with MMR (installed on left rear suspension)	2002 Chevrolet Suburban SUV (test vehicle)	Circle road of State University of New York at Stony Brook (campus road)	~ 24	~ 16
2.	Li et al. [27]	Electromagnetic energy harvesting shock Absorbers based on rack-pinion (installed on left rear suspension)	2002 Chevrolet Suburban SUV (Torsion bar in front, Multi-link coil in the rear suspension, curb mass of around 2500 kg)	Local Road (Campus road of Stony Brook University, Stony Brook)	32 48 64	~ 3 ~ 14 ~ 35
				Highway (Long Island Expressway)	88 96	~ 30 ~ 41
3.	Mossberg et al. [174]	Front and rear tractor suspension with displacement sensors and GenShock system	2010 Freightliner Cascadia tractor (gross vehicle mass of around 25,670 kg)	Highway (US Highway I-75, mixed roughness)	--	79 (Front, mean overall) 43 (Rear, mean overall)
4.	Zhang et al. [32]	Speed pump suspension module with linear electromagnetic alternator	Volkswagen TUREG SUV (body mass of 2255 kg)	Road tunnel with 4-speed pumps	20 40	61.6 V (Peak voltage) [a] 194 V (Peak voltage) [b]
5.	Audi AG. [21]	Electromechanical Rotary Damper Horizontally Installed on the Rear Axle	Passenger Car	German Roads	--	75 (Average) [c]
				Newly Paved Highways	--	2.5 (Average) [c]
				Rugged Country Road	--	306 (Average) [c]
6.	Singh and Satpute [62]	Passive Electromagnetic Hydraulic Shock Absorber (EMHSA)	C-Segment Passenger Car	Smooth City Road	35	60 (Average) [d] 94 (Average) [d]
7.	Liu [61]	Ball-screw shock absorber based on MMR (mounted on the left-rear side of a testing vehicle)	Ford F250 pick-up truck (loaded with an extra load of 300 kg)	Paved Road (Near Virginia Tech Campus)	64.37	158, 373 (Peak) 13.3, 24.7 (Average)
				Speed Bump	8.047	197.3 (Peak) 52.65 (Average)
8.	Liu et al. [46]	Ball-screw absorber based on MMR (mounted on the left-rear side of a testing vehicle)	Ford F250 pick-up truck (loaded with an extra load of 300 kg)	Paved Road (Near Virginia Tech Campus)	64.37	13, 25 W (Average) [e]

9.	Levant Power [180]	GenShock fully active internal vehicle demo	BMW 535i	-	40	75 (Average) [f]
10.	MIT students [137]	Hydraulic energy-harvesting shock absorber	Humvee	Standard Road	-	1000 (Average)

a, b: The results are stated in terms of the generated voltage from a speed pump harvester module when the vehicle hit the pump with the mentioned speeds.
c: The average power was reported for both of rear axle wheels, therefore the power was divided by 2 to get the power for one shock absorber.
d: The stated power in this case is a predicted power using a real road measurement on a city road. **e:** The ball-screw shock absorber attached to external electrical loads of 10, 3 Ω and the generated power was recorded for 8 seconds. **f:** The total average power was recorded for 0.8 g cornering.

Table 6. Compression of the harvesting energy performances for different energy-harvesting based dampers under different operation conditions according to the literature survey.

No.	Energy-Harvesting Technology	Linear-Rotary Motion Transmission	Harvestable Power Range (W)	Conversion Efficiency (%)	Refs.
1.	Rotary electromagnetic energy-harvesting dampers (indirect-drive based electromagnetic harvesters)	Rack-Pinion Based Mechanism	20 - 250	30 - 70 %	[95, 156, 181, 182]
		Ball-Screw Based Mechanism	25 - 290	20 - 65 %	[41, 46, 117, 132, 160, 166, 183-186]
		Hydraulic Based Mechanism	30 - 350	10 - 40 %	[88, 123, 127, 129, 187, 188]
2.	Linear electromagnetic energy-harvesting dampers (direct-drive based electromagnetic harvesters)	----	25 - 300	20 - 50 %	[33, 35, 39, 189-194]

5. Research Challenges, Technical Difficulties, and Research Gaps

Regarding real applications, one of the important challenges is the compactness of the harvesting-based damper that should be considered when designing the regenerative dampers because of the limited suspension space amidst the wheel axle and the vehicle body. The appropriate size enhances the reliability, flexibility, and stability of the harvester based on novel physical or geometrical configurations. A possible solution could be the retrofit designs (e.g., [13, 117]) such the horizontal electromechanical based energy-harvesting damper as invented by Audi AG. [21]. Thus, one of the future issues is to develop a compacted regenerative damper with a sufficient stroke and limited weight and dimensions.

The nonlinearity of the harvester theoretically or practically is another potential concern that could be an important and beneficial factor to obtain sufficient energy harvesting performance (e.g., [195-197]). This raises inquiries about how to enhance both the energy harvesting capability and vehicles dynamics using the nonlinearities of the energy-harvesting dampers. Moreover, the conversion efficiency is always a concern in energy-harvesting which requires more efficient motion transmissions, rectifiers, magnification mechanisms, and novel power generation circuits.

The conversion adequacy of the hydraulic transmission based energy-harvesting dampers received little attention, however, the hydraulic harvester is more beneficial practically and widely applicable especially in heavy and off-road vehicles. Therefore, the power losses in the hydraulic harvesting circuit (e.g., power loss in oil, hydraulic circuit components, parasitic power drops in the power circuit, and consumed power in the controller circuit) should be reduced using optimization and matching parameters such the hydraulic circuit components and the electromagnetic rotary-based-motor. Hence, power electronic circuits with controllable parameters are able to improve the energy efficiency by adaptively changing certain parameters according to the vibration level or external load.

Suspension vibration control using energy-harvesting based dampers is another particular challenge for both system protection and human ride comfort. This limitation means that the controlled energy-harvesting based vehicle suspension should provide a better trade-off between the damping and the

harvestable-power in which the optimum vehicle dynamics and maximum output power and efficiency cannot be achieved simultaneously. Hence, the future investigations should discuss and suggest some applicable solutions for such issue. Noteworthy, the power performance and vehicle dynamic behavior for a full verified vehicle model should be more investigated for an energy-harvesting based suspension.

Although a considerable number of concepts and models were proposed and evaluated to regenerate the wasted power from vehicle suspension, the previous simulation works used simplified models without considering parameter uncertainties and system losses. In addition, some experimental works were too simple to support the modeling, simulations and parameters optimization. Hence, some advanced optimization strategies should be investigated considering parameter uncertainties and nonlinearity to deal with the trade-off between power regeneration and ride comfort/road handling.

Most of the studies regarding suspension-based energy harvesting have only focused on illustrating and characterizing the performance of a prototype for a short period of time. Future investigations should conduct some durability tests to verify that the harvester performance can be maintained over long periods of time. In addition, it would be interesting to integrate the proposed harvester-based absorber into real vehicles for a clear understanding of the system performance compared to a real suspension. In many applications, ambient vibrations are often random and broadband as in a vehicle trip on a real road so that the design of energy harvesting devices must account for this form of excitations making the harvester work effectively in a wide range of frequency bandwidth. Thus, a parametrical bandwidth analysis needs to be included in future publications as to discuss the harvester working limitations.

Vehicle tires, as a part of the vehicle suspension, also have the potentiality to generate electricity regarding self-powered sensors for intelligent tires such as self-powered wireless sensors and tire pressure remote sensing (e.g., [76, 79, 81]). Hence, further research should be conducted in the field of intelligent vehicle tires for self-powered sensing systems.

6. Conclusions

The aim of this paper was to present a comprehensive review on automobile energy harvesting based suspension and its associated critical issues including designs, mechanisms, energy flow as well as the conducted simulations, bench tests, and real road investigations on wheeled vehicles. The corresponding energy-harvesting based damper configurations and types were debated in details. Thereafter, the present research challenges were discussed and future work was suggested regarding real applications in wheeled vehicles.

Unlike small-scale energy-harvesting systems (e.g., wireless sensors and electronic devices), automobile energy harvesting based suspensions have not been sufficiently investigated. Given the worthwhile energy that can be obtained from vehicle vibration induced by road irregularities, automobile energy harvesting technologies have attracted more attention in which a harvested average power of 350 W could be achieved for a medium-size sedan (four energy-harvesting dampers). For heavy-duty and off-road vehicles, the regenerative suspension can effectively provide a wide range of the harvestable power over 1 kW which is worthy of being recovered regarding improvements in fuel efficiency.

One advantage of the regenerative energy based suspension is that they could offer potential fuel savings up to 3%, or estimated by 0.3-0.5 liters per 100 kilometers [21]. Looking at Wal-Mart trucks as an example, it could save $13 million annually in fuel costs by harvesting the wasted kinetic energy in their trucks suspensions [137]. An additional finding for using a regenerative suspension in a hybrid vehicle is the reduction of CO_2 emissions (e.g., [198-200]). Another advantage is that energy harvesting suspension allows for an even more comfortable ride by using self-powered suspension systems like the electromechanical rotary dampers with a minimal power consumption of about 50-100W for a passenger car depending on road conditions.

Regarding our survey, it can be suggested that the hydraulic transmission based energy-harvesting damper is a promising track especially in heavy trucks and off-road vehicles despite its lower conversion efficiency compared to the mechanical based transmission. The hydraulic transmission based

electromagnetic rotary harvester can be easily fabricated in different vehicle types with a common integrated power generation circuit for all vehicle suspensions. However, the hydraulic transmission based electromagnetic rotary harvesting damper was rarely investigated especially in a real road trip of wheeled vehicles. More broadly, research is also needed to enhance the behavior of the hydraulic based harvester considering both the power-harvesting performance and vehicle dynamics.

There are some essential questions remaining under investigation towards enhancing our understanding of the real application based energy harvesting suspensions in practice. According to the literature, no attempt has been made to investigate the actual vehicle fuel savings using an energy harvesting suspension in terms of litter/100 km. The excitation frequency broadband is also a considerable challenge in which the vehicle wheels always excited by random uneven road roughness with a wide range of frequencies. In the mobility of the future, developing a smart suspension based energy-harvesting function would be interesting that can work efficaciously during the car trip on different real roads. Meaning while, as for real applications, the investigations regarding an integrated energy-harvesting based damper in a wheeled vehicle has not been considered enough yet.

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The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Abbreviations	
AC	Asphalt Concrete Pavement
AERS	Active and Energy Regenerative Suspension
CAD	Computer Aided Design
CD-EHSA	Cable-Dynamics Energy Harvesting Shock Absorber
EM	Electro-Magnetic
eROT	Electromechanical Rotary Damper Technology
EVDG	Electromagnetic Vibration Driven Generator
FTP	Federal Test Procedure
GA	Genetic Algorithm
HESA	Hydraulic Electromagnetic Shock Absorber
HMR	Hydraulic Motion Rectifier
HWFET	Highway Fuel Economy Test
IRI	International Roughness Index
MMR	Mechanical Motion Rectifier
MMR-EHSA	Mechanical Motion Rectifier-Energy Harvesting Shock Absorbers
NEDC	New European Driving Cycle
NonMMR-EHSA	Non-Mechanical Motion Rectifier-Energy Harvesting Shock Absorbers
PCC	Portland Cement Concrete Pavement
SDOF	Single Degree of Freedom
WLTP	Worldwide Harmonized Light Vehicles Test Procedure

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