A review of vibration energy harvesting in rail transportation field

Lingfei Qi, Hongye Pan, Yajia Pan, Dabing Luo, Jinyue Yan, and Zutao Zhang

SUMMARY

In this paper, we review, compare, and analyze previous studies on vibration energy harvesting and related technologies. First, the paper introduces the basic aspects of vibration energy acquisition in the railway environment, including vibration frequency, train speed, energy flow in the train, and vibration energy harvesting potential. Generally, the methods for scavenging vibration energy caused by passing trains can be divided into four categories: electromagnetic harvesters, piezoelectric harvesters, triboelectric harvesters, and hydraulic harvesters. The structure, output performance, merits, and disadvantages of different energy harvesting strategies are summarized and compared. The application of vibration energy harvesters is explained as supplying power to monitoring sensors on the line side and the vehicle side. Finally, the paper addresses the challenges and difficulties that have not been completely resolved in the current research literature, including system stability, durability, and economy. Some recommendations to fill these research gaps are put forward for further investigation.

INTRODUCTION

Railways have huge passenger and cargo capacity, and low-level economic cost, making this the main mode of transportation in various countries (Lapidus et al., 2019). Especially in certain developing and developed countries, including China, Japan, and Germany, high-speed railways are regarded as the core of transportation development because they provide passengers with a fast and convenient way of travel (Kang et al., 2018; Li et al., 2019; Liu et al., 2019a, 2019b). As the speed of trains, the number of passengers carried, and the volume of goods increase, the health monitoring of the railway system plays an increasingly important role (Asada et al., 2013; Ökühelliou et al., 2008; Entezami et al., 2016). In general, the condition monitoring of the railway system is divided into line-side monitoring (Li et al., 2021; Yüksel et al., 2018; Leone et al., 2016; Alexakis et al., 2019) and on-board monitoring (Bernal et al., 2018; Gruden et al., 2009). Regarding the power supply to these two kinds of monitoring, the traditional method is to use batteries that cause electrochemical pollution or to connect to the grid via a complicated wired system. In the past 20 years, self-powered technologies with ambient energy harvesting systems have attracted tremendous attention as promising directions in transportation research filed because of their potential to achieve environmental protection, energy saving, and real-time monitoring of sensor nodes (Fu et al., 2021; Chen and Wang, 2017; Lewis et al., 2014).

Ambient energy harvesting in the railway environment is the key technology to achieve the self-powering of monitoring systems (González-Gil et al., 2013; Bosso et al., 2021). There are considerable wind resources around moving trains, hence wind energy harvesting is considered a promising approach in the railway field (Sindhuja, 2014; Oñederra et al., 2020; Kumar et al., 2016; Nurmanova et al., 2018). Especially in tunnels, slipstream generated by passing trains has a huge potential to produce energy for powering monitoring sensors (Pan et al., 2019a, 2019b, 2019c; Guo et al., 2020; Laws et al., 2020). Some other ambient energy resources, such as thermal (Gao et al., 2019; Ahn and Choi, 2018), solar (Ruscelli et al., 2017), acoustic (Kralov et al., 2011; Noh, 2018; Wang et al., 2018a, 2018b), braking (Jiang et al., 2014; Kaleymba et al., 2017), and radio wave energy (Li et al., 2020b), have been harvested for applications in railway systems. In addition, railroad track joints, wheel-rail wear, and wind forces cause continuous vibrations in trains, tracks, and other infrastructure. Vibration energy harvesting (VEH) technologies in the railway field, both on the line side and on board, have been widely studied in recent years. Generally, VEH technology in railway systems can be divided into the following categories: electromagnetic, piezoelectric, triboelectric, and hydraulic (Duarte and Ferreira, 2017).
Electromagnetic energy harvesters have been conceptualized and prototyped in various transportation fields, such as vehicle suspension (Azam et al., 2021a, 2021b; Bai and Liu, 2021; Kireev et al., 2017) and speed-bump (Wang et al., 2016; Todaria, 2016; Azam et al., 2021a, 2021b) energy harvesters, owing to their high energy harvesting efficiency and strong controllability. Electromagnetic-based vibration energy harvesting systems in the railway field mainly include linear (Gao et al., 2017; Cleante, 2015; Ghandchi Tehrani et al., 2013) and rotary (Pourghodrat et al., 2011; Kalaagi and Seetharamdoo, 2019; Costanzo et al., 2019) generators. Both line-side and on-board linear generators absorb ambient vibration to drive permanent magnets to reciprocate linearly between coils to generate electrical energy (Gao et al., 2018; De Pasquale et al., 2012a, 2012b). Linear electromagnetic generators have the advantages of simple mechanism and structure, so they are easy to implement on the track side and on board. As for rotary electromagnetic VEH, these generators usually utilize a mechanical vibration rectifier (MVR) that converts linear vibration into rotational motion. The output performance of a rotary electromagnetic VEH is mainly affected by the structure of the MVR. In order to obtain considerable energy harvesting efficiency, MVR has been continuously updated by various research projects in recent years, yielding rack-pinion mechanisms (Mi et al., 2020; Pan et al., 2018), ball-screw mechanisms (O’Connor et al., 2017; Pan et al., 2019b), and other mechanisms (Kaufman, 2002; Dotti and Sosa, 2019). Compared with linear electromagnetic harvesters, rotary electromagnetic VEH generators have a more complex structure and higher energy density and can be more compact (Abdelkareem et al., 2018).

Piezoelectric mechanism-based vibration energy harvesting is the second most common energy regenerative strategy for application in rail transit systems (Song, 2019; Li et al., 2013; Li et al., 2012). According to the previous literature, the environmental vibrations in the environment of heavy-duty railways and high-speed railways both have millimeter-level amplitudes and wide frequencies from 30 to 650 Hz (Zhai et al., 2015; Petriaev, 2016). In addition, in order to improve the safety and comfort of railway systems, the vibration caused by trains is mitigated (Li et al., 2020c). In this kind of wide-frequency and low-amplitude vibration environment, piezoelectric generators are a promising technology for acquiring vibration energy. Nelson (2008) and Mouapi (2016), respectively, proved that line-side and on-board piezoelectric VEHs are effective solutions to supply power for low-wattage sensor nodes.

Electromagnetic and piezoelectric VEH are the two most popular regenerative vibration strategies in railway systems. In addition, triboelectric and hydraulic mechanism-based VEH have been studied by a small number of researchers (Geng et al., 2017; Mi et al., 2017; Nelson et al., 2011). Usually, triboelectric VEHs need to introduce a nanogenerator to convert the micro-vibration of the rail into electricity for monitoring sensors. Nanogenerator technology is a new technology that has emerged in recent years (Wu et al., 2019; Liu et al., 2019b; Wang et al., 2017b). This emerging technology itself has high requirements for materials and power control, hence VEH triboelectric mechanism-based VEH has not been investigated much. Similarly, owing to the high sealing requirements, complicated control, and structure
of hydraulic systems (Shen et al., 2017; Gong et al., 2019; Shi et al., 2020), research on hydraulic mechanism-based VEH is not the current mainstream. The number of publications on VEH in railway systems in the past two decades, categorized by electromagnetic, piezoelectric, triboelectric, and hydraulic principles are obtained by Google Scholar statistics and the share of publication for each VEH is illustrated in Figure 1.

Although there are several literature reviews dealing with energy harvesting technologies in the railway field, these studies cover quite a broad range of the issues, including solar energy harvesting, wind energy harvesting, heat energy harvesting, and vibration energy harvesting in railway environment. In recent years, vibration energy sources in railway transportation are considered to have considerable regenerative potential and various energy harvesting technologies are developed to scavenge the vibration energy existing in the railway system. Conducting a comprehensive review focusing on the specific vibration energy harvesting technologies in railway environment is of great significance to the further exploration and development of this field. Therefore, the novelty and driving motivation behind this review is to survey the state of the art concerning vibration energy harvesting in the railway environment, including the line side and on board. The architecture of this review is shown in Figure 2, which demonstrates that the vibration energy from the railway system can be converted to electricity by energy conversion mechanisms, and the harvested energy is capable of being stored in power storage module after the circuit processing, and then the storage module can be served as backup power of some low-watt electrical facilities like sensor nodes, monitors, and traffic lights. In the future, some technical difficulties like efficiency, stability, economy, and forecasting of the vibration energy harvesting technology should be focused on.

**GENERAL ASPECTS OF THE VIBRATION ENERGY HARVESTING IN RAILWAY**

With the rapid development of information society, big data is a basic element of ensuring the healthy and safe operation of various industries. Wireless network sensor (WSN) nodes are the backbone of achieving massive data collection (Rani et al., 2017; Kim et al., 2019). Therefore, in recent years, tremendous numbers of WSN nodes have spread in various fields, including vehicles, roads, bridges, buildings, and even humans. Considering energy saving and real-time monitoring, many researchers have studied advanced power supply systems based on environmental waste energy harvesting to replace traditional chemical batteries and wired power supplies that power WSN nodes (Qian et al., 2018; Alavi et al., 2017; Lin et al., 2017; Cahill et al., 2014). Especially in the railway industry, various line-side and on-board condition monitoring WSN nodes are employed to monitor trains, rails, and other infrastructure. Developing alternative energy technologies based on railway waste energy is a promising strategy for powering condition monitoring WSN nodes.
A prerequisite for establishing a waste energy harvesting system is to grasp the energy flow in the railway system. According to measured and calculated energy consumption data within Europe, González-Gil proposed a typical energy flow in rail systems, depicted in Figure 3 (González-Gil et al., 2014). From this figure, we can see that the gross energy supplied by the public network flows to infrastructure loss and net traction energy, which contains auxiliary load, traction loss, motion resistance, and braking loss. It can be obtained that the total energy loss consists of infrastructure loss, traction loss, and braking loss. The energy wasted in infrastructure and braking can be reclaimed through regeneration energy transfer and control strategies (Domínguez et al., 2012; Ceraolo et al., 2018). Regarding the energy loss in traction, González-Gil has indicated that it includes inefficiencies in the electric motors, the converters, and the transmission system. Alberto once pointed out the efficiencies of converters, DC motors, induction motors, and transmission systems are 98.5%–99.5%, 90%–94%, 93%–95%, and 96%–98%, respectively (de los Ferrocarriles Españoles, 2008). The energy loss of the motor and the transmission system is dissipated in the form of heat and vibration, which will be transmitted to the vehicle body and track. Such low-grade heat energy is difficult to recover and utilize, but mechanical vibration energy can be effectively harvested by external devices, such as electromagnetic, electrostatic, variable reluctance generators, and piezoelectric sheets (Diez et al., 2019). This paper presents a taxonomy of the state of the art of vibration energy harvesting technologies in rail transportation.

**Source of vibration energy in rail systems**

A prerequisite for establishing a waste energy harvesting system is to grasp the energy flow in the railway system. According to measured and calculated energy consumption data within Europe, González-Gil proposed a typical energy flow in rail systems, depicted in Figure 3 (González-Gil et al., 2014). From this figure, we can see that the gross energy supplied by the public network flows to infrastructure loss and net traction energy, which contains auxiliary load, traction loss, motion resistance, and braking loss. It can be obtained that the total energy loss consists of infrastructure loss, traction loss, and braking loss. The energy wasted in infrastructure and braking can be reclaimed through regeneration energy transfer and control strategies (Domínguez et al., 2012; Ceraolo et al., 2018). Regarding the energy loss in traction, González-Gil has indicated that it includes inefficiencies in the electric motors, the converters, and the transmission system. Alberto once pointed out the efficiencies of converters, DC motors, induction motors, and transmission systems are 98.5%–99.5%, 90%–94%, 93%–95%, and 96%–98%, respectively (de los Ferrocarriles Españoles, 2008). The energy loss of the motor and the transmission system is dissipated in the form of heat and vibration, which will be transmitted to the vehicle body and track. Such low-grade heat energy is difficult to recover and utilize, but mechanical vibration energy can be effectively harvested by external devices, such as electromagnetic, electrostatic, variable reluctance generators, and piezoelectric sheets (Diez et al., 2019). This paper presents a taxonomy of the state of the art of vibration energy harvesting technologies in rail transportation.

**How much train-induced vibration energy can be harvested?**

A moving train causes vibrations that flow into the rail track and its own vehicle body, mainly in the suspension. Whether vibrations are on line or on board, it is necessary to evaluate the energy recovery potential before considering harvesting and converting into usable electricity. A preliminary theoretical evaluation is capable of providing fundamental guidance for subsequent mechanical design. It is well known that, when there is resonance between two objects, their vibration amplitude will be the largest. Therefore, in order to evaluate as accurately as possible the vibration energy harvesting potential caused by the train, the energy harvester needs to be tuned to a specific frequency. The dominant source of track vibration is the quasi-static trainload (Triepaischajonsak et al., 2011). Ju and his team have established a mathematical model to evaluate the dominant frequency of train-induced vibration, which can be expressed as (Ju et al., 2009):

\[
R_f = nV \sqrt{L} = N_c P_{axle} \sum_{k=1}^{N_w} e^{-2\pi n s_k / L}
\]

(Equation 1)

where \(N_c\), \(N_w\), \(s_k\), \(L\), \(V\), \(P_{axle}\), and \(n\) are the number of carriages of one train, the number of wheel pairs of one carriage, the distance between the beginning of the carriage and the \(k\)th wheel, the distance between two
Through theoretical and experimental investigation, the results show that trainload vibration plays the most important role in the railway environment, and the largest kinetic energy exists at the trainload dominant frequencies nV/L. Through five case studies, Cleante demonstrated that the maximum amplitude of the track occurs at the seventh trainload frequency (Cleante et al., 2019). In addition, Cleante has investigated the effect of speed variability on the amount of vibration energy harvested; the results are shown in Figure 4 (Cleante et al., 2016). Based on the experimental data, Cleante found that only when the train speed changes within 1% will the energy harvester exhibit excellent performance.

Gatti has investigated how much energy can be acquired by train-induced vibration based on numerical study and analytical study (Gatti et al., 2016). A simple single-degree-of-freedom oscillator and a moving train with speed of 195 km/h are introduced to develop the analysis as shown in Figure 5. Through numerical investigation, the motion and energy harvested at to by the harvester can be calculated by:

\[ z = x - y \]  
\[ m \ddot{z} + c \dot{z} + kz = -m \dot{y} \]  
\[ E(t_e) = \int_0^{t_e} c \dot{z}^2 dt \]  

where x, y, z, m, c, and k are mass location, casing location, relative displacement, mass, damping, and stiffness, respectively, and the over dot represents the differentiation with respect to time. The simulation results show that the maximum amount of energy harvested does not occur under the largest relative displacement. When the energy harvesting device has a frequency of 17 Hz, damping ratio of 0.0045, and maximum relative displacement of 5 mm, it can harvest the maximum energy. Under such an optimal condition, this energy harvester can generate about 0.25 J/kg of oscillator mass.

Through analytical study, the optimum energy harvested by the device can be obtained by:

\[ \frac{E(t_e)}{m} = 0.0475 \bar{Y}^2 t_e^2 \]  

which \( t_e = 2\pi n/\omega_0 \) and \( \omega_0 = \sqrt{k/m} \). \( n \) is the number of vibration cycles, \( \bar{Y} \) is the amplitude of the base acceleration, and \( t_e \) is the input duration. Therefore, according to Equation 5, it can be concluded that the harvested energy is proportional to the square of the amplitude of the base acceleration and to the square of the input duration.

Figure 4. Energy harvested by train-induced vibration, given train speeds from 190 to 200 km/h (Reprinted [adapted] with permission from Cleante et al., 2016 under a CC BY license.)
ENERGY HARVESTING MECHANISM FOR TRAIN-INDUCED VIBRATION

It is well known that vibration is accompanied by the generation of kinetic energy, which can be transformed into electrical energy through certain conversion mechanisms. Currently, research about converting train-induced vibration energy into electricity focus mainly on line-side and on-board mechanisms. According to a review of the literature, the conversion mechanisms for acquiring vibration energy from passing trains include electromagnetic, piezoelectric, triboelectric, and hydraulic types. Regardless of line side or vehicle side, electromagnetic energy conversion mechanisms are one of the most popular technologies for vibration energy harvesting in railway systems (Perez et al., 2018; Ung et al., 2015; Kim, 2020). The electromagnetic VEH strategy has the advantages of high energy harvesting efficiency, strong controllability, quick response, and easy compactness (Montazeri-Gh and Kavianipour, 2012). Commonly, the electromagnetic VEH strategy can be divided into linear harvester-based and rotary harvester-based methods. Piezoelectric energy harvesters are the second most attractive train-induced VEH technology, which boast simple structure and high voltage output (Sun et al., 2019). Lastly, there is a small part of the literature that studies train-induced VEH technology using triboelectric and hydraulic mechanisms.

This section taxonomizes the existing VEH technologies for application in railway systems and their working principles and mechanisms. In addition, this section summarizes and compares the findings of research projects on train-induced vibration energy harvesting.

Electromagnetic energy harvesting systems

The electromagnetic method mainly consists of two approaches to harvest train-induced vibration energy. The first solution is based on a linear electromagnetic generator with simple structure and working principle to convert vibration energy into electrical energy (Wang et al., 2019b). The second type is based on a rotary electromagnetic generator that converts vibration into rotation of the shaft and then drives the generator to generate electricity (Zuo et al., 2014; Liang et al., 2015; Costanzo et al., 2020).

Electromagnetic linear harvesters

Electromagnetic linear generators generally include two core components: permanent magnets and coils. The vibration caused by the train can drive relative movement between the permanent magnet and the coil, so that the magnetic flux of the coil changes with the relative movement and then a current is generated in the coil. Currently, many studies have been performed on using electromagnetic linear generators as a carrier to harvest vibration energy from the line side and vehicle side.

Guo and his team proposed an electromagnetic railway vehicle-induced vibration energy harvester (EM-VEH), which is connected to the track slab as shown in Figure 6 (Hou et al., 2018). This proposed line-side EM-VEH is mainly composed of spring, mass, permanent magnets, and coils. When the train
passes the EM-VEH, the track slab vibrates, driving the coil and the mass to reciprocate in the vertical direction. Because there are permanent magnets on both sides, the coils can generate electromotive force energy with their own up and down movement. The spring can increase the duration of the coil movement, thereby improving the energy harvesting efficiency of the harvester. The simulation results show that the power density of the proposed energy harvester can reach up to 176.5 \( \mu \text{W/cm}^3 \), which is enough to supply power for GPS and strain detection units. In fact, the vibration caused by the train is random and variable, so a single-frequency linear energy harvester cannot efficiently absorb the vibration of various frequencies. Therefore, Guo proposed three efficient multi-frequency EM-VEHs to harvest train-induced vibration with different frequencies (Hou et al., 2020). As presented in Figure 7, the proposed multi-frequency EM-VEHs contain four submodules, corresponding to four natural frequencies. The results show that the power density for these improved EM-VEHs can reach 112.4, 253.6, and 267.2 \( \mu \text{W/cm}^3 \), with corresponding output power of 0.84, 0.91, and 1.41 W, respectively. All these outputs can meet the power demand of monitoring sensors used in railway systems.

In addition to harvesting vibration energy from the line side, on-board VEH technology is also attractive for powering vehicle-mounted monitoring sensors (Bradai et al., 2018; Brignole et al., 2016). Perez et al. have presented an innovative electromagnetic vibration energy harvester with two degrees of freedom installed on the tram (Perez et al., 2020). As shown in Figure 8, the structure of the VEH is very simple, including only permanent magnet and coils. The simplification of the structure can greatly reduce the weight of the harvester (the weights of the permanent magnet and the coil are 469 and 195 g, respectively), so that its impact on the energy consumption of the train can be ignored. Based on numerical simulation and experimental data, the results show that the presented energy harvester is able to output an average
Ma and his team also proposed a similar VEH with simple structure mounted on a railway wagon (He et al., 2020). The experiment results show that the proposed electromagnetic energy harvester can output a voltage of 3.3 V, which can drive the circuit system of monitoring sensors.

In general, the structure of single degree of freedom vibration energy harvesting system is simple, and the energy loss caused by intermediate motion transfer is small. The two-degree-of-freedom solution can realize multi-steady-state energy harvesting and broaden the energy harvesting frequency. In addition, because the coils are connected to other parts of the system, including external circuit components, moving the coil may affect the stability of other parts. Therefore, compared with moving the coil, moving the magnet is easier and does not affect other parts of the system.

Figure 7. Multi-frequency ME-VEH
(Reprinted [adapted] with permission from Hou et al., 2020. Copyright [2019] Elsevier.)

electrical power of 6.5 mW. Ma and his team also proposed a similar VEH with simple structure mounted on a railway wagon (He et al., 2020). The experiment results show that the proposed electromagnetic energy harvester can output a voltage of 3.3 V, which can drive the circuit system of monitoring sensors.

In general, the structure of single degree of freedom vibration energy harvesting system is simple, and the energy loss caused by intermediate motion transfer is small. The two-degree-of-freedom solution can realize multi-steady-state energy harvesting and broaden the energy harvesting frequency. In addition, because the coils are connected to other parts of the system, including external circuit components, moving the coil may affect the stability of other parts. Therefore, compared with moving the coil, moving the magnet is easier and does not affect other parts of the system.

Figure 8. The two degrees of freedom linear electromagnetic VEH
(Reprinted [adapted] with permission from Perez et al., 2020. Copyright [2020] Elsevier.)

(A) The permanent magnet stack, (B) The coils, (C) The complete assembly, (D) Installation location of the harvester.
Electromagnetic rotary harvesters have been favored by a large number of researchers owing to their high energy conversion efficiency and easy packaging (Lin et al., 2015; Wang et al., 2012; Wang et al., 2018a). Usually, an MVR is introduced to convert the bidirectional linear vibration into unidirectional rotation. Different rotary electromagnetic VEHs using various MVR mechanisms have been designed, prototyped, and investigated extensively. The two most common MVRs are based on a rack-pinion mechanism and a nut-screw mechanism. Zhang et al. (2016) presented a portable rotary electromagnetic VEH for applications in railroads. The proposed VEH is connected to the rail track and uses a single rack and double gear set transmission system as the MVR presented in Figure 9. The key component of a one-way bearing is utilized to convert the up and down movement of the rack into unidirectional rotation of the generator shaft. The proposed energy harvester is validated by dynamic simulation and bench test, which show that it has rapid response and high efficiency of 55.5%. In order to obtain higher energy output and a more compact structure, Zhang also proposed another optimized rotary electromagnetic VEH (Zhang et al., 2017). In this VEH, a single shaft gear transmission system is introduced to replace the previous double shaft gear transmission system, resulting in a more compact and simple structure, as shown in Figure 10. The bench test results show that the updated energy harvester can output a high voltage of 58 V, which is capable of competing with the previous version with 6.45 V output voltage.

Zuo et al. (Lin et al., 2018a) proposed an anchorless mounting-based rotary electromagnetic VEH installed on rail tires. Compared with VEHs fixed to the rail track, the proposed VEH can avoid affecting the safety of the moving train and changing the track foundation. The MVR of this energy harvester uses double racks combined with two one-way clutches to output the two-way vibration caused by the train as one-way

Figure 9. Double shaft gear transmission system-based electromagnetic VEH
(Reprinted [adapted] with permission from Zhang et al., 2016. Copyright [2016] Elsevier.)
(A) Overview.
(B) Components.
(C) Rack moves downward.
(D) Prototype.
(E) Installation.
(F) Rack moves upward.

Electromagnetic rotary harvesters
Rotary electromagnetic energy harvesters have been favored by a large number of researchers owing to their high energy conversion efficiency and easy packaging (Lin et al., 2015; Wang et al., 2012; Wang et al., 2018a). Usually, an MVR is introduced to convert the bidirectional linear vibration into unidirectional rotation. Different rotary electromagnetic VEHs using various MVR mechanisms have been designed, prototyped, and investigated extensively. The two most common MVRs are based on a rack-pinion mechanism and a nut-screw mechanism. Zhang et al. (2016) presented a portable rotary electromagnetic VEH for applications in railroads. The proposed VEH is connected to the rail track and uses a single rack and double gear set transmission system as the MVR presented in Figure 9. The key component of a one-way bearing is utilized to convert the up and down movement of the rack into unidirectional rotation of the generator shaft. The proposed energy harvester is validated by dynamic simulation and bench test, which show that it has rapid response and high efficiency of 55.5%. In order to obtain higher energy output and a more compact structure, Zhang also proposed another optimized rotary electromagnetic VEH (Zhang et al., 2017). In this VEH, a single shaft gear transmission system is introduced to replace the previous double shaft gear transmission system, resulting in a more compact and simple structure, as shown in Figure 10. The bench test results show that the updated energy harvester can output a high voltage of 58 V, which is capable of competing with the previous version with 6.45 V output voltage.

Zuo et al. (Lin et al., 2018a) proposed an anchorless mounting-based rotary electromagnetic VEH installed on rail tires. Compared with VEHs fixed to the rail track, the proposed VEH can avoid affecting the safety of the moving train and changing the track foundation. The MVR of this energy harvester uses double racks combined with two one-way clutches to output the two-way vibration caused by the train as one-way
rotation of the gear set, as depicted in Figure 11. In addition, a mechanical energy storage device like flywheel is introduced to store the energy produced by the VEH system. Field test results show that the proposed energy harvester can generate an average power of 7 W and peak power of 56 W given a train speed of 64 km/h and track deflection of 5.7 mm. In the same year, via bench test, Zuo indicated the excellent performance of the energy harvester: 10–100 W of output power and 74% energy conversion efficiency can be obtained (Lin et al., 2018b). By comparing different MVR structures, the author pointed out that the simpler the motion transmission system, the better the performance of the VEH. The above two VEHs proposed by Zuo are based on a rack-pinion MVR mechanism, which has a high possibility of backlash. In order to reduce the backlash during the motion process, Zuo (Pan et al., 2019b) designed another track-side-mounted VEH based on a nut-screw mechanical motion rectification mechanism, as shown in Figure 12. Laboratory bench test results show that the proposed VEH can obtain a peak output power of 114.98 W and an average output power of 17.5 W, given a freight train speed of 64 km/h. In addition, a field test has been conducted by the authors, and the results show that the proposed VEH can output an average power of 2.24 W given a vehicle speed of 30 km/h.

Previous VEH technologies on the track-side require additional devices to acquire vibration energy. This year, Wu et al. (2021) proposed a line-side VEH with nut-screw vibration rectification mechanism based on an existing Dowty retarder, as presented in Figure 13. The proposed energy harvester is embedded in the retarder, which not only can provide braking assistance for the train but also can harvest kinetic energy to achieve the self-powered monitoring of the retarder. A novel MVR based on a nut-screw mechanism is employed to convert the two-way linear movement into unidirectional rotation. Simulation results show that the proposed regenerative retarder possesses high-quality output performance, with 250 W of peak power and 55.4% energy conversion efficiency. In addition, the author made an assessment finding that, if all the traditional retarders in China are replaced with regenerative retarders, the total annual power generation will reach 360 MWh.
Some on-board vibration energy harvesters have also been designed as power supply equipment for train condition monitoring sensors. Zuo et al. (Pan et al., 2019c) have investigated a regenerative shock absorber installed on the train suspension. As demonstrated in Figure 14, a rack-pinion mechanism and one-way clutches are utilized cooperatively to convert bidirectional vibration into unidirectional rotation. The proposed energy harvester is wrapped in a cylindrical shell, which makes it easy to integrate into the train suspension. Field test results show that the proposed energy harvester can obtain a single-phase peak output power of 73.2 W and a three-phase average power of 1.3 W. The authors found that, after increasing the transmission ratio of the gear set, the output power can also be increased. Li et al. (2020a) also proposed a train suspension-mounted regenerative shock absorber based on twin slider-crank mechanisms, as presented in Figure 15. The laboratory test results show that the shock absorber is capable of output average power of 4.8 W under harmonic excitation with a frequency of 3 Hz and an amplitude of 12.5 mm. Wang et al. (Gao et al., 2020) developed a pendulum-based vibration energy harvester fixed on railway freight wagons. The structure of the proposed harvester is shown in Figure 16, mainly consisting of an inertial pendulum, a gear ring, a gear, and other auxiliary parts. The motion transmission process can be described as follows: the pendulum swings, driven by train vibration, thereby driving the gear ring, pinion, and motor shaft to rotate. Although the structure of this harvester is highly compact, it cannot convert the two-way swing of the pendulum into one-way rotation of the shaft. A comparison of different electromagnetic train-induced VEHs is listed in Table 1, which includes harvester type, MVR type, installation position, input, load, output, and maximum conversion efficiency. From this table, we can see that the energy output of rotary energy harvesters is generally higher than that of linear-type harvesters. Most VEHs are verified by simulation and laboratory tests, whereas only a small portion are validated by field tests.

Piezoelectric energy harvesting systems

Owing to their simple structure and energy recovery, piezoelectric materials-based VEHs are considered to be a feasible method to scavenge vibration energy caused by trains (Cahill, Hazra, Karoumi, Mathewson, & Pakrashi, 2018a, 2018b; Amoroso et al., 2015; Wang et al., 2017a). Corresponding to different installation locations, various piezoelectric train-induced VEH systems with different structures have been developed. The structures of piezoelectric energy harvesters on the line side are mainly divided into cantilever type
Piezoelectric VEHs based on a cantilever mechanism are the simplest way to harvest vibration energy in the railway environment. Cahill et al. (2018) proposed a cantilever beam-based piezoelectric energy harvester to harness the bridge vibration energy produced by passing trains. As shown in Figure 17, the proposed piezoelectric harvester has a simple structure only possessing three parts: mass, piezoelectric film, and fixed plate. Test results show that the maximum voltage output can reach 99 mV and the natural frequency can match the estimated frequency of the bridge. Gao et al. (2016a, 2016b) also proposed a cantilever-based piezoelectric transducer connected to the track for harnessing vibration energy, as presented in Figure 18. The results indicate that the proposed transducer has the capability to harvest energy at small track vibration (0.2–0.4 mm) and low frequency (5–7 Hz). The open circuit voltage can reach up to 24.4 V, and the output power is 4.9 mW. Li studied the output performance of cantilever-based piezoelectric VEHs under different resistors and frequencies (Li et al., 2014). Experiment and field test results show that each piezoelectric harvester has the same optimal working resistors. As for the optimal working frequency, it depends on the natural frequency of the harvester. At the resonance point of the piezoelectric harvester, its power output performance reaches the optimal state.

Wang et al. (2015) analyzed the performance of an energy harvesting method based on a piezoelectric stack device connected to the rail track. The research results indicate that the proposed piezoelectric energy harvesting approach has the potential to supply power for wireless sensors utilized in railway systems. Hou et al. (2020) proposed a stacked structure-based piezoelectric VEH installed on the rail transit bridge, as depicted in Figure 19. Simulation results show that the peak output voltage and current can reach up to 195.8 V and 5.6 mA, and the corresponding peak output power is 1.09 W. The average power density of the studied piezoelectric energy harvester can reach 0.048 mW/cm³, which is twice that of existing low-frequency piezoelectric VEHs. And the total energy produced by 144 arranged piezoelectric energy harvesters can reach 31.4 kJ.

Wischke et al. (2010) proposed a bilateral fixed piezoelectric energy harvester, which is connected to the rail track. Experiment results show that the proposed harvester can obtain an average output energy of 260 μWs when a train passes by.

Figure 13. Dowty retarder-based kinetic energy harvester on line side
(Reprinted [adapted] with permission from Wu et al., 2021. Copyright [2018] Elsevier.)
(A) Overview.
(B) Sectional view.
(C) Prototype.
(D) Inner components.

(Yang et al., 2021), stacked type (Abramovich et al., 2010), bilateral fixed type (Wischke et al., 2010), and circular type (Wang et al., 2014).
Yuan et al. (Tianchen et al., 2014) presented a circular drum array-based piezoelectric energy harvester to scavenge the track vibrations produced by running vehicles. The prototype, installation, and schematic diagram of location of the proposed harvester is presented in Figure 20 and has a total of 16 drum transducer units. The simulation results show that 50–70 V of peak open-circuit voltage and 100 mW of average power can be generated under a real running train scenario. After reviewing the literature, track-side piezoelectric VEHs include the four types presented above. On the train side, only bilateral fixed and cantilever piezoelectric energy harvesters have been studied.

Fu et al. (2019) developed a double-side fixed piezoelectric vibration energy harvester installed on an underground train, as demonstrated in Figure 21. The results show that the proposed energy harvester can output considerable voltage within a broad range of frequencies and the maximum voltage can reach up to 60 V.

Pasquale and his team proposed a cantilever structured piezoelectric VEH deployed on a railway vehicle (De Pasquale et al., 2012a, 2012b). A scaled railway bogie was employed to test the output performance of the proposed energy harvester. The results show that the output power generated by the harvester reaches 4.12 mW. Song et al. investigated a cantilever structure-based piezoelectric VEH installed on a superconducting Maglev train (Song et al., 2013). The experiment results indicate that, as the vibration frequency increased, the output voltage of the harvester also increased and the maximum voltage can exceed 6 V. Cho et al. (2016) also proposed a piezoelectric energy harvester based on a cantilever mechanism for supplying power to safety monitoring sensors of trains. A magnetic pendulum is utilized to excite the cantilever piezoelectric plate to vibrate, as shown in Figure 22. A comparison of different piezoelectric train-induced vibration energy harvesters is listed in Table 2, including structure, installation position, input, load, and output. From this table, it can be seen that the output power level of piezoelectric train-induced VEHs is in the microwatt to milliwatt range. A comparison of Tables 1 and 2 indicates that the output of electromagnetic VEHs is higher than that of piezoelectric VEHs. In general, the

Figure 14. On-board rotary electromagnetic energy harvester
(Reprinted [adapted] with permission from Pan et al., 2019c. Copyright [2019] Elsevier.)
(A) Electromagnetic energy harvester.
(B) Installation.
four piezoelectric energy harvesting systems with different structures have different advantages and disadvantages. Figure 23 demonstrates the structure and characteristics of the proposed four-type piezoelectric energy harvesting systems.

**Triboelectric and hydraulic energy harvesting systems**

In addition to the most common electromagnetic and piezoelectric methods, there are a few other technologies for harnessing train-induced vibration energy, such as triboelectric harvesters and hydraulic harvesters. Zhao et al. (2017) proposed a nano VEH based on a triboelectric mechanism (VEH-TE) for railway condition and health monitoring. As shown in Figure 24, the proposed energy harvester contains four components: PMMA, aluminum, aluminum nano structure, and Kapton nano structure. Experiment
| No. | Reference | Linear or rotary | Mechanical vibration rectifier | Installation position | Input Load | Output Maximum conversion efficiency | Simulation/Field testing |
|-----|-----------|------------------|---------------------------------|-----------------------|------------|-------------------------------------|-------------------------|
| 1   | Gao et al., 2017 | Linear | Line side | 6 Hz 1.2 mm | 44.6 Ω | 2.32 V 119 mW | |
| 2   | Cleante, 2015; Gatti et al., 2016 | Linear | Line side | 16.67 Hz 196 km/h | | 1.110 J | |
| 3   | Ghandchi Tehrani et al., 2013 | Linear | On board | 16.6 Hz | | 0.15 J/kg | |
| 4   | Pourghodrat et al., 2011 | Rotary | Single rack-pinion Double gear set | Line side | 60 mph | 306.277 W | |
| 5   | Gao et al., 2018 | Linear | Line side | 7–500 Hz | | | |
| 6   | De Pasquale et al., 2012a, 2012b | Linear | On board | 80 km/h | | 2.5 V, 50 mA 100 mW | |
| 7   | Pan et al., 2018 | Rotary | Single rack-pinion Double bevel gear set | On board | 100 km/h | 180 W | |
| 8   | Pan et al., 2018 | Rotary | Nut-screw Double bevel gear set | Line side | 30 km/h | 8 Ω Peak: 114.98 W Average: 17.5 W | 2.24 W |
| 9   | Dotti and Sosa, 2019 | Rotary | Pendulum | Line side | 0.5 kg | 5–6 W | |
| 10  | Wang et al., 2019b | Linear | Line side | 4 mm | | 6.4 V | |
| 11  | Ung et al., 2015 | Linear | On board | 4.16 ms⁻² | | Average: 0.874 mW Maximum: 1.71 mW | |
| 12  | Zuo et al., 2014 | Rotary | Double rack-pinion Single gear set | Line side | 4 Hz 3 mm | 2 Ω 6.4 V 21.7 W | 46.7% |
| 13  | Hou et al., 2018 | Linear | Line side | 5.5 Hz | | 35.3 W 176.5 μW/cm³ | |
| 14  | Hou et al., 2020 | Linear | Line side | 5.6 Hz | | 39.1 W 112.4 μW/cm³ | |
| 15  | Bradai et al., 2018 | Linear | On board | 27 Hz | | 1.7 V 10 mW | |
| 16  | Brignole et al., 2016 | Linear | On board | 75 km/h | | 2.7 mW | |
| 17  | Perez et al., 2020 | Linear | On board | 28 Hz, 40 Hz | | 6.5 mW | |
| 18  | He et al., 2020 | Linear | On board | Over 50 km/h | | 3.3 V | |
| 19  | Lin et al., 2015 | Rotary | Double rack-pinion Single gear set | Line side | 5 mm 70 km/h | 2-3 kW | |
| 20  | Wang et al., 2012 | Rotary | Double rack-pinion Double gear set | Line side | 0.5 inch 1 Hz | 6.2, 12, 24 Ω 5 V 1.4 W | 16.9% |

(Continued on next page)
| No | Reference         | Linear or rotary | Mechanical vibration rectifier | Installation position | a Input          | Load   | b Output                  | Maximum conversion efficiency |
|----|-------------------|-----------------|--------------------------------|-----------------------|-----------------|--------|--------------------------|--------------------------------|
| 21 | Wang et al., 2018a| Rotary          | On board                       | 300 Ω                 | Simulation: 7.07 V | 28.4 mW | 67.6%                    |                                 |
| 22 | Zhang et al., 2016| Rotary          | Single rack-pinion              | Line side: 2 Hz 6 mm   | Output: 6.45 V    | 55.5%  |                          |                                 |
| 23 | Zhang et al., 2017| Rotary          | Single rack-pinion single gear set | Line side: 1 Hz 2.5 mm | 3 Ω      | 35.4 V | 86.67 W                  | 58 V                           |
| 24 | Lin et al., 2018a | Rotary          | Double rack-pinion single gear set | Line side: 4 Hz 96 km/h | 8 Ω 8 Ω | 196.5 W 80.4 W | 56.2 W              |
| 25 | Lin et al., 2018b | Rotary          | Double rack-pinion single gear set | Line side: 1 Hz 5 mm   | 28 W    | 62%                |                                 |
| 26 | Wu et al., 2021   | Rotary          | Nut-screw Closed bevel gear set | Line side: 2 Hz 7.5 mm | 3 Ω    | 4 V 5.3 W | 55.4%                |                                 |
| 27 | Pan et al., 2019c | Rotary          | Single rack-pinion double bevel gear set | On board: 30 km/h | 4 Ω | Maximum: 73.2 W Average: 1.3 W | 56.4% | |
| 28 | Li et al., 2020a  | Rotary          | Twin slider-crank mechanisms    | On board: 3 Hz 12.5 mm | 3 Ω | Maximum: 24.6 W Average: 4.8 W | 65% |

注：a输入：输入数据包括频率、振幅、加速度和列车速度。
b输出：输出数据包括电压、功率和功率密度。
results show that the peak voltage generated by the triboelectric energy harvester can reach 3.3 V given a frequency of 10 Hz and the output peak voltage has positive linear correlation to the vibration acceleration and vibration frequency. In addition, the results indicate that the output voltage regulated by the circuit is 3.3 V, which can meet the power requirement of the Zigbee module. Mi et al. (2017) studied a hydraulic-electromagnetic mechanism-based train regenerative shock absorber, as shown in Figure 25. The simulation results demonstrate that the proposed energy harvester can output high power. When the speed of the train is 180 km/h, the output power of the first vertical hydraulic-electromagnetic shock absorber bogie can reach 7 kW and the second lateral one can maintain output power between 300 and 500 W. Information regarding triboelectric and hydraulic train-induced VEHs is listed in Table 3, including principle, installation position, input, load, and output. Owing to the limited number of research papers on these two types of VEH, it is difficult to compare their performance.

Characteristics of different energy harvesting mechanisms

By comprehensively comparing the four aforementioned energy harvesting mechanisms, we found that each has its merits and disadvantages, as demonstrated in Figure 26. Electromagnetic mechanisms have the advantages of high output power, high energy density, and good compactness, which can make the energy harvester easy to connect to the vehicle suspension and track. However, electromagnetic mechanisms have the shortcomings of complex structure, heavy weight, and large size, which can cause additional energy consumption on the vehicle side. Unlike electromagnetic mechanisms, piezoelectric energy harvesting mechanisms have the merits of simple structure, light weight, small size, and high adaptability to wide-frequency and low-amplitude vibration. On the other hand, piezoelectric mechanism performance is not very satisfactory in terms of output power and cost. Therefore, considering the merits and shortcomings, piezoelectric mechanisms are suitable for use in low-power devices such as sensors. Similar to piezoelectric mechanisms, the triboelectric strategy also has the advantage of high adaptability to low or even ultra-low-level vibration energy. However, the triboelectric mechanism has some weak points hindering its popularization in train-induced vibration energy harvesting, such as high cost, demand for materials, and complicated power control. Regarding hydraulic vibration energy harvesting mechanisms, which have been studied by a few researchers, this type has excellent performance in output power, but its shortcomings include complex structure, strict sealing, and complicated power control.
APPLICATIONS OF THE TRAIN-INDUCED VIBRATION ENERGY HARVESTING

The safe and stable operation of railway systems is inseparable from the monitoring of wireless network sensor nodes (WSNs). Both on the railway side and the vehicle side, various sensors are needed to monitor the status of the rail system in real time. The power supply technology of WSNs has been the focus of research in recent years. Traditionally, there are two ways to power WSNs: inserting lithium batteries and connecting to the grid. Lithium battery power supply has the inconvenience of manual battery replacement and electrochemical pollution, especially in remote areas and harsh environments. Grid power supply has inevitable energy loss due to long-distance power transmission. According to the literature (Wu et al., 2021; Gao et al., 2018), the parameters of the sensors used for railway environmental monitoring are listed

**Figure 19. Six multilayer piezoelectric stacks-based VEH**
(Reprinted [adapted] with permission from Hou et al., 2020. Copyright [2020] Elsevier.)

**Figure 20. Circular drum-based piezoelectric VEH**
(A) Prototype. (B) Installation. (C) Location of schematic diagram of location.
(Reprinted [adapted] with permission from Tianchen et al., 2014. Copyright [2014] IOP.)
(A) Prototype.
(B) Installation.
(C) Installation position diagram.
in Table 4. From this table, we can see that the power consumption of sensors is in the microwatt to milliwatt range. Comparing this with Tables 1, 2, and 3, which show that the power output of most VEHs is in the milliwatt to watt range, it can be indicated that VEHs are capable of satisfying the power requirement of WSNs. Therefore, self-powered WSN technology driven by train vibration is a promising method to promote the sustainable development of railway systems in a green, smart, and safe manner.

There are already some studies about using VEHs to supply power for sensors on the train-side and the track-side.

Gao et al. (2018) proposed a self-powered Zigbee WSN technology based on a magnetic levitation energy harvester for monitoring railway conditions. The field test results indicate that it is feasible to use the proposed VEH to power Zigbee WSNs. Hadas et al. (2018) also presented an energy harvesting technology for powering track-side objects. The simulation results show that the average output power produced by the proposed harvester can reach 200 mW given a train speed of 130 km/h, indicating that the VEH can meet the power requirement of microwatt and milliwatt sensors.

In addition to the self-powered strategy on the track side, a maglev porous nanogenerator (MPNG) to harvest vibration energy for powering the monitoring sensors on high-speed trains was developed by Jin et al. (2017). The results demonstrate that the energy produced by the proposed MPNG is enough to power 400 commercial light-emitting diodes and charge a supercapacitor from 0 to 3V. Wang et al. (2019a) proposed a piezoelectric VEH for self-powered application in train container monitoring. The simulation and experiment results show that the two proposed energy harvesters in series style can effectively power humidity and temperature WSNs in the frequency of 8.7–22.0 Hz.

In the remote rail transit environment, in addition to the monitoring system, there are other electrical facilities with greater power consumption, such as traffic lights, tunnel lighting, and ventilation equipment. According to Table 1, we find that the power output of the energy harvesters can reach 306 W, indicating that
Train-induced VEHs have the potential to supply power for these higher-power consumption electrical facilities along the railway. Different types of train-induced vibration energy harvesters produce different levels of energy output, so the application scenarios are not exactly the same, as demonstrated in Figure 27. From this figure, we can see that the electromagnetic and hydraulic VEHs can be used to power the heating devices and auxiliary load on the rail side, such as traffic light, speed measuring radar, lamp, ventilation, and traffic lift gate; piezoelectric and triboelectric VEHs are suitable for powering the detection sensors like temperature sensor, pressure sensor, force sensor, accelerometer, and IOT sensor.

RESEARCH CHALLENGES, TECHNICAL DIFFICULTIES, AND RESEARCH GAPS

Although there have been many studies on train-induced vibration energy harvesting, there are still some challenges and difficulties that must be overcome in order to achieve practical applications. We have summarized the top five concerns (related to train-induced VEH) that have been researched and need to be further investigated, as shown in Table 5. Most of the previous studies focused on the principles and mechanisms of energy harvesters, exploring the process from vibration to electrical energy. Generally, the energy collected from environmental vibration is messy, disorderly, and cannot be directly utilized by the load (Lan and Qin, 2017; Fu et al., 2019a, 2019b; Pereira et al., 2019). The stability of electric power is a crucial factor for whether an energy harvester can actually be put into use. The first challenge that urgently needs to be tackled is how to convert harnessed vibration energy into stable electricity that can supply power to the load. As we all know, the circuit is the bridge between the initial disordered current and the load terminal. In the future, feasible circuit design and electrical control strategies should be critical research directions in the field of train-induced VEH.

The durability of power supply is also a crucial research point that needs to be considered in depth for these emerging energy harvesters. The ability to provide long-term continuous power to the load is a decisive aspect in order for train-induced VEHs to compete with traditional lithium batteries and power grids.

Table 2. Comparisons of piezoelectric train-induced vibration energy harvesters

| No | Reference | Structure | Installation position | cInput Speed | Load | bOutput | Simulation | Lab testing | Field testing |
|----|-----------|-----------|-----------------------|--------------|------|---------|------------|-------------|---------------|
| 1  | Song, 2019| Cantilever| Line side            | 330 km/h     | 44.6 Ω| 1.855–161.4 V | 49.3 μJ–287 mJ |
| 2  | Li et al., 2013; 2012| Cantilever| Line side            | 2.06 m/s² 50 Hz | 15.1 kΩ| 1.843 mW|
| 3  | Nelson et al., 2008| Cantilever| Line side            | 10–12 mph    | 7.7 Ω| 4 mW|
| 4  | Mouapi et al., 2016| Cantilever| On board             | 26 Hz 0.13 m/s² | 11 kΩ| Average: 3 mW Maximum: 10 mW|
| 5  | Wang et al., 2017; Gao et al., 2016a, 2016b | Cantilever| On board             | 7 Hz 0.2 mm   | 100 kΩ| 24.4 V|
| 6  | Yang et al., 2021| Cantilever| Line side            | 350 km/h     | 55.24 kΩ| 1.03 mW|
| 7  | Wischke et al., 2010| Bilateral fixed| On board             | 10 m/s² | 300 μW|
| 8  | Wang et al., 2014| Circular | Line side            | 150 Hz       | 11 kΩ| 21.4 mW|
| 9  | Cahill et al., 2018a, 2018b| Cantilever| Line side            | 16.6 Hz      | 0.144 V|
| 10 | Li et al., 2014| Cantilever| Line side            | 55 and 75 Hz | 9.9 kΩ| 0.2 mW|
| 11 | Wang et al., 2015| Stack    | Line side            | 30 m/s       | 211 kΩ| 0.19 mW 4.82 V|
| 12 | Hou et al., 2020| Stack    | Line side            | 1.8 Hz 1.43 mm | 0.19 mW 0.25 mW/cm³|
| 13 | Tianchen et al., 2014| Circular drum| Line side         | 0.5 km/h     | 4 MΩ| 50–70 V 0.1 mW 50–70 V 0.1 mW|
| 14 | Fu et al., 2020| Bilateral fixed| On board             | 50 Hz        | 1 MΩ| 4 V 16 μW|
| 15 | De Pasquale et al., 2012a, 2012b| Cantilever| On board             | 5.71 Hz      | 4.12 μW|
| 16 | Song et al., 2013| Cantilever| On board             | 28 Hz        | 4.3 V|
| 17 | Cho et al., 2016| Cantilever| On board             | 3–6 Hz       | 200 kΩ| 40.24 μW/cm³|

aInput: Input data include frequency, amplitude, acceleration, and train speed.

bOutput: Output data include voltage, power, energy amount, and power density.
Since the vibration caused by the train does not exist all the time, the power generation of the energy harvester is intermittent. Efficient energy storage methods need to be introduced to store the electricity generated by VEHs. Supercapacitors have fast charging speed, high energy conversion efficiency, and low power transmission loss, hence supercapacitors can be a green and environmentally friendly power storage device for VEHs (Luta and Raji, 2019; Yang, 2019; Ibanez, 2017). In addition, flywheels have the advantages of high energy density, high energy conversion efficiency, small size, light weight, wide operating

Figure 23. Structure and characteristics of the four-type piezoelectric energy harvesting systems

Figure 24. Triboelectric mechanism-based VEH in railway system
(A) VEH-TE structure; (B) springs are utilized to build mass vibration; (C) nano structure on the Kapton surface; (D) prototype. (Reprinted [adapted] with permission from Zhao et al., 2017. Copyright [2017] Elsevier.)
(A) Three-dimensional drawing.
(B) Dynamical model.
(C) Material micrograph.
(D) Prototype.
temperature range, long service life, low power loss, and low maintenance (Arani et al., 2017; Rupp et al., 2016; Yulong et al., 2017), hence flywheels can also be a feasible strategy for storing electricity generated by VEHs, especially in cold, harsh environments.

Economy is an important factor in the popularization and application of products. Although VEH can bring economic benefits in terms of energy saving, it will incur additional material and manufacturing costs. Most previous studies only focused on the technical side of VEHs, ignoring economic performance. For piezoelectric and triboelectric VEH, the material cost is relatively high. For electromagnetic and hydraulic VEH, the device manufacturing cost is large owing to the relatively complex structure. Therefore, in future research, the technical and economic performances of train-induced VEHs should be considered comprehensively in order to obtain the optimal solution.

The amount of energy harvested on the time scale should be evaluated, not just considering the power output, voltage, and efficiency. A power supply system not only should have an output power matching the demand of the load but also needs to possess enough energy to power the load for a long time. It is easy to understand that the lesser the traffic on the line, the lesser the energy a single VEH can accumulate. On lines with low traffic volume, the electric energy accumulated by the VEH over time may not be able to support the long-term operation of the load. In order not to require too many VEHs, it is necessary to carry out real case studies to evaluate how much traffic is suitable for the deployment of VEHs.

The power output needs to be increased to meet the power needs of electrical facilities along the railway with greater power requirements, such as traffic lights and tunnel lighting equipment. Previous research has used methods such as frequency adjustment and mechanical vibration rectification to improve the energy output of VEHs. In addition, the vibration amplitude on both the vehicle side and the track side is between the micron level and the millimeter level. It is possible to further increase the power output by using a motion amplification mechanism to amplify the vibration amplitude. For piezoelectric VEHs, increasing the amplitude of the piezoelectric sheet can increase its output voltage. For electromagnetic VEHs, under scenarios with constant frequency, enlarging the displacement input of reciprocating motion can increase the rate of magnetic flux change (in linear VEH) and the rotation of the generator (in rotary VEH).

Table 3. Information regarding triboelectric and hydraulic train-induced vibration energy harvesters

| No | Reference         | Principle   | Installation position | Input (frequency, amplitude, acceleration, train speed) | Load | Simulation (voltage, power) | Lab testing (voltage, power) | Field testing (voltage, power) |
|----|-------------------|-------------|-----------------------|--------------------------------------------------------|------|----------------------------|-----------------------------|------------------------------|
| 1  | Geng et al., 2017 | Triboelectric | Line side            | 16.667 Hz, 100 m/s                                    | 100 MΩ | 60 V 2.45 μJ                |                             |                              |
| 2  | Nelson et al., 2011 | Hydraulic   | Line side            | 3.75 mm, 131 Ω                                        | 130 Ω | 11.078 W                   |                             |                              |
| 3  | Mi et al., 2017   | Hydraulic   | On board             | 180 km/h, 13.2 mm, 20.52 Hz                           | 20.52 Hz | Average: 3.5 kW             | Maximum: 5 kW               |                              |
| 4  | Zhao et al., 2017 | Triboelectric | Line side            | 1.07–1.25 m/s², 11 kΩ                                 | 1.5–3.1 V | 1.5–3.1 V                  |                             |                              |

Input: Input data include frequency, amplitude, acceleration, and train speed.

Output: Output data include voltage, power, energy amount, and power density.
CONCLUSIONS

The driving motivation behind this paper is to present the state of the art of vibration energy harvesting technology in the field of rail transit and its related research points, including rail vibration characteristics, energy harvesting potential, mechanism, and design. The principles, structures, and output performances of different types of vibration energy harvesters are introduced, compared, and discussed in detail.

Table 4. Parameters of the sensors used for railway environmental monitoring (Wu et al., 2021; Gao et al., 2018)

| No | Sensor name | Size             | Function                  | Power consumption | Manufacturer          |
|----|-------------|------------------|----------------------------|-------------------|-----------------------|
| 1  | KTC-50mm    | /                | Displacement sensor       | 120 mW            | MILONT                |
| 2  | MIK-P300    | /                | Pressure sensor           | 480 mW            | MEACON                |
| 3  | AB-SU309C   | /                | Signal light              | 400 mW            | STARS PLASTIC         |
| 4  | VL53L0      | /                | Distance measuring sensor | 20 mW             | TELESKY               |
| 5  | VS100.A     | 8.9mm*8.9mm*3.24mm | Accelerometer             | 9.9 mW            | Colibrys              |
| 6  | TS1000T     | 8.9mm*8.9mm*3.24mm | Inclinometer              | 9.9 mW            | Colibrys              |
| 7  | Z4D-C01     | 35.5mm*16mm*15mm | Displacement sensor       | 70 mW             | Omron                 |
| 8  | VY1         | 13.5mm*13.5mm    | Strain measuring          | 200 mW            | HBM                   |
| 9  | RDS20       | 28mm*25mm        | Crack propagation measuring | 200 mW           | HBM                   |
| 10 | CFT/120     | φ5.4mm*60mm      | Force measuring           | /                 | HBM                   |
| 11 | TT-3/100    | 6.6mm*4.7mm      | Temperature measuring     | /                 | HBM                   |
| 12 | P15RVA1     | φ0mm*72mm        | Pressure measuring        | 720 mW            | HBM                   |
| 13 | ADXL345     | 3mm*5mm*1mm      | Accelerometer             | 350 µW            | Analog Devices        |
| 14 | HC-SR04     | 45mm*20mm*15mm   | Ultrasonic telemeter      | 65 mW             | Jieshen               |
| 15 | HC-SR501    | 32mm*24mm        | Infrared detector         | 235 mW            | /                     |
| 16 | DHT11       | 32mm*14mm        | Humidity/Temperature      | 12.5 mW           | Ylelectronic          |
Thereafter, based on the shortcomings of existing technologies, we point out challenges and difficulties in successfully implementing train-induced vibration energy harvesting, as well as corresponding future work. Train-induced VEH mainly includes four categories: electromagnetic type, piezoelectric type, triboelectric type, and hydraulic type. Electromagnetic and piezoelectric harvesters are currently the two most popular technologies used in rail transportation. Through our survey on the existing literature, we have summarized the key characteristics of different types of vibration energy harvesters as follows: (1) electromagnetic type has large power output, reaching up to 196.5 W, high energy conversion efficiency, and complex structure; (2) piezoelectric type has simple structure, sensitive vibration response, and low power output, from 4.12 mW to 10 mW; (3) triboelectric type has high output voltage and low energy yield; (4) hydraulic type has high output power, complex structure, and strict sealing requirements.

In addition, the power supply and demand matching between the energy supply side and the energy consumption side is critical for practical applications of train-induced VEH. The power demand of monitoring sensors mounted on track side and vehicle side has large variation, from 235 μW to 72 mW. Comprehensively considering power output, system structure, and embeddedness, electromagnetic harvesters are more promising for powering monitoring sensors with milliWatt-level to watt-level power. Owing to their simple structure and easy embedding, piezoelectric harvesters are a promising solution for powering sensors with microwatt-level power.

| Table 5. Comparison between studied and to-be-studied concerns on train-induced VEH |
|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| **Concerns studied** | **Explanation** | **Concerns to be studied** | **Explanation** |
| Efficiency | Energy conversion efficiency of vibration mechanical energy into electrical energy. The existing literature focuses on how to improve the energy conversion efficiency | Stability | Rectify irregular electricity produced by the VEH into regular current, which can be used by the electrical devices |
| Output power/voltage | The power/voltage output of the energy harvester. Many researchers have paid much attention to obtain high output power and voltage | Durability | Train-induced vibration does not always exist. How to ensure that the vibration energy harvester supplies power to the load for a long time? |
| Mechanical vibration rectifier (MVR) | Transform vibration into a form of motion that is conducive to the generation of electrical energy, such as linear movement and rotation. Various MVRs have been designed, manufactured, and verified | Economy | Good economy is a crucial factor for the implementation and popularization of the energy harvester. Future work should pay much attention to the economic aspects of energy harvesters, such as life cycle cost, net profit, and return on investment |
| Self-power | Many studies have focused on embedding vibration energy harvesters into electronic devices (such as sensors) to achieve their self-powered functions | Amount of energy generated | In addition to the output power, it is also important to study how much electricity the energy harvester can generate |
| Bidirectional vibration to unidirectional rotation | In order to improve energy output, the mechanism of bidirectional vibration to unidirectional rotation has been studied a lot in electromagnetic vibration energy harvester | Motion amplification mechanism | Conceive a mechanism that can amplify the vibration amplitude of the rail to obtain greater energy output |
Although many studies have successfully proved that train-induced VEHs have good output performance, there are still some challenges and ignored concerns for real application: (1) stability: how to convert harvested vibration energy into stable electricity that can supply power to the load; (2) durability: how to provide long-term continuous power to the loads; (3) economy: analyze the costs and benefits brought by the energy harvester; (4) amount of energy: pay attention to the energy amount acquired by the VEH, not only the output power; (5) motion amplification mechanism: before converting vibration energy into electrical energy, consider using mechanisms to amplify the amplitude of vibration to increase energy output. The above five difficulties that have not been solved or even focused on in the current literature should arouse great attention in future train-induced VEH studies.

ACKNOWLEDGMENTS
This work was supported by the National Natural Foundation of China under Grant Nos. 51975490 and 5177424; the Science and Technology Projects of Sichuan under Grant Nos. 2021JDRC0118 and 2021JDRC0096; and the Sichuan Science and Technology Program under Grant No. 2020JDTD0027; Z.Z. and J.Y. are co-corresponding authors.

AUTHOR CONTRIBUTIONS
L.Q.: Data curation, writing-original draft preparation; H.P.: methodology and analysis; Y.P.: reviewing and editing; D.L.: reviewing and editing; J.Y.: supervision, reviewing and editing; Z.Z.: supervision, reviewing and editing.

DECLARATION OF INTERESTS
The authors declare no competing interests.

REFERENCES
Abdelkareem, M.A., Xu, L., Ali, M.K.A., Elagouz, A., Mi, J., Guo, S., and Zuo, L. (2018). Vibration energy harvesting in automotive suspension system: a detailed review. Appl. Energy 229, 672–699. https://doi.org/10.1016/j.apenergy.2018.08.030.

Abramovich, H., Harash, E., Milgrom, C., Amit, U., and Azulay, L.E. (2010). U.S. Patent No. 7,830,071 (U.S. Patent and Trademark Office). https://patents.google.com/patent/US7830071B2/en.

Ahn, D., and Choi, K. (2018). Performance evaluation of thermoelectric energy harvesting system on operating rolling stock. Micromachines 9, 359. https://doi.org/10.3390/mi9070359.

Figure 27. Applications of VEHs with different mechanisms

**Applications**

- **Electromagnetic**
  - Temperature sensors
  - Pressure sensors
  - Force sensors
  - Accelerometers
  - IoT sensors

- **Piezoelectric**
  - Heating devices
  - Heating tracks for snow removal at turnouts

- **Triboelectric**
  - Auxiliary load
  - Traffic light
  - Speed measuring radar
  - Ventilation
  - Traffic lift gate

- **Hydraulic**

**Figure 27. Applications of VEHs with different mechanisms**

Although many studies have successfully proved that train-induced VEHs have good output performance, there are still some challenges and ignored concerns for real application: (1) stability: how to convert harvested vibration energy into stable electricity that can supply power to the load; (2) durability: how to provide long-term continuous power to the loads; (3) economy: analyze the costs and benefits brought by the energy harvester; (4) amount of energy: pay attention to the energy amount acquired by the VEH, not only the output power; (5) motion amplification mechanism: before converting vibration energy into electrical energy, consider using mechanisms to amplify the amplitude of vibration to increase energy output. The above five difficulties that have not been solved or even focused on in the current literature should arouse great attention in future train-induced VEH studies.

ACKNOWLEDGMENTS
This work was supported by the National Natural Foundation of China under Grant Nos. 51975490 and 5177424; the Science and Technology Projects of Sichuan under Grant Nos. 2021JDRC0118 and 2021JDRC0096; and the Sichuan Science and Technology Program under Grant No. 2020JDTD0027; Z.Z. and J.Y. are co-corresponding authors.

AUTHOR CONTRIBUTIONS
L.Q.: Data curation, writing-original draft preparation; H.P.: methodology and analysis; Y.P.: reviewing and editing; D.L.: reviewing and editing; J.Y.: supervision, reviewing and editing; Z.Z.: supervision, reviewing and editing.

DECLARATION OF INTERESTS
The authors declare no competing interests.

REFERENCES
Abdelkareem, M.A., Xu, L., Ali, M.K.A., Elagouz, A., Mi, J., Guo, S., and Zuo, L. (2018). Vibration energy harvesting in automotive suspension system: a detailed review. Appl. Energy 229, 672–699. https://doi.org/10.1016/j.apenergy.2018.08.030.

Abramovich, H., Harash, E., Milgrom, C., Amit, U., and Azulay, L.E. (2010). U.S. Patent No. 7,830,071 (U.S. Patent and Trademark Office). https://patents.google.com/patent/US7830071B2/en.

Ahn, D., and Choi, K. (2018). Performance evaluation of thermoelectric energy harvesting system on operating rolling stock. Micromachines 9, 359. https://doi.org/10.3390/mi9070359.
González-Gil, A., Palacin, R., and Battye, P. (2013). Sustainable urban rail systems: strategies and technologies for optimal management of regenerative braking energy. Energy Convers. Manag. 75, 374–388. https://doi.org/10.1016/j.enconman.2013.06.039.

González-Gil, A., Palacin, R., Battye, P., and Powell, J.P. (2014). A systems approach to reduce urban rail energy consumption. Energy Convers. Manag. 80, 509–524. https://doi.org/10.1016/j.enconman.2014.01.060.

Gruden, M., Westman, A., Platbardsj, J., Hallbjörner, P., and Rydberg, A. (2009). Reliability experiments for wireless sensor networks in train environment. In 2009 European Wireless Technology Conference (IEEE), pp. 37–40. http://signsver-teknikum uu.se/Pubs/Pdf/cf0916.pdf.

Guo, Z., Liu, T., Xu, K., Wang, J., Li, W., and Chen, Z. (2020). Parametric analysis and optimization of a simple wind turbine in high speed railway tunnels. Renew. Energy 161, 825–835. https://doi.org/10.1016/j.renene.2020.07.099.

Hadas, Z., Smilie, J., and Rubes, O. (2018). Energy harvesting from passing train as source of energy for autonomous trackside objects. In MATEC Web of Conferences, 211MATEC Web of Conferences (EDP Sciences), p. 05003. https://doi.org/10.1051/matecconf/201821105003.

He, W., Shi, W., Le, J., Li, H., and Ma, R. (2020). Geophone-based energy harvesting approach for railway wagon monitoring sensor with high reliability and simple structure. IEEE Access 8, 35882–35891. https://doi.org/10.1109/ACCESS.2020.2968089.

Hou, W., Li, Y., Guo, W., Li, J., Chen, Y., and Duan, X. (2018). Railway vehicle induced vibration energy harvesting and saving of rail transit segment prefabricated and assembling bridges. J. Clean. Prod. 182, 946–959. https://doi.org/10.1016/j.jclepro.2018.02.019.

Hou, W., Li, Y., Zheng, Y., and Guo, W. (2020). Multi-frequency energy harvesting method for vehicle induced vibration of rail transit continuous rigid bridges. J. Clean. Prod. 254, 119981. https://doi.org/10.1016/j.jclepro.2020.119981.

Hou, W., Zheng, Y., Guo, W., and Pengcheng, G. (2020). Piezoelectric vibration energy harvesting for rail transit bridge with steel-spring floating slab track system. J. Clean. Prod. 291, 125283. https://doi.org/10.1016/j.jclepro.2020.125283.

Ibanez, F.M. (2017). Analyzing the need for a balancing system in supercapacitor energy storage systems. IEEE Trans. Power Electron. 33, 2162–2171. https://doi.org/10.1109/TPEL.2017.2697406.

Jiang, Y., Liu, J., Tian, W., Shahidehpour, M., and Krishnamurthy, M. (2014). Energy harvesting for the electrification of railway stations: getting a charge from the regenerative braking of trains. A. IEEE Electrification Mag. 2, 29–48. https://doi.org/10.1109/MELE.2014.2335361.

Jin, L., Deng, W., Su, Y., Xu, Z., Meng, H., Wang, B., and Yang, W. (2017). Self-powered wireless smart sensor based on maglev porous nanogenerator for train monitoring system. Nano Energy 38, 185–192. https://doi.org/10.1016/j.nanoen.2017.05.018.

Ju, S.H., Lin, H.T., and Huang, Y.J. (2009). Dominant frequencies of train-induced vibrations. J. Sound Vib. 319, 247–259. https://doi.org/10.1016/j.jsv.2008.05.029.

Kalagai, M., and Seetharamduo, D. (2019). Electromagnetic energy harvesting systems in the railway environment: state of the art and proposal of a novel metamaterial energy harvester. In 2019 13th European Conference on Antennas and Propagation (EuCAP) (IEEE), pp. 1–5. https://ieeexplore.ieee.org/abstract/document/8739912.

Kaleybar, H.J., Koobadji, H.M., Brenna, M., Foadelli, F., and Zaninelli, D. (2017). An intelligent strategy for regenerative braking energy harvesting in AC railway electrical substation. In 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS) (IEEE), pp. 391–396. https://doi.org/10.1109/MT-ITS.2017.8005703.

Kang, C., Schneider, S., Wenner, M., and Marx, S. (2018). Development of design and construction of high-speed railway bridges in Germany. Eng. structures 163, 184–196. https://doi.org/10.1016/j.engstruct.2018.02.059.

Kaufman, W.M. (2002). U.S. Patent No 6,362,534 (U.S. Patent and Trademark Office). https://patents.google.com/patent/US6362534B1/en.

Kim, B.S., Kim, K.I., Shah, B., Chow, F., and Kim, K.H. (2019). Wireless sensor networks for big data sensors. Sensors 19, 1565. https://doi.org/10.3390/s19071565.

Kim, J. (2020). A study on the optimal design and the performance evaluation of electromagnetic energy harvesting device for the rolling stock application. J. Intell. Mater. Syst. Struct. 31, 2362–2377. https://doi.org/10.1177/1045389X20948599.

Kiriev, A.V., Kozhemyaka, N.M., Burdugov, A.S., and Klimov, A.V. (2017). Test bench trials of the electromagnetic regenerative shock absorber. Int. J. Appl. Eng. Res. 12, 6354–6359. https://www.ripublish.com/iaer/iaer12/17_05.pdf.

Kralov, I., Terzieva, S., and Ignatov, I. (2011). Analysis of methods and MEMS for acoustic energy harvesting with application in railway noise reduction. Rom. Rev. Precision Mech. Opt. Mechatron. 123–128. https://www.indrmt.ro/editura/documente/pag%20123%20-128%20Analysis%20of%20methods%20and%20MEMS%20%20for%20Acoustic%20Energy%20Harvesting%20with%20Application%20%20on%20Railway%20Noise%20Reduction.pdf.

Kumar, K.R., Morab, S., Shekar, S., and Mahalingam, A. (2016). January. Energy harvesting from vortex induced vibrations using vented cylinders mounted on light rail locomotive. In 2016 7th International Conference on Intelligent Systems, Modelling and Simulation (ISMS) (IEEE), pp. 268–275. https://doi.org/10.1109/ISMS.2016.33.

Lan, C., and Qin, W. (2017). Enhancing ability of electromechanical regenerative shock absorber. In 2017 13th European Conference on Antennas and Propagation (EuCAP) (IEEE). pp. 1–1. https://ieeexplore.ieee.org/abstract/document/8739912.

Ma, L., Liu, Y., Liu, W., and Wei, Y. (2020). Governing factors of the dynamic performance of axial wind turbine blades. Int. J. Mech. Machines. 14, 93285904627. https://doi.org/10.21595/jve.2016.16938.

Matsuda, T. (2019). Development of design and construction of high-speed railway bridges in Germany. Eng. structures 163, 184–196. https://doi.org/10.1016/j.engstruct.2018.02.059.

Matsukawa, K., Nishihara, K., and Nishihara, K. (2018). Development of design and construction of high-speed railway bridges in Germany. Eng. structures 163, 184–196. https://doi.org/10.1016/j.engstruct.2018.02.059.

Matsukawa, K., Nishihara, K., and Nishihara, K. (2018). Development of design and construction of high-speed railway bridges in Germany. Eng. structures 163, 184–196. https://doi.org/10.1016/j.engstruct.2018.02.059.

McManus, P., Ghandchi Tehrani, M., Gatti, G., Brennan, M.J., and Thompson, D.J. (2013). Energy Harvesting from Train Vibrations. In eprints soton.ac.uk/358025/.

Meng, Y., Wang, P., and Liu, W. (2018). Condition monitoring of urban rail transit by local energy harvesting. Int. J. Distributed Sens. Netw. 14, 1550147718814469 https://doi.org/10.1155/ijdsn.2018.14699.

Meng, Y., Wang, P., Liu, W., and Liu, W. (2018). Condition monitoring of urban rail transit by local energy harvesting. Int. J. Distributed Sens. Netw. 14, 1550147718814469 https://doi.org/10.1155/ijdsn.2018.14699.

Müller, J.W., and Schmid, A. (2019). Evaluating the potential of piezoelectric energy harvesting for bridge monitoring. In 2019 19th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS) (IEEE), pp. 1–3. https://doi.org/10.1109/powmems49317.2019.9328904672.

Nasir, M., and Iqbal, M. (2020). Energy harvesting with application in railway environment. In 2020 Noise Reduction.pdf.
Shi, H., Yue, Y., Wang, H., Xu, J., and Mei, X. (2020). Design and performance analysis of human walking induced energy recovery system by means of hydraulic energy conversion and storage. Energy Convers. Manag. 217, 113008. https://doi.org/10.1016/j.enconman.2020.113008.

Sindhuja, B. (2014). A proposal for implementation of wind energy harvesting system in trains. In Proceedings of the 2014 International Conference on Control, Instrumentation, Energy and Communication (CIEC) (IEEE), pp. 1945-1979. https://doi.org/10.1109/CIEC.2014.6991980.

Song, D., Jang, H., Kim, S.B., and Sung, T.H. (2013). Piezoelectric energy harvesting system for the vertical vibration of superconducting Maglev train. J. Electromech. 31, 35–41. https://doi.org/10.1007/s10832-013-9817-9.

Song, Y. (2019). Finite-element implementation of piezoelectric energy harvesting system from vibrations of railway bridge. J. Energy Eng. 145, 04018076. https://doi.org/10.1061/(asce)je.1943-7897.0000595.

Sun, Y., Chen, J., Li, X., Lu, Y., Zhang, S., and Cheng, Z. (2019). Flexible piezoelectric energy harvester/sensor with high voltage output over wide temperature range. Nano Energy 61, 337–345. https://doi.org/10.1016/j.nanoen.2019.04.055.

Tianchen, Y., Jian, Y., Ruigang, S., and Xiaowei, L. (2014). Vibration energy harvesting system for railway safety based on running vehicles. Smart Mater. Struct. 23, 125045. https://doi.org/10.1088/0964-1726/23/12/125046.

Todaria, P. (2016). Design, Modelling, and Test of an Electromagnetic Speed Bump Energy Harvester (Doctoral Dissertation, Virginia Tech). http://hdl.handle.net/10919/37395.

Tripaichajonsak, N., Thompson, D.J., Jones, C.J.C., Ryue, J., and Priest, J.A. (2011). Ground vibration from trains: experimental parameter characterization and validation of a numerical model. Proc. Inst. Mech. Eng. F: Rail Rapid Trans. 225, 140–153. https://doi.org/10.1177/0954409712431730.

Wang, J., Shi, Z., Xiang, H., and Song, G. (2015). Modeling on energy harvesting from a railway system using piezoelectric transducers. Smart Mater. Struct. 24, 105017. https://doi.org/10.1088/0964-1726/24/10/105017.

Wang, L., Luo, G., Jiang, Z., Zhang, F., Zhao, L., Yang, P., and Maeda, R. (2019a). Broadband vibration energy harvesting for wireless sensor node power supply in train container. Rev. Scientific Instrum. 90, 125003. https://doi.org/10.1063/1.5127243.

Wang, L., Todaria, P., Pandey, A., O’Connor, J., Chernow, B., and Zuo, L. (2016). An electromagnetic speed bump energy harvester and its interactions with vehicles. IEEE ASME Trans. Mechatron. 21, 1985–1994. https://doi.org/10.1109/TMECH.2016.2546179.

Wang, P., Wang, Y.F., Gao, M.Y., and Wang, Y. (2017a). Energy harvesting of track-borne transducers by train-induced wind. J. Vibroengineering 21, 384–395. https://doi.org/10.21595/jve.2017.17952.

Wang, P., Yang, F., Gao, M., and Wang, Y. (2017b). Study on an elastic lever system for electromagnetic energy harvesting from rail vibration. J. Vibroengineering 21, 838–912. https://doi.org/10.21595/jve.2018.19715.

Wang, W., Huang, R.J., Huang, C.J., and Li, L.F. (2014). Energy harvester array using piezoelectric circular diaphragm for rail vibration. Acta mechanica sinica 30, 884–888. https://doi.org/10.1007/s10409-014-0115-9.

Wang, Y., Zhu, X., Zhang, T., Bano, S., Pan, H., Qi, L., and Yuan, Y. (2018a). A renewable low-frequency acoustic energy harvesting noise barrier for high-speed railways using a helmholtz resonator and a PVDF film. Appl. Energy 230, 52–61. https://doi.org/10.1016/j.apenergy.2018.06.080.

Wang, Z.L., Jiang, T., and Xu, L. (2017b). Toward the blue energy dream by triboelectric nanogenerator networks. Nano Energy 39, 9–23. https://doi.org/10.1016/j.nanoen.2017.06.035.

Wischke, M., Biancuzzi, G., Fernehabach, G., Abbass, Y., and Woaiss, P. (2010). Vibration harvesting in railway tunnels. Proc. Power Mems. 123–126. https://www.researchgate.net/profile/Yawar-Abbass-5/publication/267506929/VIBRATION_HARVESTING_IN_RAILWAY_TUNNELS/links/557a70cb32eb6e039f4693/VIBRATION-HARVESTING-IN-RAILWAY-TUNNELS.pdf?_chl=managed_tk__a=BA9hPS0f0xk6f059rJag5fSJs769K0TPA0MQahHyEGc1642942808-0-gaNvCzGzDNBo.

Wu, C., Wang, A.C., Ding, W., Guo, H., and Wang, Z.L. (2019). Triboelectric nanogenerator: a foundation of the energy for the new era. Adv. Energy Mater. 9, 1802906. https://doi.org/10.1002/aenm.201802906.

Wu, X., Qi, L., Zhang, T., Zhang, Z., Yuan, Y., and Li, Y. (2021). A novel kinetic energy harvester using vibration rectification mechanism for self-powered applications in railway. Energy Convers. Manag. 228, 113720. https://doi.org/10.1016/j.enconman.2020.113720.
Yang, F.Y., Gao, M., Wang, P., Zuo, J., Dai, J., and Cong, J. (2021). Efficient piezoelectric harvester for random broadband vibration of rail. Energy 218, 119559. https://doi.org/10.1016/j.energy.2020.119559.

Yang, H. (2019). A Supercapacitor-Based Energy Storage System for Roadway Energy Harvesting Applications (Mineta Transportation Institute), –Report, 19-03. https://transweb.sjsu.edu/sites/default/files/1866-Yang-Supercapacitor-based-Energy-Storage-Roads.pdf.

Yüksel, K., Kinet, D., Moeyaert, V., Kouroussis, G., and Caucheteur, C. (2018). Railway monitoring system using optical fiber grating accelerometers. SMART Mater. Struct. 27, 105033. https://doi.org/10.1088/1361-665X/aadb62.

Yulong, P., Cavagnino, A., Vaschetto, S., Feng, C., and Tenconi, A. (2017). June. Flywheel energy storage systems for power systems application. In 2017 6th International Conference on Clean Electrical Power (ICCEP) (IEEE), pp. 492–501. https://doi.org/10.1109/ICCEP.2017.8004733.

Zhai, W., Liu, P., Lin, J., and Wang, K. (2015). Experimental investigation on vibration behaviour of a CRH train at speed of 350 km/h. Int. J. Rail Transportation 3, 1–16. https://doi.org/10.1080/23248378.2014.992619.

Zhang, X., Pan, H., Qi, L., Zhang, Z., Yuan, Y., and Liu, Y. (2017). A renewable energy harvesting system using a mechanical vibration rectifier (MVR) for railroads. Appl. Energy 204, 1535–1543. https://doi.org/10.1016/j.apenergy.2017.04.064.

Zhao, X., Wei, G., Li, X., Qin, Y., Xu, D., Tang, W., and Jia, L. (2017). Self-powered triboelectric nano vibration accelerometer based wireless sensor system for railway state health monitoring. Nano Energy 34, 549–555. https://doi.org/10.1016/j.nanoen.2016.04.012.

Zuo, L., Wang, J., and Lin, T. (2014). Energy Harvesting from Rail Track for Transportation Safety and Monitoring (No. 49111-31-21) (University Transportation Research Center). https://rosap.ntl.bts.gov/view/dot/27121.