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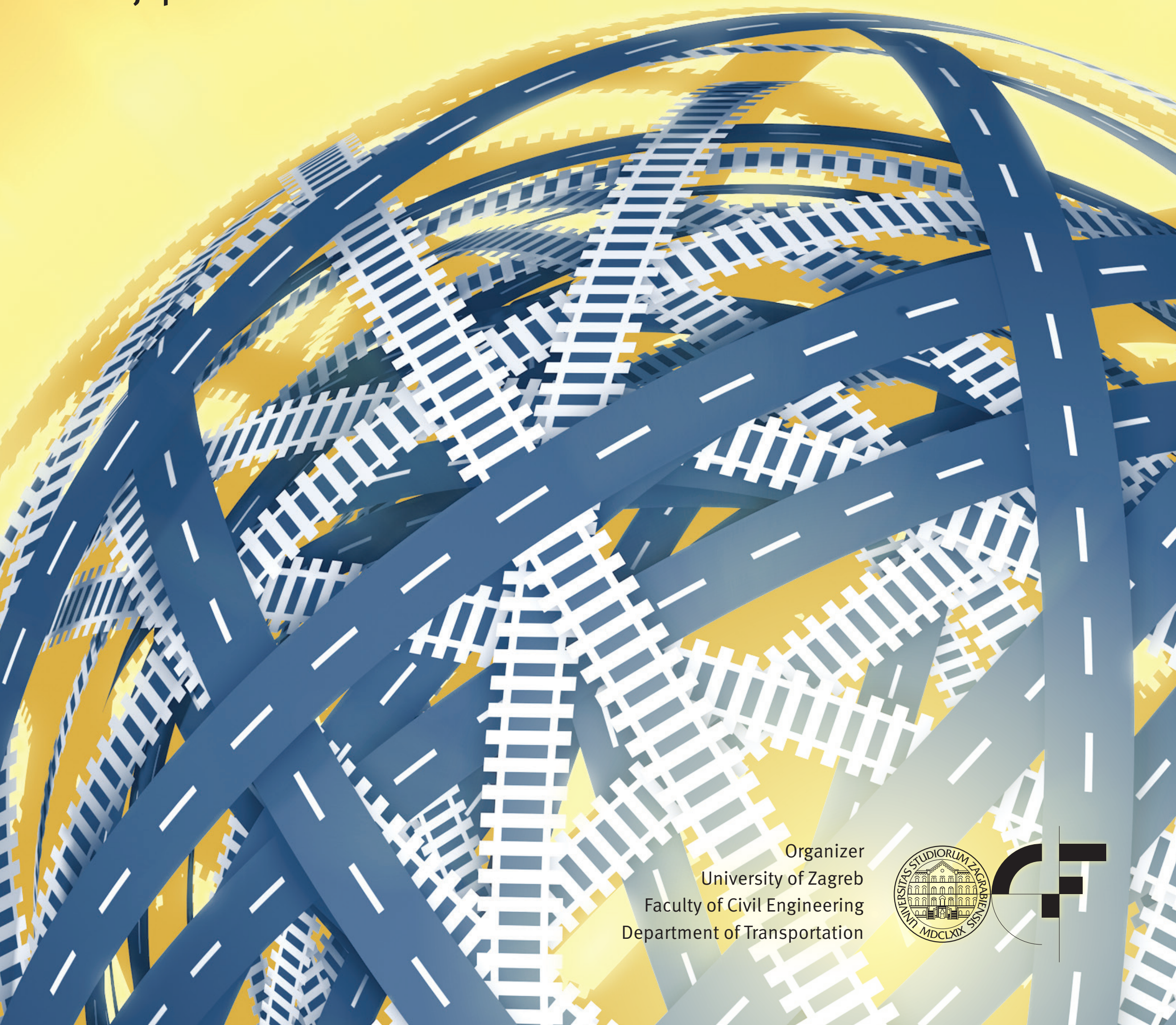
23–25 May 2016, Šibenik, Croatia

Road and Rail Infrastructure IV

Stjepan Lakušić – EDITOR



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ENERGY HARVESTING ON TRANSPORT INFRASTRUCTURES: THE SPECIFIC CASE OF RAILWAYS

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Abstract

With the growing need for alternative energy sources, research into energy harvesting technologies has increased considerably in recent years. The particular case of energy harvesting on railways is a very recent area of research. Railways are continuously exposed to train loads, making it possible to extract energy from them which, using specific technologies, can be transformed into electrical energy. This paper deals with the development of energy harvesting technologies for railways, identifies the technologies that are being studied and developed, examines how such technologies can be divided into different classes and gives a technical analysis and comparison of those technologies, using the results achieved with prototypes.

Keywords: Energy harvesting, renewable energy, energy conversion, railways

1 Introduction

With the present energy paradigm, most electrical energy production uses fossil fuels as its energy source, leading to irreversible environmental damage, as well as making economies dependent on fuel costs. According to the International Energy Agency [1], in 2011, globally, more than 80% of energy production came from fossil fuels. In terms of renewable energy, hydro power plants represent the most significant energy source.

Urgent action is required to change the paradigm of electric energy generation. Presently, energy is mostly produced in large power plants, consuming non-renewable resources and inducing energy losses between the point of production and the point of final consumption. Energy production must be based on renewable resources, decentralized, produced near to the point of consumption and, preferably, when it is needed.

In the area of renewable energies, besides the major energy sources (hydro, solar, wind, waves), energy harvesting has recently been considered on a micro scale, where it is possible to generate electricity from small energy variations, such as thermal gradients, pressure, vibrations, radiofrequency or electromagnetic radiation, among others [2].

Railways are continuously exposed to train loads, making it possible to extract energy from them which, using specific technologies, can be transformed into electrical energy. This is a very recent research area, denominated railway energy harvesting.

Besides other alternative energy generation methods which do not consume the planet's resources, this is also practical in terms of energy efficiency, as it can work as a solution to generate electrical energy where and when it is needed, avoiding expensive electrification of specific sites, distribution inefficiencies, and storage costs.

The present research work aims to study energy harvesting technologies with possible implementation on railways, using the energy released by trains as an energy source.

2 Railway energy harvesting technologies

Energy Harvesting is described as a concept by which energy is captured, converted, stored, and utilized using various sources, by employing interfaces, storage devices, and other units [2, 3]. Put simply, energy harvesting is the conversion of ambient energy present in the environment into electrical energy [4].

Energy harvesting is divided in two main groups: macro energy harvesting and micro energy harvesting. Macro energy harvesting sources are associated with solar, wind, hydro and ocean energy, while micro energy harvesting sources are associated with electromagnetic, electrostatic, heat, thermal variations, mechanical vibrations, acoustics and human body motion [2, 5]. The main difference between these two groups is the scale. Macro energy harvesting sources are related to the harvest of great amounts of energy in a single unit, while micro energy harvesting is concerned with smaller power generation units, typically dimensioned to supply specific electric and electronic applications [4].

The discontinuous nature of energy harvesting sources has consequences in the way the electric devices powered by energy harvesting are operated. Two situations are common [6]: the power consumption of the device is lower than the average harvested power, which allows the device to be operated continuously; or the power consumption of the device is higher than the average harvested power, meaning there is discontinuous operation, with the time between operations being dependent on the stored energy of the device.

In the case of railways, the concept of energy harvesting started with the goal of directly supplying the trackside electrical infrastructures for safety and monitoring purposes. These consist of electric and electronic equipment such as sensors, cameras, electric panels, among others. These devices typically have a power consumption of 10-100 W [7], so this was set as the energy generation goal for several research projects [7, 8, 9].

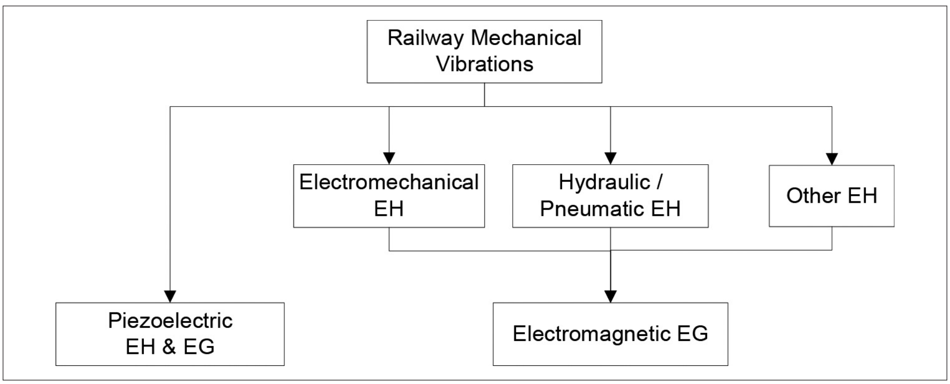

Figure 1 Railway energy harvesting and generation technologies

Different systems were developed for this purpose, both for harvesting the mechanical vibrations induced by trains into the railways, as well as converting these into electricity. Energy conversion (or energy generation) technologies are mostly electromagnetic and piezoelectric but, in the case of electromagnetic technology, the systems to actuate the energy generation components can be electromechanical, hydraulic, pneumatic, or other specific systems. The electromagnetic generators can be linear or rotational. Figure 1 presents the segmentation of the developed systems, with EH representing Energy Harvesting and EG representing Energy Generation.

3 Technical analysis

3.1 Definitions

To perform a technical analysis and evaluate an energy generation technology, the most commonly used parameters are the conversion efficiency and the energy generation of the technology under its normal operation (Table 1). As these are mostly new technologies, it is important to classify them according to their development status. Also, as the installation method can vary between different systems, this is an important issue regarding the final cost of the solution as well as the maintenance operations of the equipment. Therefore the technologies should also be classified according to their installation method.

Table 1 Parameters for performing a technical analysis

Parameter	Description
Conversion Efficiency	Energy conversion efficiency (η) is the ratio between the useful output of an energy conversion device and the energy input. In the case of electrical machines, the output is electrical energy measured in Joules (J), or electrical power measured in watts (W). The energy conversion efficiency is a dimensionless parameter, usually expressed as a percentage.
Energy Generation	Energy generation is used to quantify the amount of electrical energy generated under the operating conditions. It gives the energy input of the system, its efficiency, and the installed power. Usually it is expressed in Joules, but in some micro energy harvesting devices, it can also be related to the volume (J/m^3). In the analysis of energy harvesting devices, sometimes power generation is also presented, related to the volume of the device (W/m^3).
Installation Method (IM)	The different energy harvesting devices can be installed on the railways using different techniques, and in different zones of the railway. Four main installation methods were identified.
Technology readiness level (TRL)	Technology readiness levels (TRLs) are measures used to evaluate the maturity of a technology during its developmental stages. These levels were initially defined by NASA [10], but are now commonly used in project evaluations.

3.2 Comparison of technologies

Following the analysis of the different technologies presented in this paper, the main characteristics of each one are presented in Table 2. For this analysis, only technologies with results published in scientific papers were considered. From Table 2, it may be seen that most of the studies does not quantify the conversion efficiency of the technologies, but almost all reveal the power/energy generation, the installation method and identify the TRL. From this analysis, one can conclude that most current research is based on electromechanical systems, and these are the ones that permit higher values in terms of electrical energy production.
The system developed by Lin et al. [7], which results from an optimization of two previous studies [11, 12] , presents the highest value in terms of energy generation, proved experimentally, and is the more advanced in terms of technology readiness level. Piezoelectric technology, besides being on an advanced TRL, presents very low energy production values, making it a technology with low economic viability for generating electrical energy. Hydraulic systems, especially the system developed by Pourghodrat [8], present an interesting potential, as with one unit a good value was achieved in terms of energy production (the second highest, proved experimentally), which can be multiplied with the use of more hydraulic units connected to the same electromagnetic generator.

Table 2 Technical analysis of different railway energy harvesting technologies

Technology	Ref.	Conversion Efficiency	Power/ Energy Generation	Installation Method (IM)[1]	TRL[2]
Piezoelectric	[17]	N.A.	0.05 mW	1	5
	[16]	N.A.	N.A.	2	3
	[18]	N.A.	0.26 mJ	2	5
Hydraulic	[19]	N.A.	N.A.	3	2
	[8]	N.A.	11.08 W	1	4
Electro-mechanical	[11]	N.A.	10.05 W	1	4
	[12]	22.0%	2.50 W	1	4
	[8]	N.A.	4.24 W	1	4
	[8]	N.A.	50.00 W (T)	3	2
	[9]	N.A.	5.29 W	1	4
	[7]	45.6%	49.8 W	1	5
Other	[17]	N.A.	0.15 W	1	3
	[13, 14]	N.A.	N.A.	3	N.A.

1 – IM 1 – Fixed on the railway lateral area, harvesting the railway vibrations;
IM 2 – On the railway basis, between the railway and the sleeper;
IM 3 – On the railway track, harvesting the train's wheel mechanical pressure.
2 – TRL 1 – Basic principles observed and reported;
TRL 2 – Technology concept and/or application formulated;
TRL 3 – Analytical and experimental critical function and/or characteristic proof-of-concept;
TRL 4 – Component validation in laboratory environment;
TRL 5 – Component validation in relevant environment;
TRL 6 – System/subsystem model or prototype demonstration in a relevant environment;
TRL 7 – System prototype demonstration in an operational environment;
TRL 8 – Actual system completed and qualified through tests and demonstration;
TRL 9 – Actual system proven in operational environment.

In terms of installation, most of these technologies are fixed on the railway lateral area, harvesting the mechanical vibrations of the railway. The exceptions are the piezoelectric systems, installed between the railway and the sleepers, and some other systems that use the train's wheels pressure to be actuated, harvesting the mechanical energy directly from the train's weight.

In terms of TRL, the Mian's system [13, 14] is already available on the market by the International Electronic Machines Corporation [15], but no values regarding energy production or conversion efficiency were published. Besides this system/product, Innowattech [16] also presents some piezoelectric solutions in their portfolio, without presenting energy generation or energy conversion efficiency of the systems. Apart from these two systems, which are related to their company's R&D, the electromechanical system presented by Lin et al. [7] is the one which is at the most advanced stage, as it has been tested and validated in real environment. Most of the other solutions analysed were only tested in laboratory.

4 Conclusions

The concept of railway energy harvesting is a very recent area of research, which has only taken off in the last five years. Unlike wind energy, the present situation shows a wide variety of energy harvesting systems at several stages of development, competing against each other to get an opportunity in the market. Different technologies are being investigated in order to convert mechanical energy induced by trains onto the railways into electrical energy. Piezoelectric and electromagnetic technologies are dominant, with electromagnetic generators being actuated by different harvesting systems.

In terms of systems/technologies validated in real environment, with published results, only one system is available. This system was developed by Lin et al. [7] and achieved a power production of 49.80 W for each train passage. Multiplying the number of devices, higher values of energy production can be achieved for each train passage. However, the investment in the solution would be multiplied by the number of devices. In that sense, the hydraulic system proposed by Pourghodrat [8] could be a very interesting solution, as with one hydraulic energy harvester and one electromagnetic generator, a power production of 11.08 W was achieved in laboratory for a train passage; as this system allows us to multiply the hydraulic harvesters for the same electromagnetic generator, the harvested energy (and consequently, the electrical energy produced) can be multiplied without the need to multiply the number of generators. So, with a lower investment increase compared with the electromechanical system proposed by Lin et al. [7], the energy production can be greatly increased.
In terms of application, most researchers have targeted electric and electronic devices used to monitor the railway tracks and to guarantee the user's safety, with power consumptions of 10.00 to 100.00 W [20]. To supply these electric and electronic devices, the two systems mentioned previously could be interesting solutions. These are the most targeted solutions mainly due to the fact that on railway lines there are many areas with no electricity, which makes it a challenge to supply electric devices in those areas.
However, multiplying the number of energy harvesters and generators, higher values of energy production can be achieved, and the concept of railway energy harvesting can increase its potential by injecting the produced energy into the electrical national grid. This is also based on the considerable available power in a railway track if long distances are considered, allowing the extraction and generation of a great amount of energy. These two major applications should be considered when the technical and economic viability of the developed technologies are studied, considering the cost of each solution to analyse the return on the investment.

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