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# Laboratory and Field Evaluation of an Energy Harvesting Tie for Energy Generation on Railroad Tracks

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## Abstract

This study provides the design and performance evaluation of a novel energy harvesting tie for railroad applications. The design concepts will describe the working principle and successful implementation of a kinetic energy harvesting mechanism in a conventional railroad tie. The evaluation includes both laboratory and field testing of a prototype energy harvesting tie. The tie is of identical dimensions to a standard railroad tie and can harvest the kinetic energy of the track's downward movement under passing wheels, without resisting the upward (rebound) movement. Two energy harvesters, placed directly under each rail, are integrated into a composite tie. The small rail movement is converted into rotational motion to operate two generators using novel ball-screw, half-wave mechanical motion rectification (HMMR) mechanisms. To assess the practical effectiveness of the proposed energy harvesting tie, laboratory and field tests are performed on in collaboration with one of the Class I railroads in the U.S. The test results indicate that approximately 5 – 30 Watts of average power can be harvested for freight trains traveling at speeds ranging from 24 to 48 km/hr. Higher speeds are expected to result in larger harvested power.

**Keywords:** energy harvesting, half-wave mechanical motion rectification, railroad tie, field testing, tie, power generation.

## 1 Introduction

Trackside equipment—including various sensors, cameras, and communication devices—is increasingly being used to monitor and control trains as well as to monitor the condition of railway infrastructure [1, 2]. This is crucial for improving rail safety and operational efficiency. However, these electronic devices require electricity to function, which is not readily accessible in railways, especially in tunnels, mountains, and remote/rural areas with short supply of grid power [3, 4]. This has led to a growing need and interest in developing energy harvesting technologies that can power the trackside safety equipment [5-8]. In addition to providing power, energy harvesting solutions reduce the need for trackside wiring and the power infrastructure, improving safety, reliability, and cost-effectiveness.

Energy harvesting technology has been under investigation for more than 20 years [9]. The focus has been on converting energy from mechanical movement, shock and vibration, or heat into electrical energy, to power electronic devices [10, 11]. To fulfill the need for usable electricity for trackside applications, solar energy harvesting systems have been invented and used to supply power with a nominal power rating of up to 150 W/m$^2$ [2, 12]. Wind turbine systems that can harvest energy from the train aerodynamics, environmental wind, or a combination of both have also been considered as sources of power for various railroad applications [2, 13]. Another energy harvesting solution proposed in a recent study [14] is converting the thermal gradient between the rail and ground into usable electrical power. These technologies, however, are highly dependent on geographic and weather conditions.

As an alternative, the concept of harvesting energy from naturally occurring track movements under the passing wheels has been proposed [15-17]. Such concepts capture the kinetic energy of the track deflection either through a direct trackside connection or within an integrated track component such as the energy harvesting tie that is studied here.

The objective of this study is to develop a novel energy harvesting tie capable of converting the kinetic energy from the vertical movement of the track (caused by passing wheels of trains) into usable electrical energy. The system is designed with the same size and dimensions as a standard railroad tie. The tie-embedded harvesters convert the vertical movement caused by the passing wheels into rotary motion an electromagnetic generator. A prototype full-size energy harvesting tie is developed and tested both in the laboratory and in the field environments, to evaluate the effectiveness of the system for harvesting trackside energy.

## 2 Existing Trackside Energy Harvesting Methods

Energy harvesting from track vibrations and deflections has gained popularity in recent years since it is independent of geographic and weather conditions and has significant energy potential. Piezoelectric materials have been considered in some studies for harvesting energy from rail vibrations. Several researchers have investigated their use in trackside energy harvesting applications, such as Wischke et al. [18], Cahill et al. [19], and Gao et al. [20]. However, the piezoelectric materials have large impedance resulting in the output power being relatively low, which limits their use solely for sensors and electronics with extremely low-power demands.

In addition, linear electromagnetic components have been used for the development of track vibration energy harvesters. One such device with an inductive voice coil was developed by Pourghodrat and Nelson et al. [21] to capture energy from the rail deflection. The test evaluation indicates that a 4-mW average power is generated by the developed system for an empty rail car at the speed of 18 km/h, while a three times more average power is obtained for a loaded rail car at the speed of 21 km/h. Gao et al. [22] developed two types of harvesters—a resonant harvester and a magnetic-floating harvester—using linear electromagnetic induction technology. The resonant harvester can be mounted on the rail base and generates a peak power of 119 mW, while the magnetic-floating harvester yields 49.2 mW. Compared to piezoelectric harvesters, linear electromagnetic harvesters provide higher power output, but which is still insufficient for high-power sensors due to the input of the track vibration occurring at a relatively low frequency.

To increase the power output, rotary electromagnetic energy harvesters were proposed for trackside applications. Wang et al. [17] and Gopinath [23] developed an energy harvesting system for railway track applications using mechanical motion rectification (MMR) mechanisms. It could convert both rail compression and rebound into the rotation of an electromagnetic generator. The lab results showed that the developed system can generate an average power of 1–1.4 W. However, a ground anchor is required in all the above rail track energy harvesters. This makes the system difficult to implement in practice as it requires long traffic interruption for installation.

## 3 Energy Harvesting Tie Development

In this study, a novel energy harvesting tie is developed, which can harvest energy from the downward motion of the track without causing any resistance during the track rebound. This helps eliminate the need for ground anchoring. The railway tie has the same dimensions as a traditional tie, allowing for easy and safe installation by simply replacing a traditional tie without using extra rail space. Figure 1 shows the cross-section view of the 3D model design of the tie, which includes two identical electromagnetic energy harvesters, one on each side, to simultaneously capture energy from the rail compression on both sides. Additionally, four coil steel springs are preloaded to return the tie box to its initial height as the rail rebounds to the deflected position. On the other side, the preloaded springs keep compressing the base plate and secure it to the supporting ballast foundation, eliminating the need to anchor the base plate to the ground.

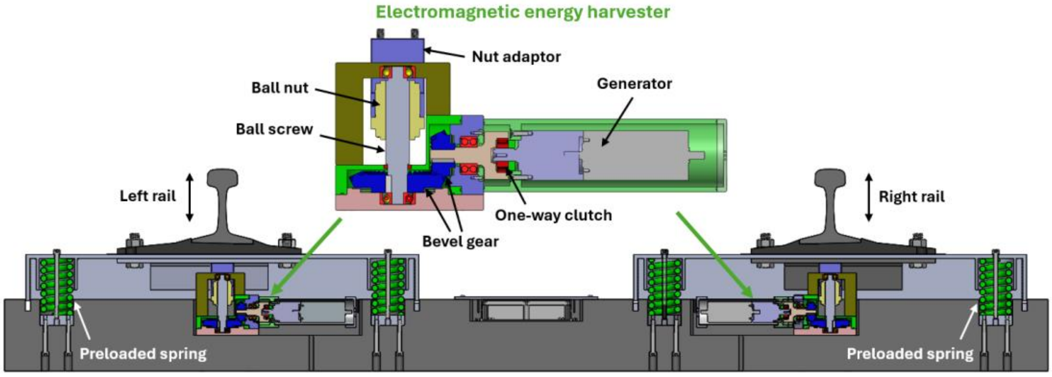


Figure 1: Cross-sectional view of the energy harvesting tie showing the integration of the generator within a standard railroad tie.

When a train passes over the tie, the wheels compress the rail causing the ball nut to move downwards. This movement results from the nut adaptor connecting the tie box and rail to the ball nut. The compression of the ball screw shaft is transformed into rotation via a pair of bevel gears. The output shaft rotates at a higher speed due to the smaller bevel gear. The torque is then transmitted to the gearhead shaft through the one-way clutch, which drives the generator at an amplified speed to produce electrical power. During the rebound, the gearhead shaft is disengaged from the generator due to the one-way clutch, which cuts off the line of torque transmission with the generator. This disengagement makes the system free of the electrical damping effect in the rebound. According to the design, a full-size energy harvesting tie prototype was created, as shown in Figure 2. To measure the compression of the harvester, a displacement sensor (Banner Q4X) is mounted on each side of the tie box fixed to the rail to detect the relative displacement between the rail and the tie basement. A data acquisition unit is connected to the energy harvesting tie to store data, including the phase voltage of the generator and the displacement sensor readings. To evaluate the effectiveness of the developed system, extensive tests were conducted in both lab settings and the field environment, as detailed next.

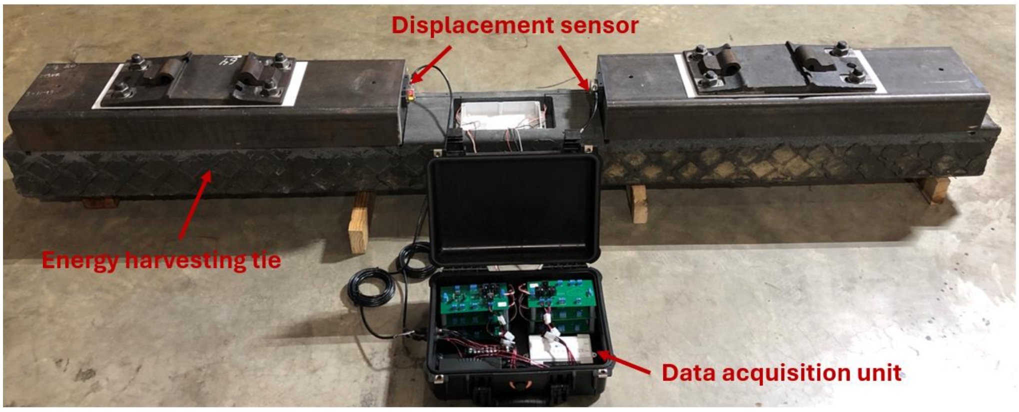


Figure 2: Energy harvesting tie prototype and the data acquisition used for collecting laboratory and field data.

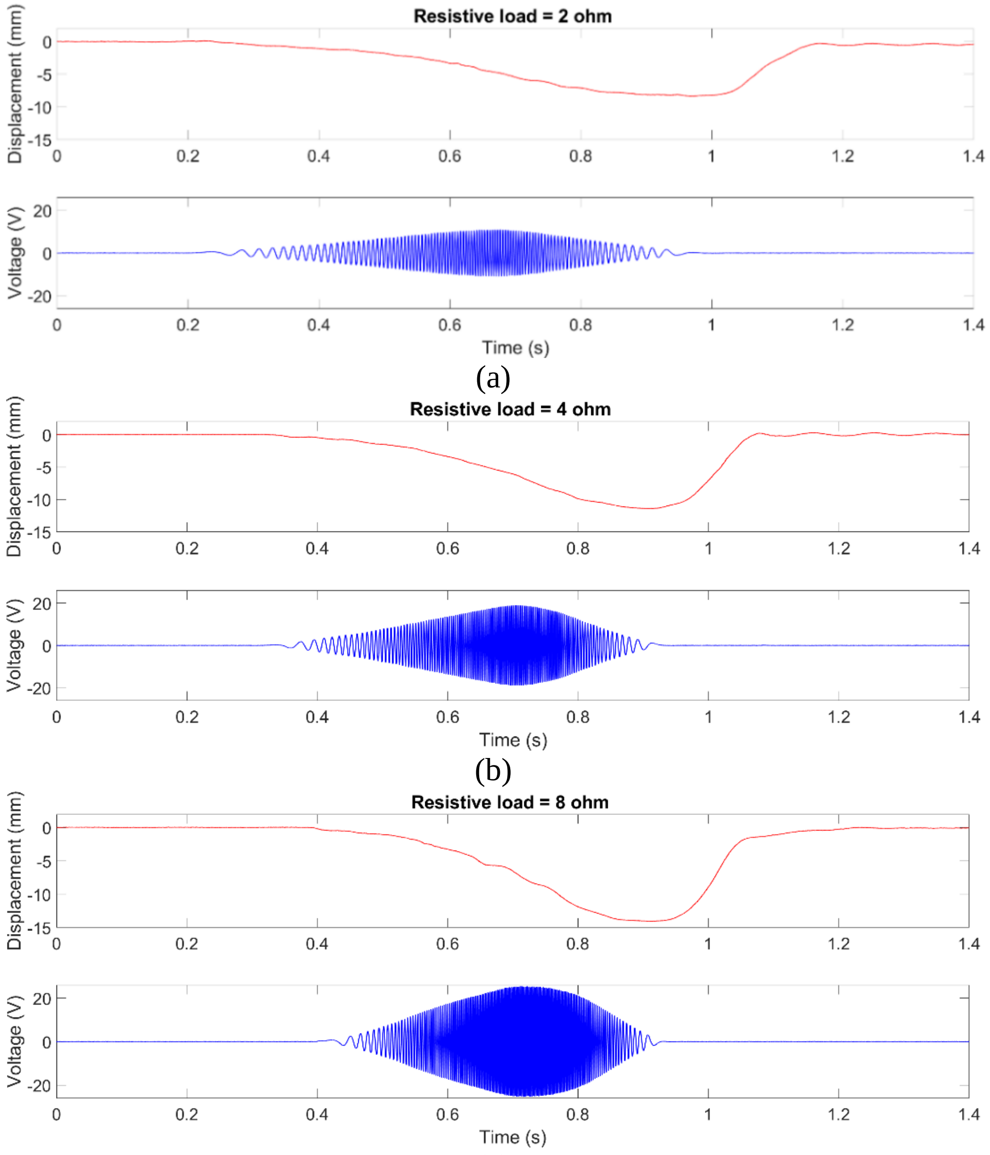
# 4 Lab Testing and Evaluation

A preliminary lab test was performed to examine the functionality of the harvesters and sensors, ensuring the success of the subsequent field test. In this test, a loading force of approximately 8540 N is applied to the tie by slowly operating a pickup truck over the tie using two wooden ramps, as shown in Figure 3. The test was performed separately on the two harvesters (#1 and #2) and repeated for three different resistive loads of 2, 4, and 8 Ohms.

Figure 3: Laboratory setup for testing the functioning and response of the energy harvesting tie to wheel loading.

Figures 4a to 4c show the displacement and phase voltage of harvester #1 under the three different resistive loads. Only the results of harvester #1 are presented here as similar results are obtained for the other harvester. As indicated, when the tie is loaded with the same amount of force, a larger electrical resistive load results in a larger displacement (and compression velocity) due to less electrical damping from the generator. Larger displacements generate large voltages, somewhat proportionally. For a given displacement, the harvester with smaller resistive loading generates more current and electrical power but requires more force to rotate the generator shaft.

The test results in Figure 4 s 4a to 4c also indicate that the generator produces voltage only when the tie is compressed and not during the rebound cycle. This implies that the one-way clutch is working properly, allowing engagement to occur only when the tie moves downward. During the rebound, the system disengages from the generator, so there is no resistance from the generator when the tie returns to its initial height (rail undeflected position). This helps keep the base of the tie stable during the rebound (with the assistance of pre-loaded springs), eliminating the need for anchoring the tie at its base.



(a)

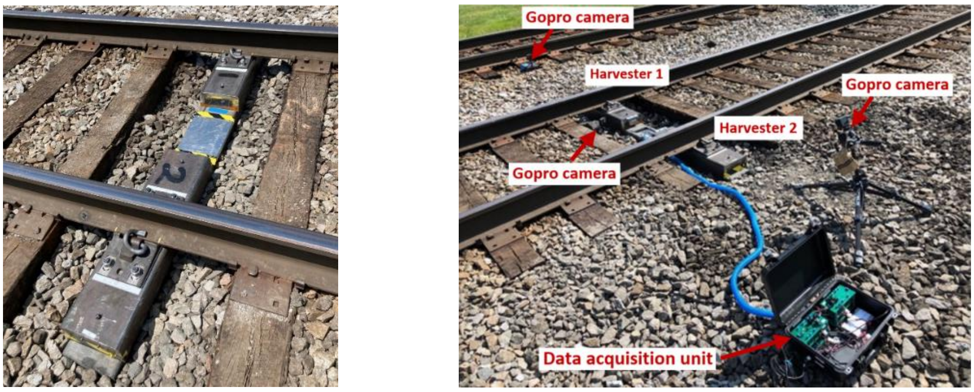
(b)

(c)

Figure 4: Tie displacement (mm) and generated voltage (V) from laboratory tests with various electrical resistances; (a) 2 ohm; (b) 4 ohm; (c) 8 ohm.

## 5 Field Testing and Evaluation

Field tests were conducted in collaboration with one of the Class I railroads in the U.S. to assess the performance of the system. One traditional tie was replaced with the prototype energy harvester tie, as shown in Figure 5a. During the testing, three Gopro®11 cameras, shown in Figure 5b, were used to record the dynamic behavior of the tie. The data acquisition unit was wired to the tie from a safe distance away from the tracks.



(a) (b)

Figure 5: Energy harvesting field installation; (a) attachment arrangement to the rail; (b) test instrumentation for collecting data

The energy harvesting tie remained installed on the revenue-service track for four months. During this time, data in five separate days from 11 passing freight trains at random. The length of the trains and their loading conditions were not controlled. The train speeds were categorized into three ranges: relatively low (24-32 km/hr), medium (32-40 km/hr), and relatively high (40-48 km/hr). To assess the effect of resistive load on the power production and performance of the system, the three electrical resistive loads mentioned earlier were used for the tests.

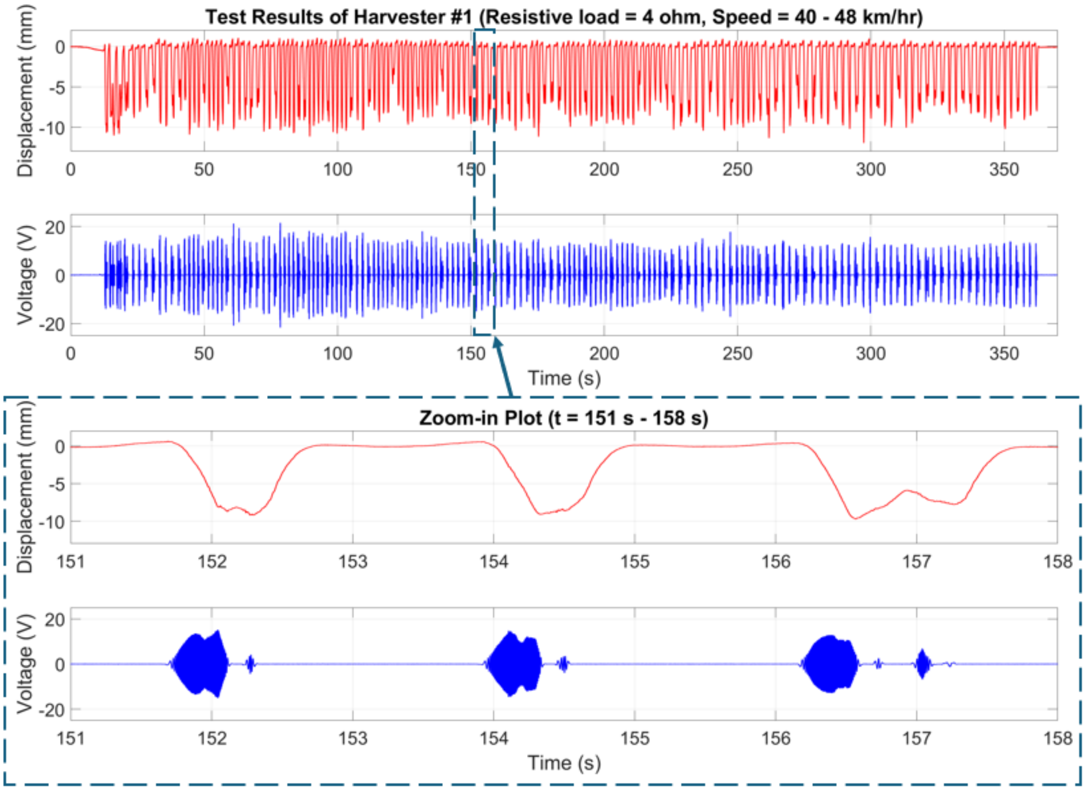


Figure 6: Time trace of tie's vertical displacement and voltage output of harvester #1 with 4-ohm resistive load for train speed of 40 to 48 km/h.

Figure 6 shows the time trace of the displacement and phase voltage for a single harvester (harvester #1) with 4-ohm resistive loading at train speeds of 40 to 48 km/h. The passing wheels compress the rail by 5 to 11 mm, resulting in maximum voltages of 10 to 20 V. The zoomed-in results between 151 and 158 seconds indicate that the harvester is engaged during the downward cycle and generates energy in response to the compression of the rail caused by wheel load. During the rebound cycle, the one-way clutch disengages the generator and yields no voltage output, consistent with the lab testing results discussed earlier.

The total average power generated by both harvesters for various resistive loads is summarized in Table 1. A smaller resistive load yields more current (at a given voltage) and larger generated power. It, however, results in more mechanical resistance to the downward motion and rotation of the generator, hence requiring a large force to press down the tie. For railroad applications, the wheel loads are so large that we do not anticipate the required force for small resistive loading (even those smaller than the ones considered in this case) to be a limiting factor for the operation of the tie. Of course, larger loads require more stout mechanical components that must be considered for the design of the harvester. Table 1 also suggests that higher speeds result in greater average harvested power, due to the higher frequency of the tie compression.

For the tested speeds, the field results suggest that each energy harvesting tie can successfully generate an average power of approximately 5 to 30 Watts at speeds ranging from 24 to 48 k/hr. Higher speeds or lower resistive loadings could increase the generated power.

Table 1: Total average power for harvesters 1 and 2 obtained during revenue-service track testing for various resistive loads.

| Resistive Load | Speed Range | Total Average Power of Harvesters #1 and #2 |
|---|---|---|
| 8 Ohms | Relatively Low | 6.15 W – 8.57 W |
| | Medium | 5.71 W – 13.09 W |
| 4 Ohms | Relatively Low | 8.58 W – 16.62 W |
| | Relatively High | 30.16 W |
| 2 Ohms | Medium | 19.28 W |
| Note: Relatively Low = 24-32 km/hr; Medium = 32-40 km/hr; Relatively High = 40-48 km/hr | | |

## 6 Conclusions

A novel energy harvesting tie that can harvest energy from the vertical movement of rail was successfully designed, prototyped, and tested in the laboratory and on a revenue-service track. The energy harvesting tie is the same size as a standard railroad tie and can be easily retrofitted for a conventional tie. It consists of two identical harvesters, placed directly under each rail. The energy harvester that is embedded within the tie uses half-wave mechanical motion rectification (HMMR) mechanisms to capture the kinetic energy of the track's downward movement under passing wheels, without resisting the upward (rebound) movement. Both the lab and revenue-service track tests show that the system is capable of successfully generating an average of 5 to 30 Watts of power at train speeds ranging from 24 to 48 km/hr, depending on the electrical resistance of the harvester and the speed of the train. In practice, we envision installing the energy harvesting tie as a single unit to accommodate power trackside sensors and electronics that may be needed for condition monitoring or similar field measurements, without the need to rely on a replaceable battery. One can also choose to install them as a "gang" of ties to increase the power out, to operate track equipment that requires more power. In such a case, however, further laboratory and field evaluation of the ties is needed to ensure they meet the required lateral strength for track stability.

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