Energy Harvesting for Monitoring Bridges over their Operational Life

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Abstract

The use of energy harvesting materials for large infrastructure is a promising and growing field. In this regard, the use of such harvesters for the purpose of structural health monitoring of bridges has been proposed in recent times as one of the feasible options since the deployment of them can remove the necessity of an external power source. This paper addresses the performance issue of such monitors over the life-cycle of a bridge as it deteriorates and the live load on the structure increases. In this regard, a Lead Zirconate Titanate (PZT) material is considered as the energy harvesting material and a comparison is carried out over the operational life of a reinforced concrete bridge. The evolution of annual average daily traffic (AADT) is taken into consideration, as is the degradation of the structure over time, due to the effects of corrosion. Evolution of such harvested energy is estimated over the life-cycle of the bridge and the sensitivity of harvested energy is investigated for varying rates of degradation and changes in AADT. The study allows for designing and understanding the potential of energy harvesters as a health monitor for bridges. This paper also illustrates how the natural growth of traffic on a bridge over time can accentuate the identification of damage, which is desirable for an ageing structure. The paper also assesses the impact and effects of deployment of harvesters in a bridge as a part of its design process, considering performance over the entire life-cycle versus a deployment at a certain age of the structure.

1 INTRODUCTION

The integration of energy harvesting technology for civil infrastructure applications is an ever growing field. There has been intense study in recent times into the merits of different forms of energy harvesting techniques and their uses for specific structural applications [1]. Of such available energy harvesting techniques, it is the use of vibration-based energy harvesting which has come to the fore when considering civil engineering applications [2]. This is in part due to the increased optimization of harvester designs, notably piezoelectric based energy harvesters [3], coupled with the magnitudes of the responses associated with large scale civil infrastructure under operational conditions [4]. This has resulted in energy harvesting from bridge structures becoming the focus of a number studies. The formulation of using piezoelectric energy harvesters for highway bridges is available [5], as it is with rail bridges [6]. While such harvested energy can be used to power small scale electronics, it is the applications that arise in structural health monitoring (SHM) of the host structure which is most promising.

The use of vibration based energy harvesting devices for the purposes of SHM for civil structures offers many benefits. Existing methods for SHM which utilize vibration based data [7] can potentially be modified to utilize the output of energy harvesters, allowing for inexpensive monitoring of structures. Such monitoring has been illustrated for laboratory based testing of concrete beams and damage detection using energy harvesters demonstrated [8, 9]. Bridge-vehicle interaction has often been used as a signature for SHM [10] and utilizing the energy harvested from devices due to such interactions has been demonstrated for both highway bridges [11] and railway bridges [12]. The use of energy harvesting for SHM from train-bridge interaction has been shown to compare favorably against traditional methods such as strain gauges and ultrasonic testing [13]. Utilizing energy harvesters for obtaining information regarding the health of the host structure, it becomes necessary to determine what practice to adopt for bridge maintenance management over the operational life of the structure.

As infrastructure degrades, deterioration and subsequent rehabilitation over a structures life cycle has important implications at not only individual levels but also at network levels [14]. Such network based maintenance management is becoming increasing popular and allows for the prioritization of maintaining infrastructure in the most efficient and cost effective manner [15]. The use of sensitivity analysis and the analysis of parameter importance measures, through structural reliability methods, has demonstrated the benefits that arise from network level management protocols [16]. Similarly, the rehabilitation of infrastructure at an individual level has been shown to have significant implications on all elements and users [17] and will influence the potential of integrated sensors such as energy harvesting devices over the lifespan of the structure.

This paper investigates the effects of energy harvesting from a bridge structure over operational life. By averaging the amount of energy harvested over a prolonged period of time, rather than focus on a single vehicle passage, the effects of degradation and repair on the energy harvesting potential can be obtained. A damage model used to simulate initial vehicle passages is outlined as is the energy harvesting device. A typical AADT curve for a variety of roads and vehicles is presented and the effects of such on the energy harvesting potential over the lifetime of the bridge determined. The effects of degradation are assessed through a degrading of the road surface and the bridge structure and the effects of intervention assessed through a structural reliability assessment.

2 METHODOLOGY

2.1 Overview of Energy Harvesting from Bridge Vibrations

Vibration based energy harvesters are based upon three main transduction methods, namely: electromagnetic, electrostatic and piezoelectric [18]. Piezoelectric energy harvesters utilize active piezoelectric elements which convert fluctuations in strain into electrical energy. The most common piezoelectric device is based on a cantilever arrangement, whereby the active piezoelectric element is bonded to the surface of a cantilever substrate. The cantilever is attached onto the host structure at the base, with the ambient vibration of the host structure providing the base excitations of the harvester. A tip mass can be added to the cantilever and can be used to tune the harvester by altering its mass. The electromechanical behavior of such cantilever devices can be expressed by the coupled linear equations [19]

$$m_c \ddot{x} + c_c \dot{x} + k_c x = -m_c \ddot{y}_b \tag{1}$$

$$\Theta \dot{x} + C_p \dot{V} + V/R_l = 0 \tag{2}$$

Where m_c, c_c and k_c are the mass, damping and stiffness of the energy harvester respectively and x is the relative displacement of m_c, whereby overdots denote differentiation with respect to time and y_b is the base acceleration from the host structure. The electromechanical coupling coefficient is given as Θ, V is the voltage and the capacitance and load resistance are given as C_p and R_l respectively.

The use of piezoelectric energy harvesters for the purposes of SHM for civil structures offers many benefits [20]. By generating energy from the host structure, the device can be used independent of external power supplies and can allow for long term monitoring of structures in a cost effective manner. As the devices utilize the host structure to generate energy, the output signals of the harvesters therefore contain a signature of the host. The analysis of such signals can be utilized to determine the structures health and can be used to monitor degradation of the host due to the evolution of damage. Such degradation would have an impact on both the generated signal and the amount of energy being harvested from the structure.

2.2 Bridge-Vehicle Interactions Responses

For the purposes of modelling the energy harvesting output from a bridge structure, a simply supported Euler-Bernoulli beam with a bilinear breathing crack being traversed by a single degree of freedom (SDOF) oscillator was used as considered in Jaksic et al. 2012 [21]. Also incorporated to the model is the effects of road surface roughness (RSR), allowing for damages in the form of both a crack to the structure and deterioration of the road surface to be considered. The equation of motion and the interaction of the moving oscillator is given by

$$EI\frac{\partial^4 y_i(x,t)}{\partial x^4} + c\frac{\partial y_i(x,t)}{\partial t} + \rho A\frac{\partial^2 y_i(x,t)}{\partial t^2} = \overline{P}\,\delta(x-\upsilon t) \qquad i = 1, 2 \tag{3}$$

$$y_i(x_i,t) = \sum_{i=1}^{n} \phi_i(x_i)\, q_i(t) \tag{4}$$

where E and I are the Young's Modulus and second moment of area, respectively, $y_i(x,t)$ is the transverse deflection of the i^{th} beam at a location of x from the left hand support along the length of the beam, L, at time t. The structural damping of the beam is given by c and ρA is the mass per unit length. The vehicle is characterized by a force, $\overline{P}$, comprising of it weight and inertial effects. The vehicle traverses the bridge with a constant speed of v. Degrees of freedom coming from the bridge and that from the vehicle are coupled in this model, thereby allowing RSR to have an impact on energy harvesting. The Direct delta function is represented by δ. The transverse deflection is given by Equation 4, where $\phi(x)$ is the modeshape and *q(t)* is the time dependent amplitude. The influence of RSR is taken into account using ISO 8606:1995(E). For this study a total of five different RSR are considered, ranging from very poor to very good [21]. The parameters chosen for the bridge in this paper for simulating the responses due to the passage of a vehicle are outlined in Table 1.

Parameter	Symbol	Value	Unit
Length	L	15	m
Damping ratio	ζ	2	%
Youngs Modulus	E	200×10^9	N/m^2
Density	P	7900	Kg/m^3
Second moment of area about the neutral axis	I	0.0021	m^4
Height	h	0.439	m
Breadth	b	0.293	m
Cross-Sectional Area	A	0.1287	m^2

Table 1: Parameter values of model bridge

For the purposes of this study a piezoelectric energy harvesting device with an active piezoelectric material consisting of Lead Zirconate Titanate (PZT) is considered. PZT is a ceramic material with good piezoelectric efficiency and is the most popularly utilized piezoelectric material for energy harvesting. For the purposes of this study the energy harvesting device is modelled as being attached at the mid-span of the model bridge structure, utilizing the bridge response given by Equations 3 and 4 as the base excitement of the harvester and Equations 1 and 2 to calculate the energy harvesting potential from the vehicle passage. The device parameters outlined in Table 2. When considering the energy harvesting potential over the operational life of the bridge, attention must turn to multiple vehicle passages and account for predicted growth in traffic over this return period. To understand the possibilities of applications, this study considers an equivalent number of single passages over vehicles over the bridge. Consequently, while all parameters assumed for the bridge, the harvester, the vehicle and the traffic flow patterns are realistic, the conclusions drawn from the study is qualitative for similar, detailed study should be carried out for specific bridge to calibrate them for monitoring over operational life.

Parameter	Value	Unit
m_h	2.5	g
γ_h	0.038	
k_h	0.4286	N/m
Θ	7.501	μC/m
C_p	2.866	nF
α	0.9	

Table 2: Parameter values Energy harvester parameters

2.3 Growth of Annual Average Daily Traffic (AADT)

When considering a long term return period for the energy harvesting potential of a device from a bridge structure, the daily traffic is a metric which can be adopted to project the likely energy harvested. By taking an average energy harvesting value from vehicles travelling at range of speeds and accounting for the average daily traffic, such an estimate for the energy harvesting potential can be obtained and the effects of deterioration over years can be obtained and the influence of projected traffic growth accounted for. The annual average daily traffic (AADT) is an average value of traffic per day taken over a year long period. The AADT of passenger cars and heavy goods vehicles (HGV)'s is adjusted based on a projected growth of traffic in the future. For this study, the AADT of three different road classifications are considered along with the projected growth for two vehicle types, namely a light vehicle and HGV, over a forty-year period [Figure 1][17]. The influence of percentage increase in traffic on the energy harvesting potential allows for an accurate prediction of the energy harvesting potential from a bridge structure when considering future trends. While in reality these values will differ from bridge to bridge, the data presented provides a realistic estimate of what typically takes place in many bridges. It also allows distinguishing between light vehicles and Heavy Goods Vehicles (HGV) and the fact that their evolution with time follow different rates.

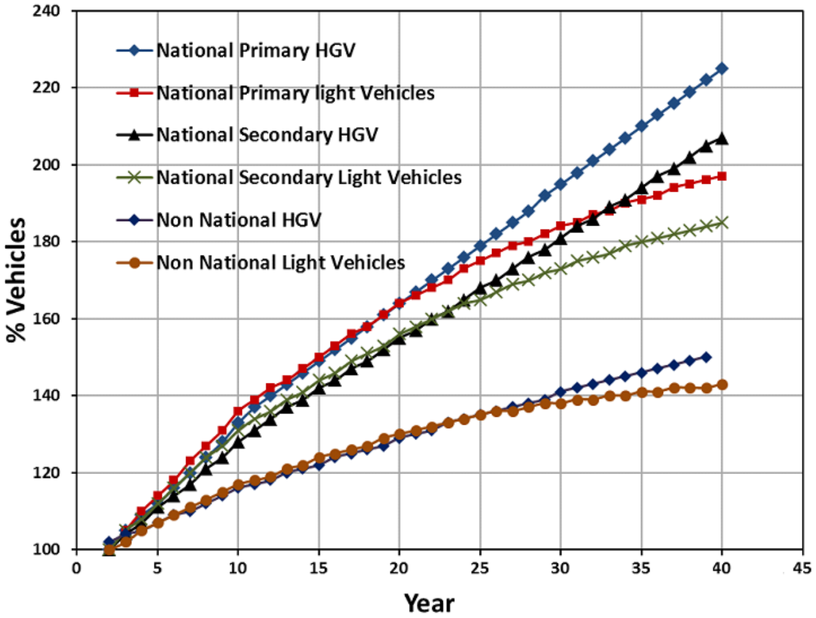

Figure 1: Example projected growth of AADT for three road types and two vehicle types.

2.4 Degradation of Bridge over its Life

The accurate assessment of a bridge structure over its life requires the use of probabilistic methods, accounting for load, material, and model uncertainties. As such, the reliability index, β, is a measure of the structural safety of the structure and is a function of the probability of failure, P_f, and can be expressed by

$$\beta = -\Phi^{-1}(P_f) \tag{5}$$

where Φ is a joint standard normal distribution consisting typically of variables related to load and capacity of the structure for various limit states.

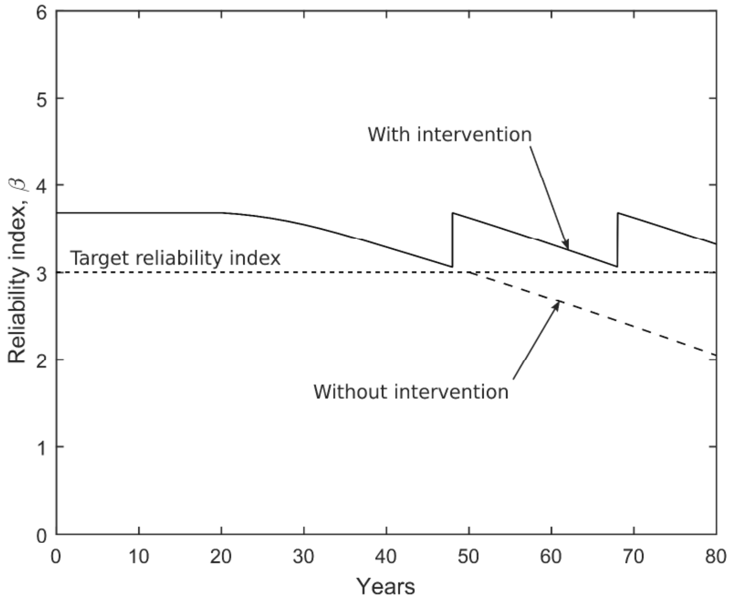

Figure 2: Example probabilistic curve for a slab bridge with and without intervention.

For a reinforced slab bridge, a life-cycle assessment was conducted using a time-variant reliability analysis, with time-variant degradation of flexural steel area due to a uniform corrosion model considered. Considering the effects of intervention and no intervention, the reliability was found to be stable for an initial twenty-year period, with a $\beta = 3.68$, followed by a decrease in the reliability index due to the ingress of corrosion cause a degradation in the flexural steel area [Figure 2]. A target reliability index of $\beta = 3$ was obtained at 47 years, with a continued decrease to $\beta = 2.06$ until year 80 without intervention, whilst intervention resulted in a return to $\beta = 3.68$ and a decrease in the reliability index until year 68, after which intervention is again considered. The use of such a reliability index coupled with AADT projected figures and the influence of degradation on the energy harvesting potential allows for the prediction of the life cycle of a structure using energy harvesting as a metric. This paper will use degradation curves similar to that presented in Figure 2, in conjunction with the AADT growth pattern presented in Figure 1 to understand the effect of energy harvesting and its possible applications over a long period of time.

3 RESULTS

With structural degradation having implications on the amount of energy harvested from a structure, long term estimates of energy harvesting over the lifespan of a structure consequently have the potential to act as important indicators over a structures health. From this perspective, and to obtain an initial idea of such possible effects of harvesting, this paper considers an average amount of energy which can be harvested from a structure rather than vehicle specific passages.

3.1 Estimated Harvesting Values for Degrading Road Conditions

Considering an AADT of 18,000 for light vehicles 4,000 for HGV, the normalized energy harvested over a day was considered for five different RSR conditions [Figure 3]. The baseline case is taken as the light vehicle passage ($500kg$) with very good RSR, with a corresponding normalized harvested energy for HGV ($5000kg$) passages of 0.327. There is a continued increase in the energy harvesting potential with degrading road surface conditions, with a maximum found for very poor RSR. This indicates that poor road conditions will not only respond with significantly higher levels of energy harvesting with time, but also that fact that a calibrated HGV can be used to compute the ratio of energy harvested by HGVs to average harvested energy from light vehicles to provide a condition assessment of the road.

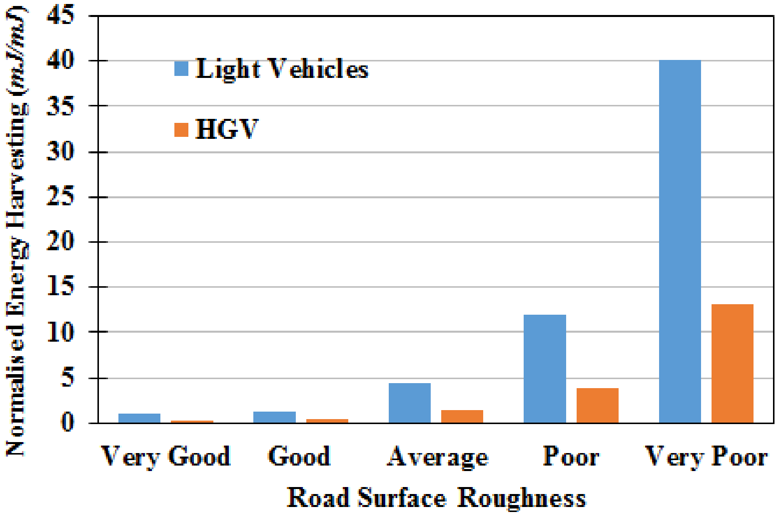

Figure 3: Energy harvesting potential from light vehicles and HGV's with degrading road conditions.

3.2 Estimated Harvesting Values for Evolution of Damage

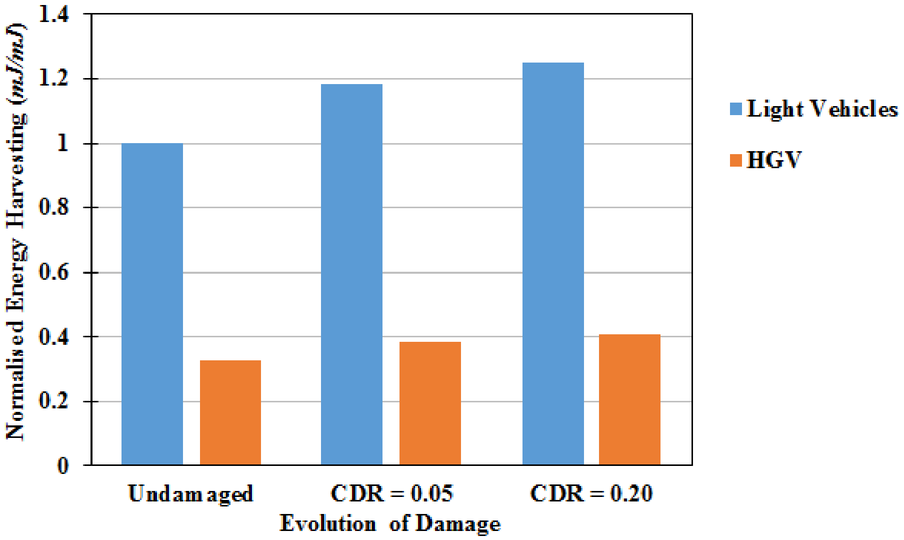

Figure 4: Energy harvesting potential from light vehicles and HGV's with increasing structural damage.

Along with the influence of the road surface degradation, the effect of damage evolution through the loss of stiffness of the bridge structure must also be accounted for when considering the energy harvesting potential over the life-cycle of a bridge. Considering two damage states and assessing for very good RSR, it was found that the increase in damage to the bridge structure has less of an impact on the normalized accumulative daily harvested energy when compared to the degradation of the road surface [Figure 4]. This is due to the fact that the energy is averaged for a range of vehicle speeds, rather than focusing on a single speed close to the natural frequency of the damage structure. The time over which damage takes place (either over a significantly longer term for corrosion, or over a very short period of time for accidents) and the time over which the surface degrades may or may not match and in the condition that they do, effects of surface roughness should be calibrated or at least estimated from calibration. Another option is to obtain the readings from multiple passages to make an estimate of the surface roughness effects in case a pre-selected benchmarking is not available.

3.3 Effect of Growth of Annual Average Daily Traffic and Degradation

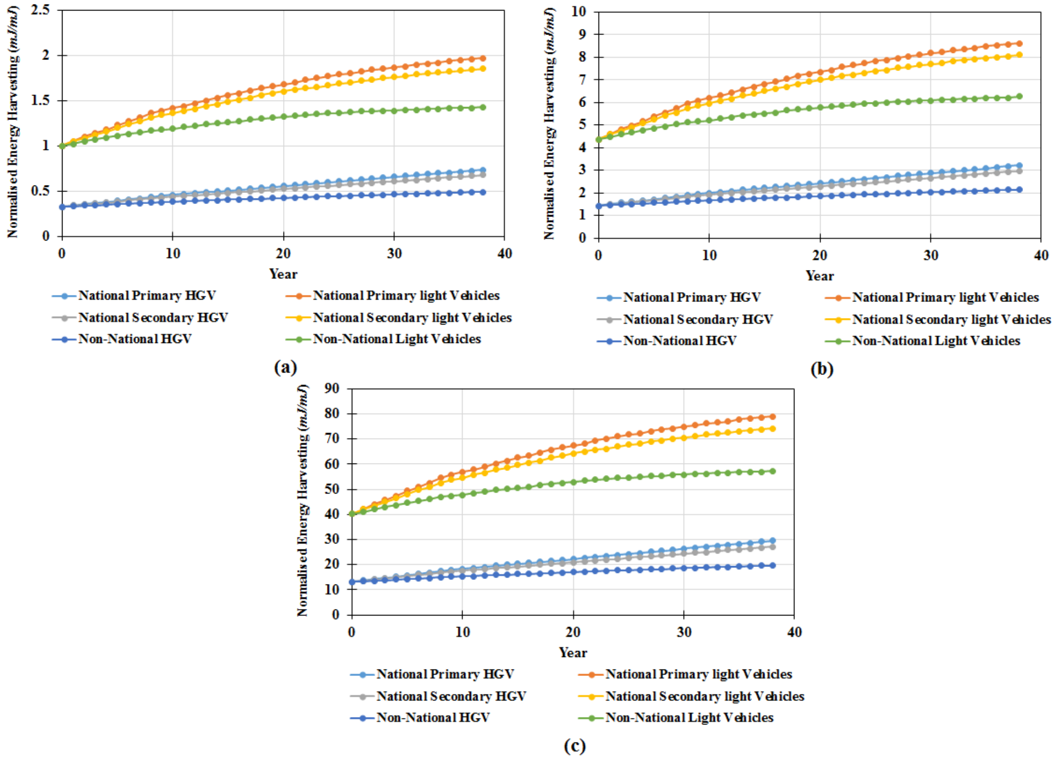

Figure 5: Estimated energy harvesting potential from light vehicles and HGV's accounting for projected increase in AADT for (a) Very good RSR, (b) Average RSR and (c) Very poor RSR.

The increase in daily traffic will result in an increase for the average daily harvested values. Taking into account the two types of vehicles for differing RSR and accounting for the three road types with projected AADT growth, the projected increase in energy harvesting values for increased traffic can be determined [Figure 5]. It was found that for light vehicles on primary roads, the normalized daily energy harvested after 40 years increased to 1.97, 8.62 and 79.04 times for RSR of very good, average and very poor respectively. For a similar road, HGV's resulted in a 0.735, 3.22 and 29.5 times of normalized accumulative energy for RSR's of very good, average and very poor respectively on national roads. The normalization is carried out considering the value of unity to represent the energy harvested at the initiation time for the operation of the bridge, represented as Year 0.

3.4 Assessment of Energy Harvesting Potential from Bridge Structure over Life-Cycle

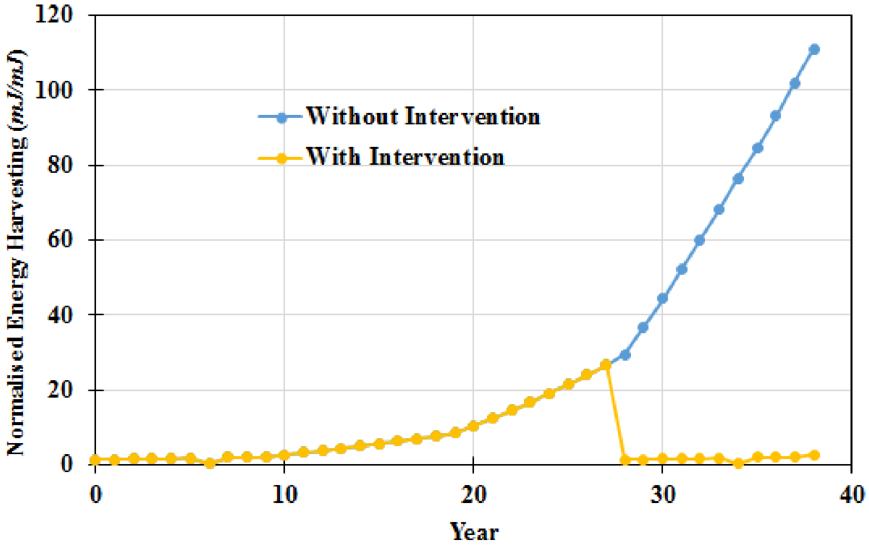

Figure 6: Energy harvesting potential over 40-year period for bridge structure with and without intervention.

The use of energy harvesting devices as a mechanism for monitoring a structure over its operational life is finally investigated. By utilizing an average daily growth in AADT accounting for light vehicles and HGV's over three types of road classes, the projected energy harvesting growth over a 40-year period for a bridge can be estimated. This was coupled with the effects of a deterioration in road surface conditions and the evolution of damage in the bridge structure, as presented in the preceding sections, with a 40-year time period considered from an undamaged state to an RSR of very poor and a CDR = 0.20. It was found that after a 27-year period, the daily normalized energy harvesting values had increased from 1.326 to 23.63 [Figure 6]. Following the reliability index curve previously presented, should intervention occur at year 27, the subsequent year shows a 22.1 times difference between no intervention compared to the effects of intervention and by year 40, this rises to 42.18 times difference. This illustrates the influence of intervention on energy harvesting levels and also the potential for utilizing energy harvesting devices for life-cycle monitoring of structures.

4 CONCLUSIONS

This paper investigated the feasibility of utilizing energy harvesting devices to a monitor a bridge structure over its operational life. In this regard, a piezoelectric energy harvesting device was considered for a reinforced concrete bridge structure. The estimated growth in traffic and related energy harvesting was estimated by assessing average daily energy harvesting outputs from a range of vehicle types and speeds travelling on different road types and using AADT projections. The effect of deterioration in the state of the road surface and the bridge structure was subsequently considered. The evolution of harvested energy is estimated over the operational life of the bridge taking into account intervention and non-intervention, and the sensitivity of harvested energy is investigated for varying rates of degradation and changes in AADT. This initial study highlights the possibility of utilizing energy harvesting devices to monitor a bridge structure over its life, and while precision is lost through the averaging of energy harvesting values, it provides an important benchmark from which further studies can be assessed and continued from. It is also observed that busy bridges, bridge with deterioration or those with combined effects of increased traffic and deterioration harvest significantly more energy when these changes take place, making energy harvesting a natural choice for long term monitoring.

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