Energy Harvesting in Pneumatic Tires through Piezoelectric Material and its Life Cycle Environmental Impact

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Abstract

This research aims to seek the current status of piezoelectric energy harvesting technology in running vehicles and its life cycle assessment. The goal is to assess the piezoelectric value to be considered as a future reliable energy source for vehicles which rely on results from prototype demonstrations. Piezoelectric materials can transfer mechanical energy into electrical energy. This kind of energy can be stored and used for other devices. In this case, piezoelectric materials have the potential to provide reliable and cost effective replacement of energy sources. Thus, it can ultimately have potential to replace the battery and reduce user costs. This project evaluates the future potential of piezoelectric energy harvesting technology in cars and their environmental impacts. The use of piezoelectric materials in pneumatic tires enables capturing waste energy of cars because of deformations in the tire and weight of the vehicle as well. In the experimental phase a set-up was designed to simulate movement and pressure inside the contact patch of a given car. Outside of the model tire, piezoelectric elements were used to harness energy. Experimental results were compared to a research found in the literature. Comparison showed that this method harvests more energy. Based on the experimental results, this method produced 2.31 w for 56 piezo elements comparable to 2.3 w for 160 piezo elements found in the literature.

Environmental impacts of these kinds of resources of renewable energy were considered through a life cycle assessment study. The results of the research showed that further evaluation of technology is required to measure the durability and lifetime of piezoelectric materials. Anyway, to have cleaner and more sustainable forms of energy, it is required to keep costs lower and insure a healthier environment for the next generation.

Keywords: Piezoelectric, energy harvesting, waste energy, car, tires, Life cycle assessment

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Environment and waste energy

Concerns for depletion of fossil fuels and their adverse effects on the surrounding environment are increasing. Therefore, alternative nonconventional energy sources are gaining popularity in the society. Solar cells, wind turbines, hydroelectric power generation, biogas and biodiesel plants have been implemented successfully. Nowadays, new technologies have been found to provide sustain- able energy to harness waste energies with self-power energy harvester to supply power needs of vehicles. This type of need is better to offer clean, more sustainable forms of electrical power to decrease the costs, to preserve reliable and fruitful connection with society members and to guarantee a healthier environment for next generation [76]. As a new technology, piezoelectric materials and their effect can have a major role in solving the mentioned problems. Vibration harvested from human and vehicle motion, machines, and any surface under vibration is one of the easiest ways to harvest energy by piezoelectric materials. They convert mechanical energy into electrical energy. One of the natural piezoelectric materials already in use is quartz. There are some artificial piezoelectric materials like $BaTiO_3$, lead zirconium titanate etc [53]. On the other hand, since the invention of the vehicle, passenger's car fuel consumption has risen consistently. According to Canadian greenhouse gas (GHG) emissions by economic sector, in 2015, the transportation sector was the second largest source of GHG emission which have local, regional or global effect on environmental receptors (people, materials, agriculture, ecosystems, climate, etc.) [76](Figure 1.1).

Approximately more than a hundred million car tires currently are in-use in Canada. This encour-

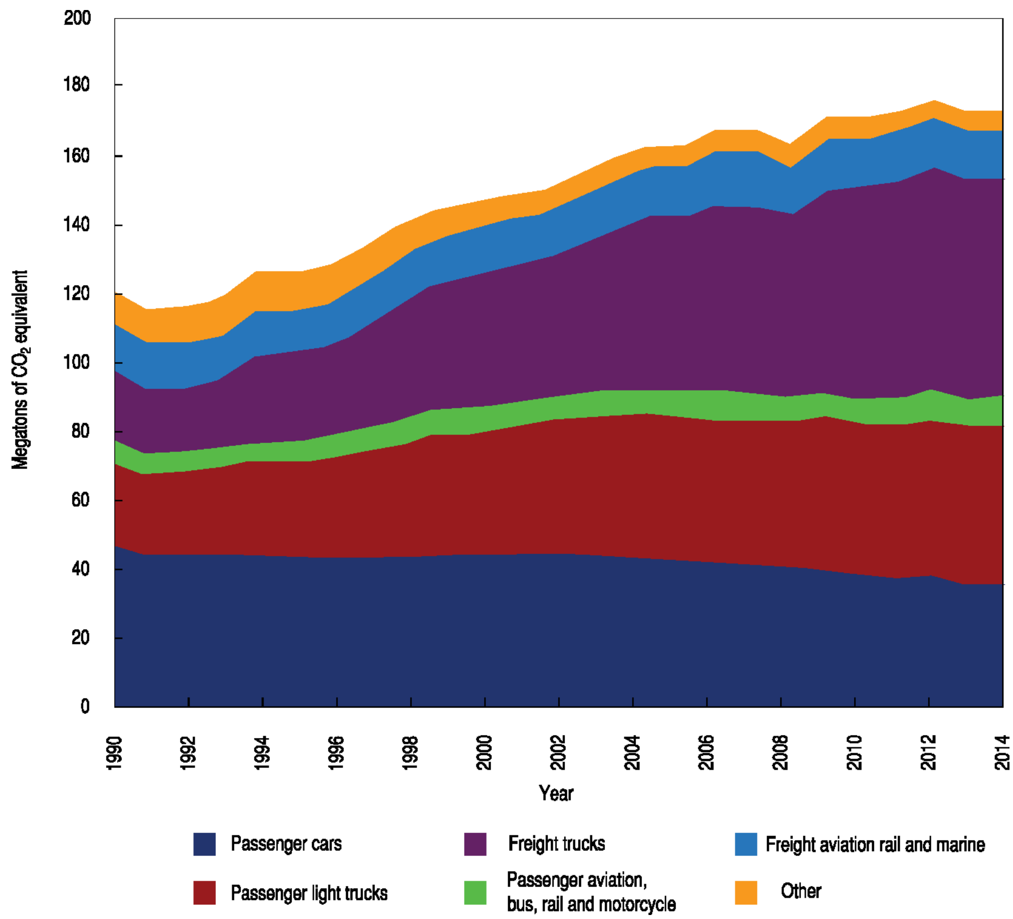


Figure 1.1: Transportation sector greenhouse gas emissions, Canada, 1990 to 2015[26]

ages manufacturers and policy makers to think about more environmentally friendly and efficient cars to compete with similar ones. Therefore, it is important to consider every part of vehicle to determine which part could be improved. In the year 2020, the government of Canada is committed to reduce GHG emission to 130 megatons (Mt) lower than to those in 2005 [26]. The government regulation, restrictions regarding pollution control, as well as customers trends to eco-friendly products, have driven manufacturers to develop sustainable products. Identification of environmental impact would be the first step to generate greener products.

Decreasing GHG emission and harvesting waste energy are two important reasons that cause thinking about vehicle tires and their impact on the environment. Vehicle tires experience periodical normal and shear loads under dynamic conditions. This load can be used as a source of mechanical stress for piezoelectric harvesters. The use of piezoelectric devices installed in pneumatic tires will enable the capture of kinetic energy from vehicle weight. This energy can be used to power other parts of the vehicle to save the fuel consumption such as low power electronics. This kind of energy shows potential as a power supply compared to batteries with a short lifespan.

1.2 Life cycle assessment

In the early 90's, the Life Cycle Assessment (LCA) was developed to investigate probable environmental effects of the different products. According to Stavropoulosa [75], the goal of LCA is that the environmental performance of products and services will be compared to choose the least burdensome one over the lifetime. LCA makes it possible to assess the environmental impacts of a process or service, taking into account the extraction and processing of raw materials, manufacturing processes, transport and distribution, use, reuse, recycling and management of end-of-life waste [33]. LCA results can thus complement the basic data needed to know and improve a system, while avoiding that local environmental improvements are the result of an export of pollution to other systems or to other types of impacts (i.e. burden shifting).

According to the life cycle assessment (LCA) standard ISO 14040, LCA is defined as "a systematic set of procedure for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle." [33]. LCA is a technique for assessing all environmental aspects associated with a product from "cradle-to-grave", or from a product's manufacturing stage through its life, and into its disposal route [37]. The standards ISO 14040, 14041, 14042, 14043, 14044 are crucial tool for environmental assessment and are used to compare the current tire technology and new one with adhering to mentioned standards. These standards outline a basic four step process to complete a life cycle analysis consisting of a goal and scope, inventory analysis, impact assessment, and interpretation [33].

Definition of the four phase of LCA

An LCA study involves four different phases [33]. Each step is dependent on the previous steps. In the following subsections each phase of an LCA study is explained.

Goal and scope definition

The problem, and the objectives and scope of the study are defined. The function, functional unit and system boundaries are determined in this phase. Also, the main and alternative scenarios are described in detail. This phase decides which extraction and emissions are based.

Inventory analysis

The resource used required for the function, polluting emissions to air, water, and soil , the extraction of raw materials are quantified.

Impact assessment

This phase evaluates environmental impacts due to emissions defined in the inventory step.

Interpretation

In this section, the obtained results are interpreted and the uncertainties are evaluated. Sensitivity analysis and uncertainty studies can evaluate the effect of system boundaries and improvement options can be identified. The purpose of the interpretation phase is to identify the life cycle stages at which intervention can substantially reduce the environmental impacts of the system or product, as well as analyze the uncertainties involved [37]. Figure 1.2 presents these four phases and the relation between them.

1.3 Significance of the current research

The population across the world is growing and needs energy resources to remain. This demand guides the researchers to generate alternative clean, efficient and sustainable energy resources to provide the current needs while considering the future generation needs. This brings sustainable

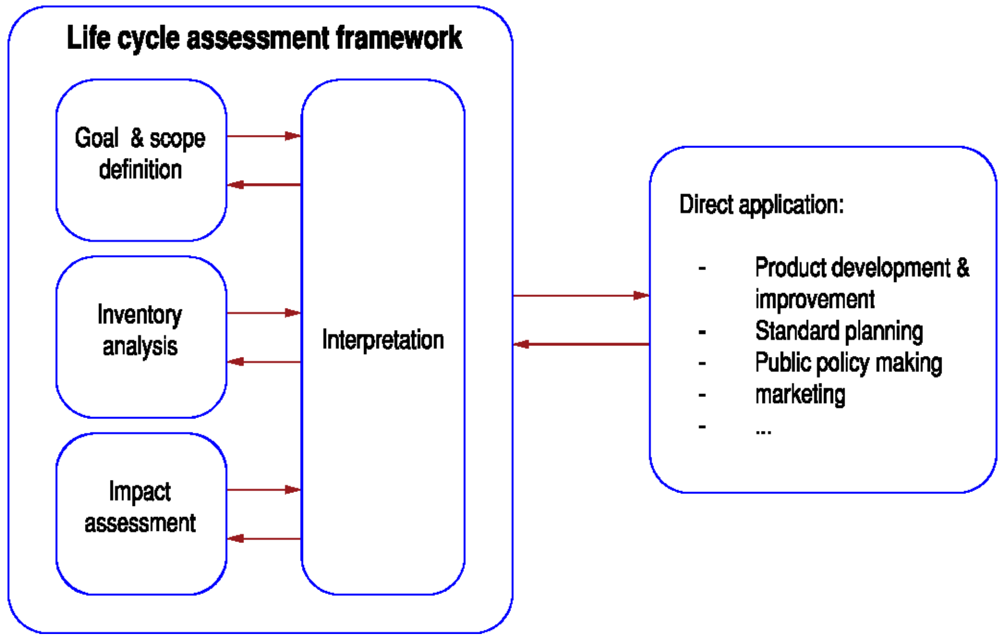


Figure 1.2: Components of a product life cycle assessment (LCA) [33].

energy concepts, which is getting more important nowadays. In addition, it can help reduce the cost, environmental impacts and health risks associated with carbon emission. According to the U.S Energy Department [79], only about 13-14 percent of the energy from the fuel put in a conventional vehicle is used to move it down the road, depending on the drive cycle. The rest of the energy is gone to the engine, idling, drive train, power to the wheels, and parasitic losses. The approximate amount of losses is shown in Figure 1.3. A vehicle must expend energy to move air out of the way as it goes down the road, less energy at lower speeds and progressively more as speed increases. Overcoming the vehicle's inertia that is directly related to the weight, and braking losses six percent of the energy in average. Aerodynamic drag averagely absorbs more than two percent of the mechanical energy [79]. Almost four percent of the energy is lost by the rolling resistance in the tires. Rolling resistance is a measure of the force necessary to move the tire forward and is directly proportional to the weight of the load supported by the tire while rolling. The main source of energy dissipation in tires is the visco-elasticity of the materials of which tires are made .Visco-elastic materials lose energy in the form of heat whenever they are deformed. Deformation-induced energy dissipation is the cause of about 90 % of rolling resistance [82]. A number of tire operating conditions affect rolling resistance. The most important are load, inflation pressure and temperature. Rolling resistance is an important tire-road force product and is basically due to the energy dissipated by tires. The constant deformation of the tire is the main source for loss of energy. In other words, rolling resistance is the energy that is lost when the tire is rolling and the main reason for loss of energy is the constant deformation of the tire. In this research, the main goal is harvesting a part of this lost energy using piezoelectric materials and assessing the environmental effects of the employed harvesting system.

The Government of Canada announced, there are 33, 168, 805 motor vehicles registered in Quebec, Ontario, and Manitoba provinces in 2015 [26]. In terms of the above losses in energy of cars [79] and registered cars in Canada; there is a lot of wasted energy in Canada and in the world, which has the potential to be converted to useful and clean energy. Moreover, the tires account for approximately 21% of a car's fuel consumption- or approximately 5.2% per tire to be taken into consideration here as the environmental impact [73]. Table 1.1 shows and explains the category assignments in terms of vehicle acceleration resistance and contribution of tires to fuel consumption.

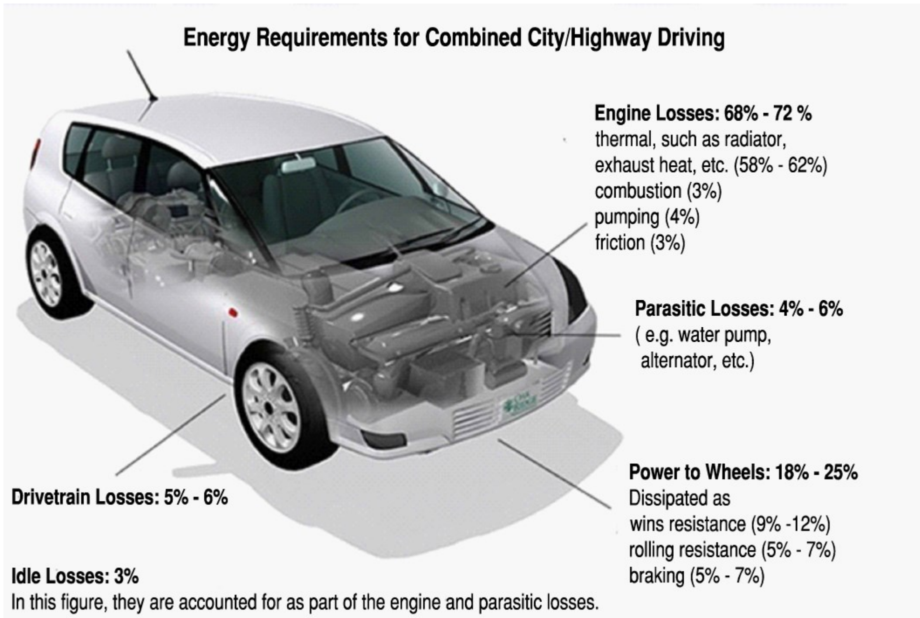


Figure 1.3: Energy losses in cars [79]

Table 1.1: Allocation and evaluation of road resistance [73].

	Total share of vehicle consumption (%)	Reference to the tire	Share of fuel consumption attributable to the 4 tires	Contribution of one tire to fuel consumption
Rolling resistance	16	Vehicle weight	16	4
Aerodynamic resistance	36	Wheel and wheel house account for approx. 25 % of vehicles Aerodynamic resistance; about 50% of that amount is assignable to the tires	45	1.1
Propulsion resistance(internal friction)	32	No reference to the tie		
Acceleration resistance (loss due to braking)	16	Tire weight and moment of inertia	0.4	0.1
Total resistance	100		20.9	5.2

Any product that generates any amount of energy from ambient energies could influence the environmental impacts and decrease rolling resistance energy loses effect. The running cars produce energy when they are running by piezoelectric materials. It is aimed in this study to look for information to use in making a decision to promote a new product. Here, a new product is proposed, namely an intelligent tire which can harvest energies of underneath of the tire by means of tire specific characteristic (e.g. weight). A full life cycle assessment is done to determine the future advantages of this product. The piezo-tire (the name is an integration of "tire" and "piezoelectric elements") is a common pneumatic tire combination with a set of piezoelectric elements bonded to a wheel outer surface as shown in Figure 1.4.

Figure 1.4: Piezoelectric elements bonded to a tire

The piezo-tire aims at performance levels beyond those possible with conventional pneumatic tire technology because of its piezoelectricity characteristic which adds the possibility of harvesting ambient energy through revolving tire. This feature has not changed the rolling resistance which mentioned above, but it can help to capture environmental mechanical stress and convert it to electricity. The environmental impact of this new design is unclear. LCA will help in evaluating the environmental impacts throughout a tire's lifespan from raw material extraction to tire disposal (cradle-to-grave). The current project considers the environmental impacts of piezo-tire assembly and compares it to current tires. The life cycle assessment of all stages of a tire from extraction of raw materials until end of life of tire shows that 92.6% of the environmental impact of a tire comes from the period of use [52].

The whole service life of tire is constantly interacting with its local environment (i.e. pavement). To reduce the negative environmental impact, the detailed knowledge of this interaction is required. The analysis of this report aims to compare the newly developed piezo-tire with current pneumatic tires.

To perform the LCA of this report, SimaPro software version 8.3 is used to facilitate this analysis. This software allows the user to model the environmental inventory by inputs such as resources and outputs namely emissions.

1.4 Research objectives

The main objective of the research is to investigate harvesting waste energy related to running vehicles because of the weight of the device and deformation of pneumatic tires. Therefore, we examine whether piezoelectric materials could generate energy when there are installed in outside of the tire. The project objective includes:

- To evaluate of the amount of energy harvested in pneumatic tires when piezoelectric materials places outside of the tire.
- Evaluation of the impact over the life cycle of this proposed product and comparing it with base line tire.

To reach the above mentioned goals, this work is followed:

- Designing and fabricating an experimental set-up to simulate the tire rotation;
- Installing piezoelectric elements outside of the tire;
- Development of a data acquisition system to store data related to voltage generated by piezo-electric elements. A code for micro-controller we developed to connect to a computer using

wireless. A MATLAB code is developed to gather wireless data in real time data and store it for post processing usage.

1.5 Outline of thesis

Chapter 2 provides an introduction to piezoelectricity and their characteristics; constants and different types of modes of vibration. A review of fundamental equations of piezoelectric effects and their concepts are presented. Different circuits utilized in piezoelectric energy harvesting come in Chapter 3. Chapter 4 is concerned with a literature review of harnessing energy from different application of piezoelectric materials because of kinetic energy. Also, a procedure as a guideline to derive a model for a piezoelectric tire under mechanical stress is discussed. A literature review about life cycle assessment is presented in this chapter as well. The energy harvesting concept and influences of using this self-power harvester from socio-economic point of view are considered in Chapter 5. Chapter 6 is concerned with development of the proposal for the running cars application. In this chapter, it is showed how the piezoelectric elements derived waste energy under running tires. In Chapter 7, the results of fabricated prototype are presented and discussed. The experiment results are compared with previously done work. Also the results of the LCA study are presented. Finally, Chapter 8 is dedicated to conclusion and recommendation for future work.

Chapter 2

Piezoelectric energy harvesting

Jaques and Pierre Curie found the piezoelectricity concept in 1880. They discovered there are some materials in nature, which have piezoelectric property, for instance quartz, tourmaline, and sodium potassium tartrate [53]. To exhibit the piezoelectric effect, each crystal has to be unsymmetrical. A stress (tensile or compressive) applied to such a crystal will alter the separation between the positive and negative charge sites in each elementary cell leading to a net polarization at the crystal surface [53]. Piezoelectric materials can produce charges when they are subject to external mechanical loads. The magnitude and direction of the electrical current determined by the magnitude and direction of the mechanical stress/ strain applied to materials.

Piezoelectric materials have two effects: direct and inverse effects. If pressure produces a charge in piezoelectric materials this effect is called the direct effect (generator or sensor) which means these elements convert mechanical energy to electrical energy. However, if electrical voltage causes a change in the length of materials it is called inverse piezoelectric effects(actuator). These materials convert electrical energy into mechanical energy.

The most commonly produced piezoelectric ceramics include barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$) and lead zirconate titanate ($Pb(ZrTi)O_3$, PZT).The asymmetric location of Ti or Zr in the unit cell generates an electric dipole moment. During poling, an electrical field is applied, which causes the movement of Ti or Zr, and the change of dipole moment direction (see Figure 2.1) [78]. Piezoelectric materials are similar to a spring. Vibration can be produced through springing on the piezoelectric materials because of mechanical stress like loads from a vehicle,

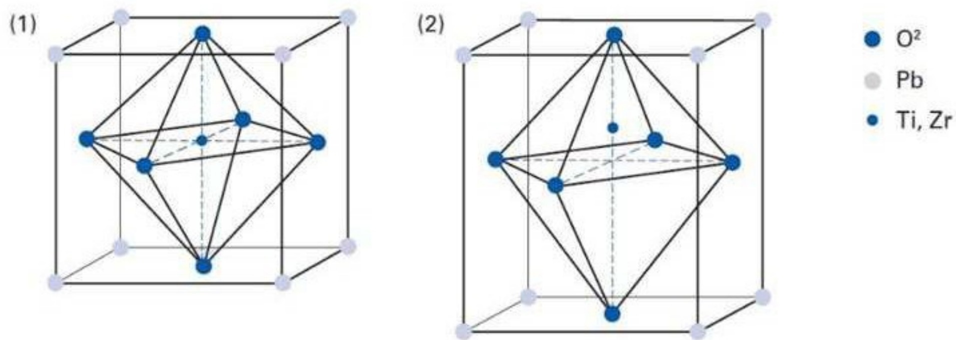


Figure 2.1: Direct and adverse effect of piezoelectric [59]

human foot, railway track, and dance floor. By applying stress, piezoelectric crystals polarized. The amount of polarization is a function of stress, which is applied (Figure 2.2). "When a spring

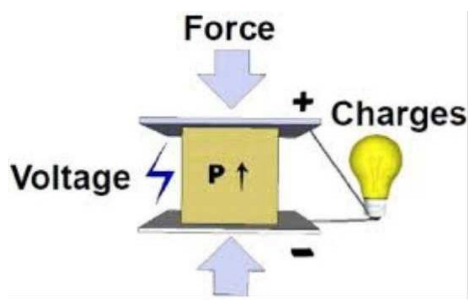


Figure 2.2: Energy generation through vibration [38]

contracts and expands continually many times, it creates a mechanical stress on the piezoelectric crystal places below the springs. This creates electromagnetic induction resulting in electric voltage. In the figure below, carbon nano-tube shape molecules of pure carbon which can be formed into tiny springs. These materials are capable of storing a large amount of energy, which more durable, reliable" (Figure 2.3) [38]. Figure 2.4 [11] shows the principle of working with a piece of piezoelectric material. One important group of piezoelectric materials is the piezoelectric ceramics of which PZT is an example. In this figure, positive and negative charges center shift, which results in an external electrical field. Firstly, piezoelectric materials produce AC voltage and then are converted to DC by a rectifier [77].

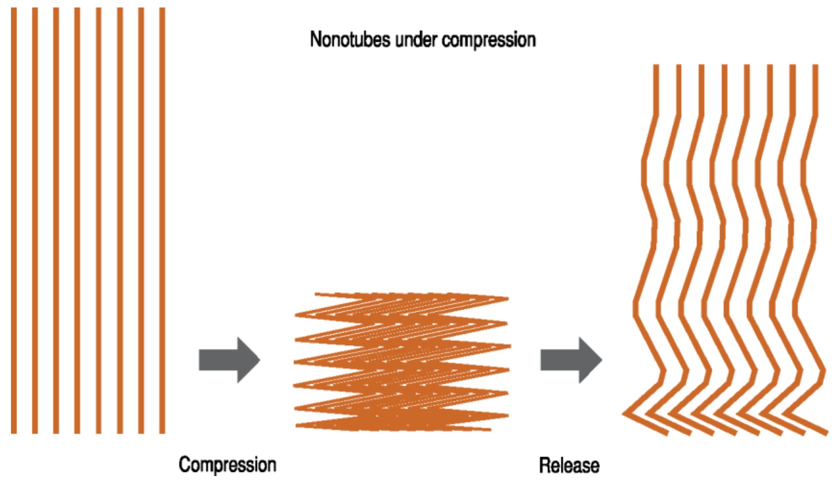


Figure 2.3: Spring in action [38].

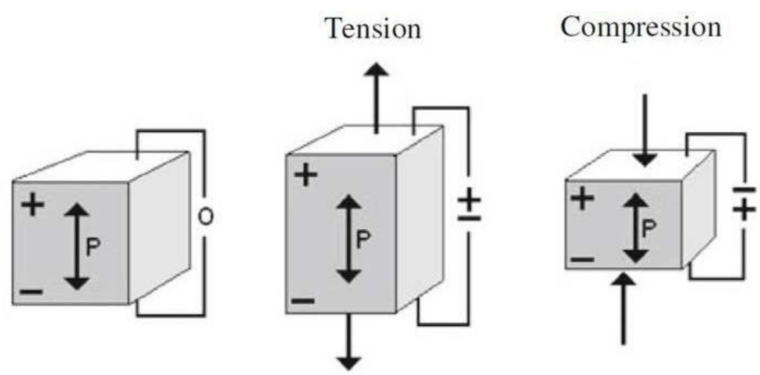


Figure 2.4: Schematic showing the response of a piece of piezoelectric ceramics to an external mechanical simulation [11].

2.1 Stability

”The properties of piezoelectric materials are a function of time and temperature. The poling ages approximately logarithmically so that the rate of change in permittivity, coupling factor, frequency constant, decreases rapidly in the course of time. Therefore, stability dependence of time is more interest. Powerful ambient influences are likely to change the original aging pattern. This applies particularly to the permittivity, the mechanical Q factor and dielectric loss factor.” [53].

2.2 Depolarization

”As already mentioned, after its poling treatment a PZT ceramic will be permanently polarized, and care must therefore be taken in all subsequent handling to ensure that the ceramic is not depolarized, since this will result in partial or even total loss of its piezoelectric properties. The ceramic may be depolarized electrically, mechanically or thermally” [53].

2.3 Basic behavior of piezoelectric elements

Figure 2.5 illustrates the behavior of a cylinder of piezoelectric materials. In the no-load state, cylinder has no charge. Applied strain or stress in compressive or tensile mode results dipole state in the material and causes a voltage to appear between electrodes. As compressive load resumes, the original form of cylinder and the voltage have the same polarity of poling voltage.

If the cylinder is stretched, the poling voltage and polarity will have an opposite direction. This is called a generator action and it means the conversion of mechanical energy to electrical energy. In this state piezoelectric material is a generator. So, generators convert force and strain to voltage and charge. Microphones, gramophones, and cigarettes are examples of generator action.

If the voltage polarity and the poling voltage is the opposite side, the cylinder will be shortened and vice versa. This is called the actuator. In addition, piezoelectric elements with this property are called piezo motors or actuators. Therefore, actuators convert electrical energy to mechanical energy. Actuators have not considered in thesis research. Figure 2.5 demonstrates all of the above description.

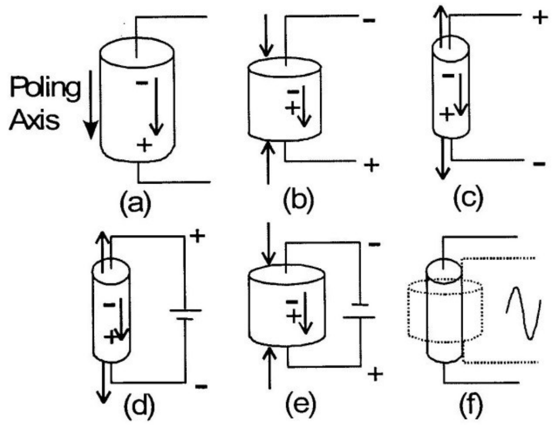


Figure 2.5: The piezoelectric effect in a cylindrical body of piezoelectric ceramic [33]

There are two kinds of generators: one layer generators (longitudinal and transverse generators), two layer generators (extension and bending generators), and multilayer generators (Stack generators). In this research, only one layer generators are discussed.

2.4 Longitudinal generators

”When a mechanical stress is applied to a single sheet of piezoelectric in the longitudinal direction (parallel to polarization), a voltage is generated which tries to return the piece to its original thickness” [60] (Figure 2.6).

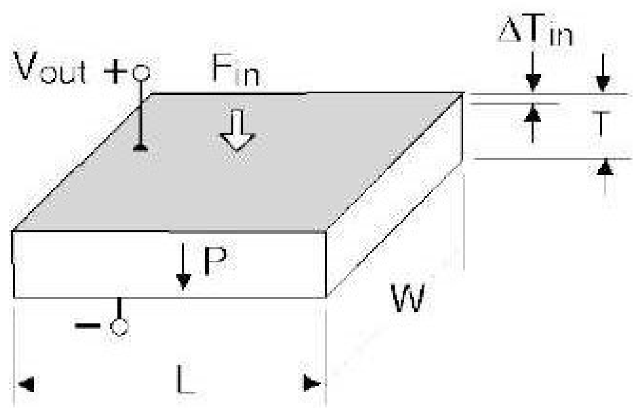


Figure 2.6: Longitudinal (d33) generator [60].

2.5 Transverse generators

”When a stress is applied to a sheet in a transverse direction (perpendicular to polarization), a voltage is generated which tries to return the piece to its original length and width. A piezo sheet bonded to a structural member who is stretched or flexed will induce electrical generation” [60] (Figure 2.7).

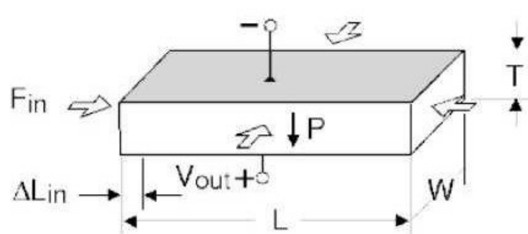
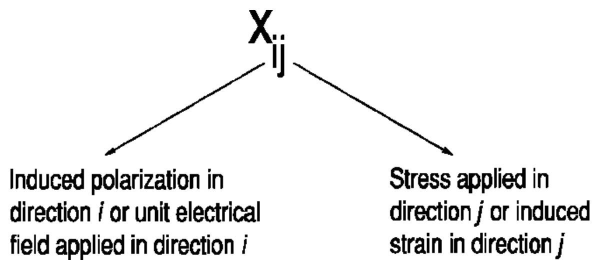


Figure 2.7: Transverse (d31) Generator [60].

Piezoelectric materials are anisotropic and their physical constants relate to the direction of applied stress or strain and directions perpendicular to a applied force. Consequently, each constant has two components. The direction of positive direction is along the z-axes of rectangular system of X, Y, and Z-axes. Subscripts 1, 2, 3 represent the global axes direction and shear related to these axes represented with 4, 5, 6. Most frequently used constants for piezoelectric materials constants are summarized in Figure 2.8 and 2.9. In all definitions, the first subscription refers to the direction of strain and the second one is the direction of stress:



2.8: Direction of applied stress [11].

2.6 Piezoelectric constants

Properties of piezoelectric materials are generally characterized by k_p, k_{33}, d_{33}, d_{31}, g_{33} as piezoelectric constants [11].

2.6.1 Piezoelectric charge constant d

The piezoelectric charge constant is defined as the electric polarization generated in materials per unit mechanical stress applied. Alternatively, it is the mechanical strain experienced by the material per unit electric field applied to it [53]. The factor *d* is an important indicator of material suitability for strain-dependent(actuator) application.

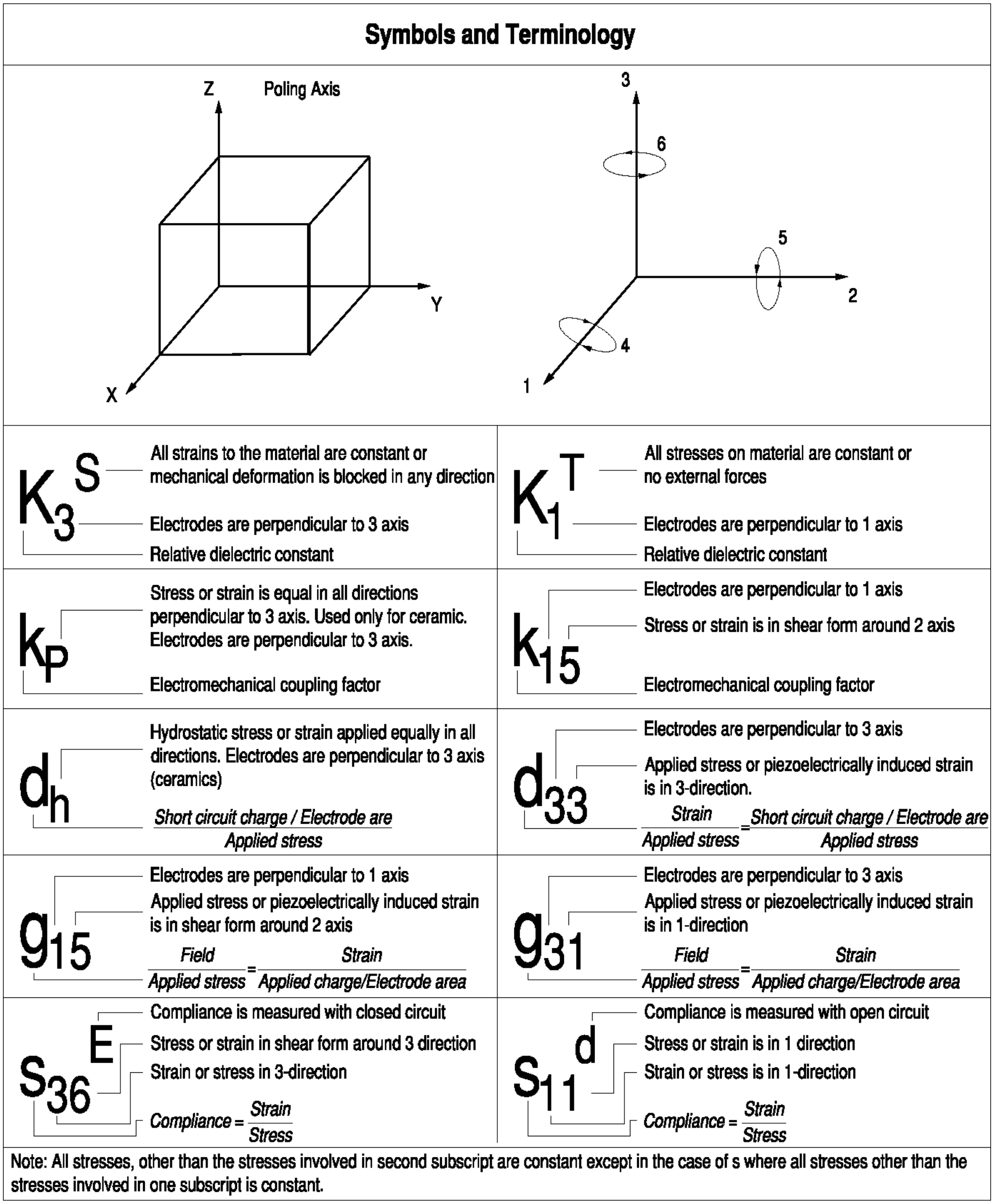


Figure 2.9: Basic Symbols and Terminology in Piezoelectricity [23].

2.6.2 Piezoelectric voltage constant g

The piezoelectric voltage constant is defined as the electric field generated in a material per unit mechanical stress applied to it. Alternatively, it is the mechanical strain experienced by the material per unit electric displacement applied to it [53]. The factor *g* is an important indicator for assessing suitability for sensing application. The *g* factors called open circuit coefficients, and it is parameter to evaluate the ability of piezoelectric material to generate large amount of voltage.

2.6.3 Permittivity E

The permittivity is represented by ε and is defined as:

$$\epsilon = \frac{Electrical\ displacement}{Unique\ electrical\ field} \tag{1}$$

2.6.4 Elastic compliance S

The elastic compliance S of materials is defined as: strain produced per unit of stress.

2.6.5 Young’s modulus

The Young’s Modulus constant is an indicator of the stiffness (elasticity) of ceramic materials.

2.6.6 Electromechanical coupling factor

This factor is an indicator of the effectiveness which piezoelectric material converts mechanical energy into electrical energy and vice versa. This constant represented by K. This constant is continent measurement of the overall strength of electromechanically effects. K is always less then unity because the conversion electrical to mechanical energy or vice versa is incomplete. Equations 2 and 3 represent direct effect and converse effect of coupling factor, respectively [11].

$$Direct\ effect = \frac{Energy\ output\ in\ electrical\ form}{Total\ mechanical\ energy\ input} \tag{2}$$

$$Converse\ effect = \frac{Energy\ output\ in\ mechanical\ form}{Total\ electrical\ energy\ input} \tag{3}$$

2.6.7 Dielectric dissipation factor

The tangent of the dielectric loss angle is shown with δ or tan(δ). In parallel circuits are defined by the ratio of effective conductance to effective susceptance and are measured by an impedance bridge. Figures 2.10 and 2.11 present the different modes of vibration of piezoelectric materials and their charge and voltage amount production under stress.

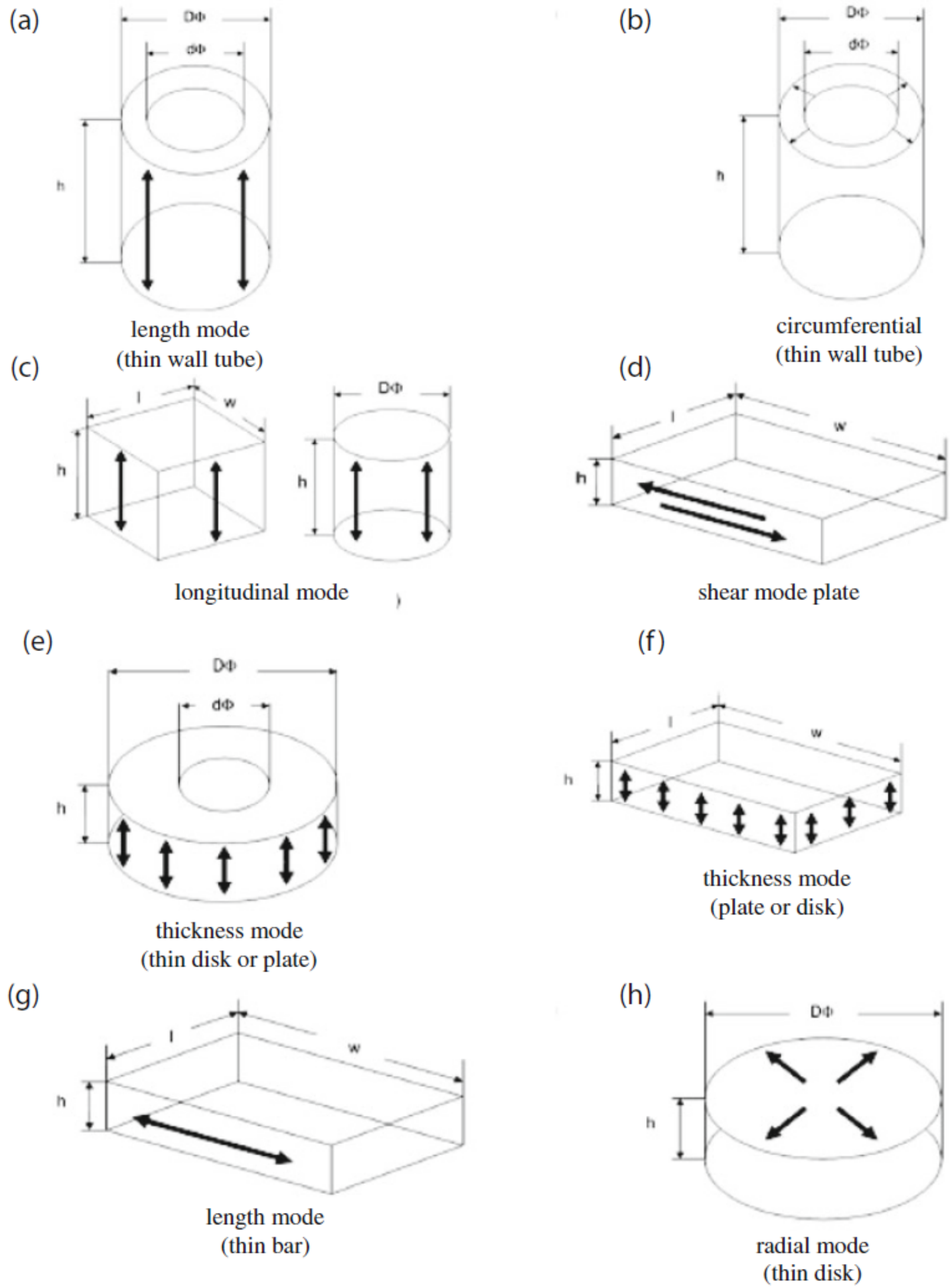


Figure 2.10: Different modes of vibration [11].

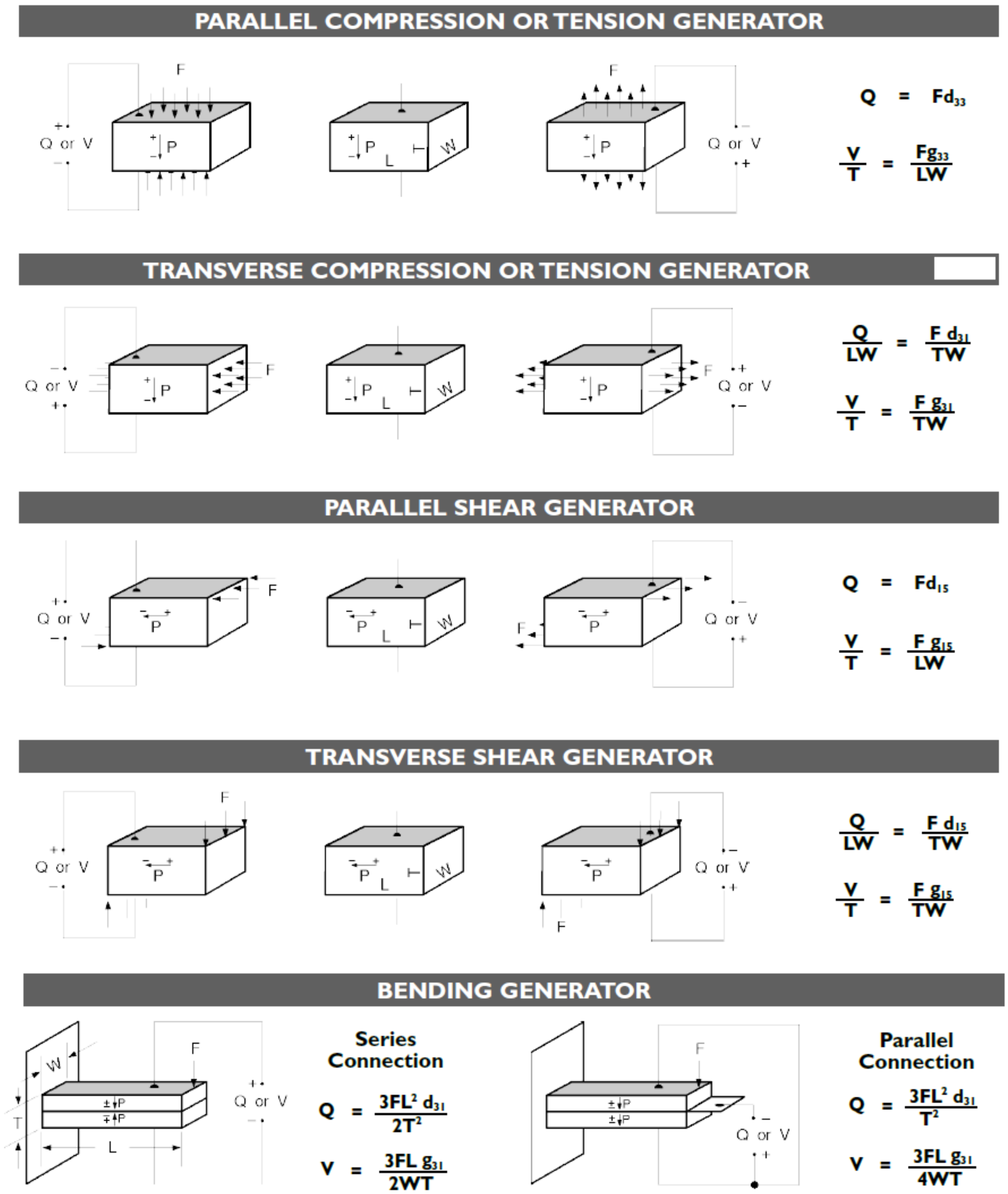


Figure 2.11: Generator transducer relations [60].

Chapter 3

Conditioning circuity

Piezoelectric devices are subject to resistive loads in electrical domain for evaluation of the performance of alternative current (AC) power generation. This alternating voltage should be converted to a direct voltage to use electricity. This can be gained with a rectified voltage, and a smoothing capacitor to form an AC-DC convertor. This energy could be stored in capacitors or charge the batteries. A power manager uses a DC-DC voltage output regulation to maximize power in energy storage, and match impedance. Power managers cope with challenges of transferring energy harvesting from the source to the final device or storage element like a battery. Figure 3.1 shows a typical schematic diagram of a power manager.

In the case of alternate sources, a rectifier is required. In the case of direct sources, impedance

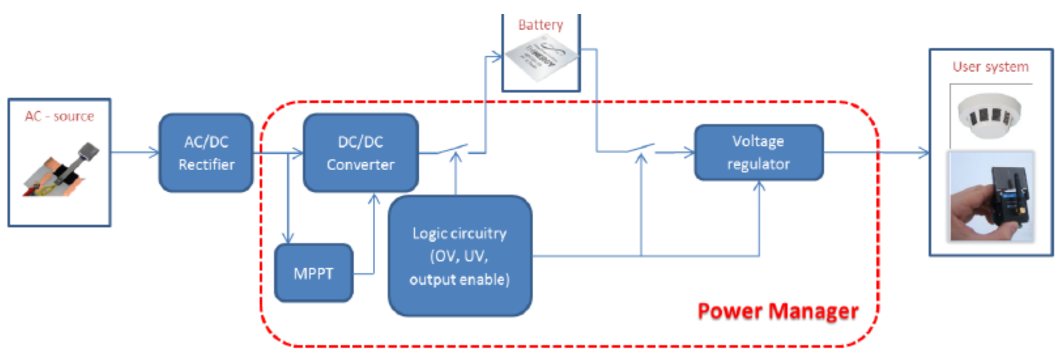


Figure 3.1: Typical schematic diagram of power manager [14].

matching can be achieved using a maximum power point tracker (MPPT) [14]. The charge and discharge phases control with logic circuitry. Piezo electric materials are AC sources; so, their output needs to rectify and adjust for output devices. The simplest rectifier can be a diode bridge rectifier (see Figure 3.2). These components are necessary for practical application of energy harvesters [11]. Another possible circuital interface is the parallel-SSHI (synchronized switch harvesting on induc-

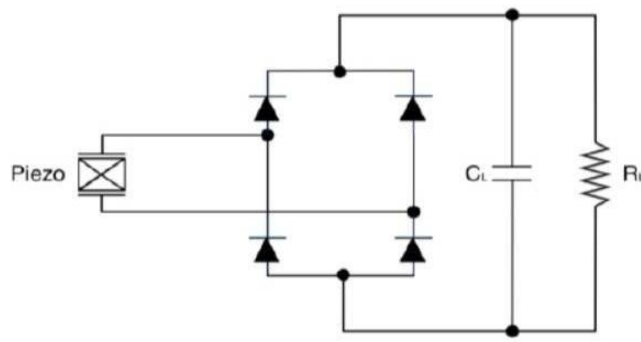


Figure 3.2: Diode bridge rectifier [14].

tor) [27].This approach allows enhancement of the coupling coefficient of the electromechanical system using piezo materials [64], it allows gaining up to 10 times of harvested energy [29]. The technique is derived from a semi-passive technique developed for mechanical structures, called SSD (synchronized switch damping) [10, 71]. Such confirmation adds an inductor-switch branch in parallel to the source (see Figure 3.3). When the device displacement is a maximum amount, the

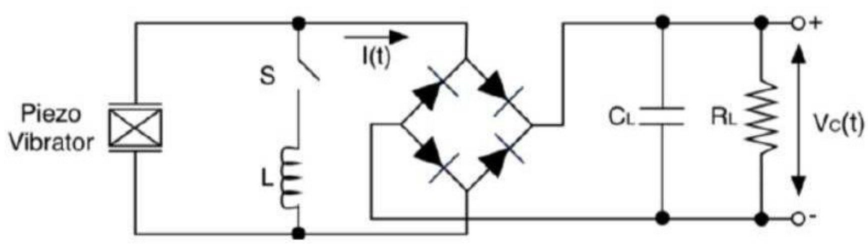


Figure 3.3: Parallel SSHI interface [14].

switch is turned ON, the condition of the internal capacitance and the inductor constitute an oscillator, where the characteristic electrical period must be much smaller than the mechanical vibration period. The circuit allows inverting quasi-instantaneously the voltage of the piezoelectric element and thus to put in phase the vibration velocity and generate voltage [28].

A possible implementation of the parallel-SSHI interface consists of two switches, one for the positive half-wave and another one for the negative. The switches implement through two MOS transistors driven by the output of a comparator that reads the derivative of the piezoelectric voltage, in order to catch the peak and let the inductor to discharge the parasitic capacitance [27].

This technique allows increasing the voltage output or to obtain the same output of a standard interface device while reducing the volume of piezoelectric element. Based on the same concept, a series-SSHI rectifier consists of an inductor-switch branch added in series to the piezoelectric element, followed by a diode bridge rectifier (Figure 3.4). Based on the same concept, a series-SSHI rectifier consists of an inductor-switch branch adds in series to the piezoelectric element, followed by a diode bridge rectifier (Figure 3.5). The switch control is the same as described above for parallel-SSHI [44].

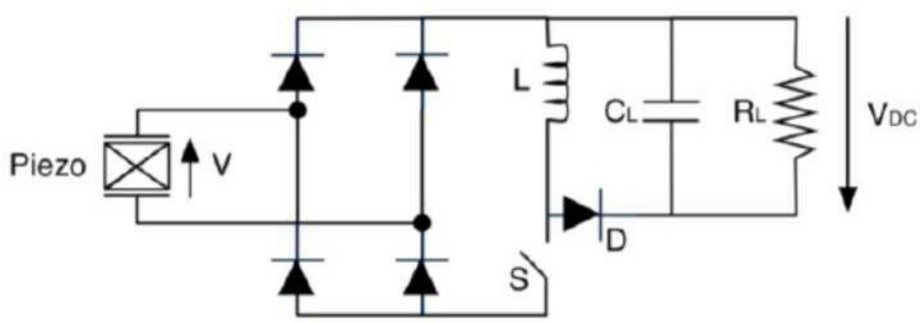


Figure 3.4: Synchronous charge extraction interface [44].

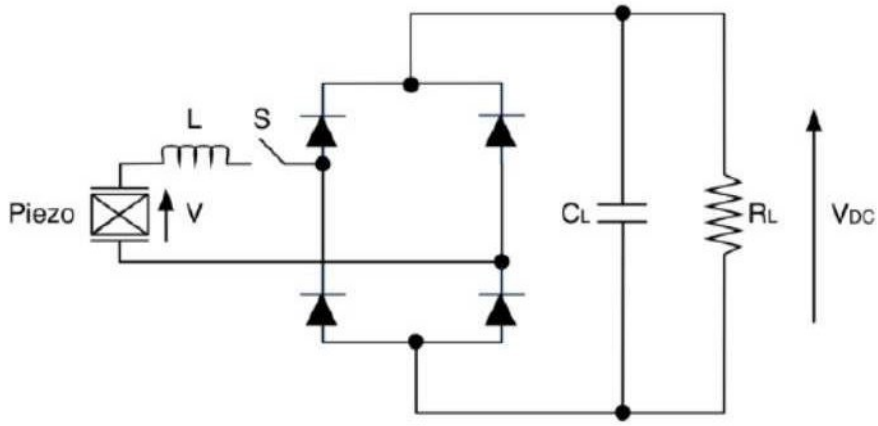


Figure 3.5: Series SSHI configuration [44].

The four techniques have the same maximum harvested power, but at different values of the electromechanical coupling factor. Practically, the synchronous charge extraction technique reaches the maximum of lower electromechanical coupling factor, enabling reduction in required amount of piezoelectric materials, since k2 is roughly proportional to the amount material. Moreover, synchronous charge extraction is indifferent to impedance matching. Commercial solutions are available because of the research progress achieved in the last years [14].

Linear technology (Milpitas,CA,USA) has developed a series of conditioning devices for energy harvesting. Those circuits are targeted for piezoelectric-based harvesters (Appendices C and D).

Chapter 4

Energy Harvesting

4.1 Literature review

This literature review aims at reflecting the previous scholars done to harvest the waste energy of ambient. First, herein, advantages of the energy harvesting are discussed according to the previous researches. Following that, the capability of the piezoelectric materials in harvesting this kind of energy is explained. After that, the automobile industry pioneered as a candidate, results of recently done work, and methodology related to energy harvesting in the car industry are described. And finally, some of the examples which are performed or contemplated to harvest energy are explained. The definition of waste energy could include two aspects: i) waste to produce energy or energy from waste and, ii) energy that can be used but is wasted instead [11].

The energy harvesting is the process of capturing and conversion of small amounts of readily available energy in the environment into usable electrical energy [40]. Such as solar panels, which convert energy in sunlight to electricity, the other harvesters also, take the environmental energy, mostly vibration and heat which is wasted and convert it to the useful forms of energy such as electrical and mechanical.

Stromdahl [76] reveals that from an environmental point of view, the energy issue is central and ever-present, and there are several ways to increase the environmental benefits by focusing on different stages of the chain. One way is to invest in cleaner forms of energy. Another is to switch to more energy-efficient appliances. A third is to choose technologies that minimize the losses in the distribution and transformation - and there are big gains to make. Over a quarter of the energy produced is lost on the way to the user.

The harvesting waste energy has the potential to replace batteries with other small and low power electronic devices. This provides several advantages. Free maintenance is one of them. It is also environmentally friendly and the disposal batteries are avoided. Batteries usually contain chemicals and toxic heavy metals that are harmful to the environment and hazardous to human health. It has potential applications to monitor remote or underwater locations. Different types of waste energy should be captured using different technologies and materials. For example, with the increasing computer components speed, they produce a huge amount of heat, which is wasted in the environment. This heat can be used as a source of energy or some other devices. This also cuts the cost of computers and energy consumption.

There is a lot of energy waste in daily use; so, as long as, the waste energy is recoverable, it is useful and brings many environmental and economic benefits. According to Newton's third rule, energy converts from one form to another without destroying it. Always there are losses along the chain. For example, chemical energy is converted into motion. There are two metrics to determine the amount of energy harvesting of piezoelectric materials: power and energy. Power is the unit of energy per second and designated in watt (W). Power is an indication of how quickly energy can be delivered [31]. A high power air conditioner can cool the room quicker than a weak power heater which is used to heat a room. The other metric is energy. This is defined in different units like Joules, kWh; but, for electricity is most common to use watt-hour which it means how many watts are produced in an hour. Power and energy are stated as power density and energy density. These are the amount of energy which can be made in area or volume. A typical solar panel might measure $60\,\mathrm{cm} \times 90\,\mathrm{cm}$, or 0.54 square meter (0.54 m^2). Its power density would then be 200 watts in six square feet, or $200/0.54 = 370\,\mathrm{W/m^2}$) [31].

Piezoelectric energy harvesting is one of the most reliable power sources. There is much debate about whether a piezoelectric harvester can be classified as a renewable energy or not. Renewable energy tends to be inexhaustible in the context of energy. Regardless of these concepts, harnessing waste energy can increase the efficiency of system.

Figure 4.1 demonstrate the schematic diagram of power density versus voltage for different energy harvesting [17]. Among all energy harvesting techniques, piezoelectric devices are the most promising technologies because of their simple structures which make their application easy. Additionally,

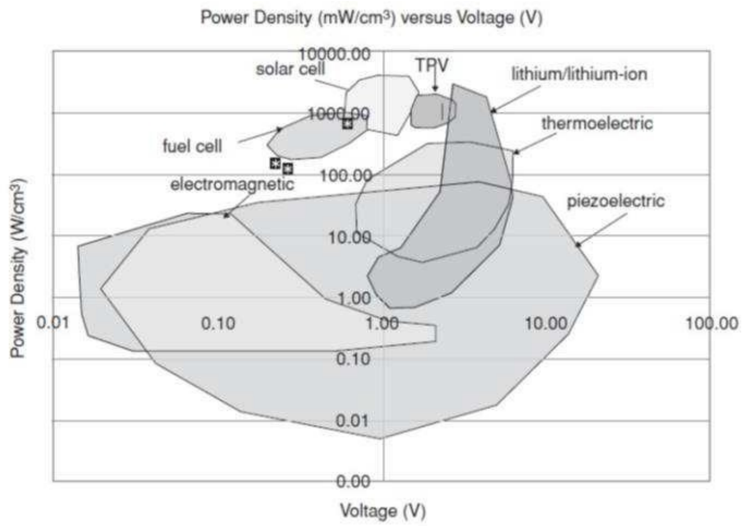


Figure 4.1: Power Density versus Voltage for various Energy Harvesting Technologies [57].

they are not simply affected by external and internal electromagnetic waves [81]. As indicated before, piezoelectric materials can convert waste energy into electricity and reduce the fuel needs of vehicle and improve fuel economy by at least 5 percent [57]. This process has rapidly gained momentum due to energy efficiency and environmental benefits. Piezoelectric energy is no longer viewed as a being unreliable source of energy with low power output and there has been considerable development in utilization. These materials were introduced in detail before.

A large number of passing vehicles through the roads have a large source of waste energy, which can potentially generate electrical energy. Among all industry, car industry due to having the biggest consumer among all energy dependent technologies is more interested. There is no significant research related to amount of waste energy in cars subjected to vibrations and deformations like tire. Kim et al. [39] investigated the capability of piezoelectric transducer to scavenge electric power from automobile engine vibration. In recent years, some research has been done related to tire energy harvesting. Their fundamental problem is that they do not consider viscoelastic deformation of rubber. Moreover, there are no analytical studies for the amount of energy which can be harvested from tire. Researcher's findings demonstrate that there are three forces and one torque acting on an automobile tire. The shown forces in Figure 4.2 are the results of different characteristics of a car. The vertical force is due to the sprung mass of the vehicle, aligning torque is caused by the steering torque on the tire, longitudinal force is originated by the traction/acceleration or braking/deceleration, and the lateral force is the reaction of the forces to turn vehicle [5].

Among these forces, the share of the vertical component in deformation of tire is dominant (tread

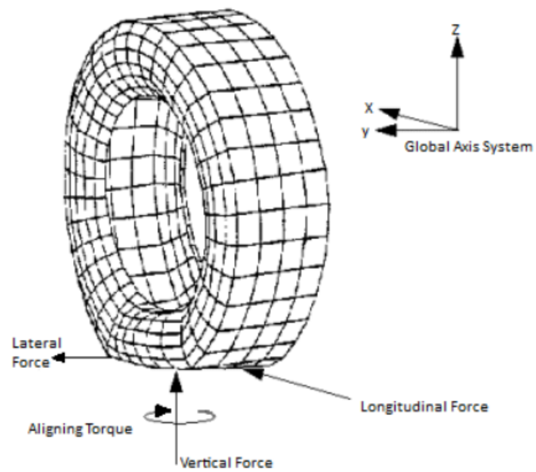


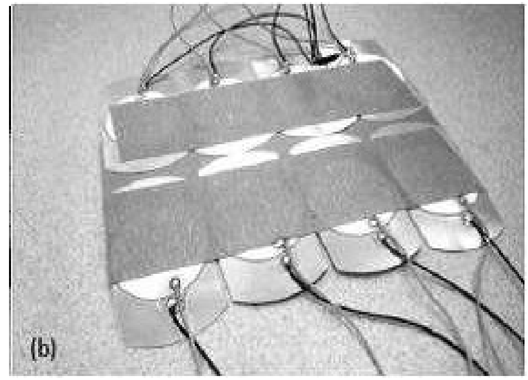
Figure 4.2: Forces and Torque at the Center of the Tire-Road Surface Contact Patch [5].

region73%)[15]. Although, piezoelectric materials has low power and efficiency, but, it can be improved by modification of materials, changing stress direction, and changing of the electro patterns [3]. The important thing for future of energy harvesting thing by piezoelectric materials, is that these kinds of sources increase the transmission of wireless sensor and decrease the battery replacement and disposal costs. The contemporary ambient vibration energy occurs in a low frequency range of 1-100 Hz for machine induced motion [41]. Different factors and state of the art solution which influence the output of piezoelectric harvesters such as geometrics, type of materials, and techniques to match the resonance frequency of piezoelectric materials, and electric circuits are indicated in Li and Strezov [47]. Also, resonant frequency influence the power output performance waves [81]. New methods to improve energy harvesting from low frequencies is developed by Ashraf at al. [6].

So far, much research has been done to harvest waste energy of cars to propose one alternative low cost and reliable system to power small parts of cars namely tire pressure monitoring system (TPMS). Using piezoelectric energy harvester in cars can replace batteries in TPMS module which is mandatory in United States and European cars. As an example, Manla et al. [49] used centripetal force to generate an impact on the piezoelectric transducer. This new designed system produced 4 mW of electrical power at 800 rpm. On the other study, the problems and challenges of energy harvesting considered for TPMS in terms of design point of view. Previously scholars demonstrated that the wheel of a car is an energy rich environment [69]. Wei and Jing [81] presented the state-of-the-art investigation related to vibration based energy technology, i.e., theory, modeling, approaches in piezoelectric materials. Although, their findings showed that piezoelectric energy harvesters have some disadvantages such as low coupling factors and depolarization in unloading, these materials are hardly affected by electromagnetic waves in comparison to current energy harvesters. In addition, the advantage of piezoelectric energy harvesting is to decrease the fuel consumption and off-balance problems of the tire [50]. Therefore, these kinds of energy supplies eliminate the need for the battery replacement. The battery-less self-power systems could be a future technology and it is required to do more research for achieving the sufficient efficiency. To use better of these kinds of energy, the design problem and significant challenge should be solved.

In the research done by Makki and Pop-Iliew [48] showed that how piezoelectric materials could generate power by assembling these elements within the vehicle's wheel. The previous studies just have used one or two piezoelectric elements to harvest small amounts of energy which could be used in small devices. On the other hand, the type of piezoelectric which they used was different. In this study, piezo benders in circular shape with 44 mm diameter and 23 mm in thickness are used. This PZT is mostly used in a buzzer. Development of this idea can decrease the dependency of current hybrid cars to utilize conventional fuels to charges batteries. In this research, 40 rows of 4 piezo elements bonded on a ribbon and then installed inside of tire. Figure 4.3 shows the installment of the elements inside of the tire. To test and measure power generation, a dynamometer was used to simulate the speed and weight of car on the tire. All elements were connected in parallel in a row to a rectifier bridge and then all of them were connected in parallel to each other. When the test is run, the elements which producing power acts as a voltage/current source and the rest of rows act as open circuit.

(a) Piezo elements bonded to inner side of tire



(b) Two rows of piezoelectric materials

Figure 4.3: Piezo elements installed inside tires [48].

Approximately 2.3 watts of power was generated by this experiment by around 160 PZT boned to the inside of a tire of 185/65R14 at 100 km/h at load of 1000Ω [48]. As indicated in this work, increasing the piezo elements could affect the amount of power. For two series of elements which bonded to present series, the amount of power increase to twice of previous one. Power output is strongly depends on surface area, round per minute (RPM) and piezo bender deformation. This relationship is direct, and increases the amount of output as one of these items increase.
In the subsections to come a couple of other piezoelectric technologies and applications are explained.

4.1.1 Virus-Based energy harvester (Bacteriophage)

Bacteriophage devices are an innovative technology to generate energy from every day mechanical vibration. This material invented by the Lawrence Berkeley National Laboratory (LBNL) to provide a sustainable energy source from environmental kinetic energy and convert it into electrical energy via piezoelectric properties of a biological material that is a harmless virus [43]. This new invention can cope with the future energy challenge of battery-driven devices. It can provide a sustainable, cost effective, nontoxic, and biocompatible energy source [42]. Figure 4.4 illustrates one experiment of a bacteriophage energy harvester. When a virus film is pressed with a finger, it generates enough electrical energy to operate the LED device, showing the number ”1” [43].

The manufacturing cost for the Bacteriophage Power Generator is estimated to be between $0.02

Figure 4.4: Bacteriophage energy harvester [43].

(materials cost) and $.78 (materials and labor) for a device measuring 1 cm x 1 cm, depending on its application [43].

4.1.2 Energy harvester mounted on a shoe

A Moonie harvester is embedded inside the shoe (see Figure 4.5) to estimate the amount of harvested energy because of heel presses. The ”Moonie,” [45] is a metal ceramic composite transducer that has been developed by sandwiching a poled lead zirconate titanate (PZT) ceramic (PZT-5H) between two specially designed metal end caps. The energy output of one step was recorded as 81 μJ which translates to 162 μW for two shoes when walking 2 steps per second. The power density at 1 step per second frequency was measured as 56 $\frac{\mu W}{cm^3}$ [45].

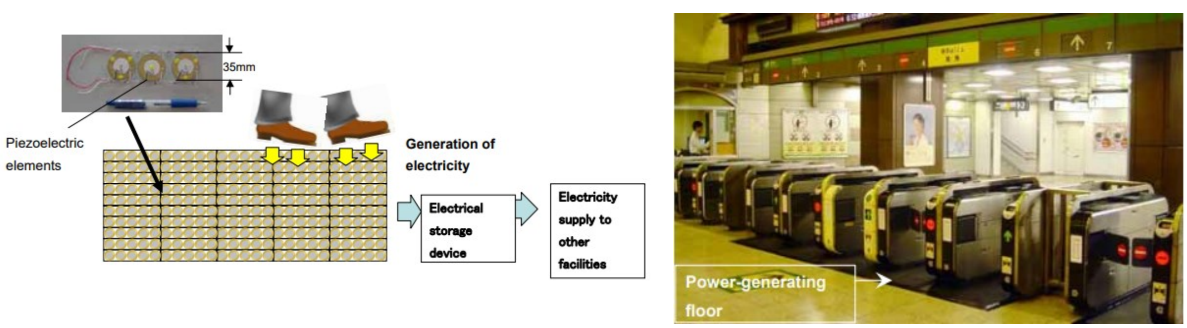
4.1.3 Energy harvesting in transport terminals, airports, and streets

Currently, there is more need to use renewable energy at airports, terminals, high traffic streets, and sidewalks because of passenger foot traffic. Clean, more sustainable forms of energy can be generated with capturing waste energies in these places to insure a healthier environment for future generation. To reach this goal, piezoelectric energy harvester is a good candidate to be installed in airports and terminals to capture kinetic energy from foot traffic. This energy can offset some

Figure 4.5: Shoe measurement system [45].

amount of grid power. This type of energy is clean and renewable.

One example of harnessing piezoelectric energy at a terminal and airport was conducted at The East Japan Railway Company (JR East) at 2008 (see Figure 4.6). They embedded 600 per square of piezoelectric elements with 35 millimeters in diameter and disc-shaped components at ticket gates. While the loudspeaker creates sound by converting electric signals to vibrations, the floor adopts the reverse mechanism that produces electricity by harnessing the vibrational power generated from passengers' steps [35]. The maximum electricity production reached to 10000 watt-seconds per day which is enough to light a 100 W light bulb for 100 seconds [35].



(a) Walking generates energy. (b) Tokyo Station.

Figure 4.6: Power generating floor at Tokyo station [35].

4.1.4 Proposal adopting piezoelectric energy harvesting in educational buildings

An experiment performed by Rastegar et al. [65] in the building sector as the demand for energy needs for enhancement of building services and comfort levels is growing with the population. So, integrating alternative energy resources is of paramount importance to minimize the growing energy requirement. In this research, to improve power generation efficiency, two stage energy harvesters were designed for very low frequency vibration environment in 0.2-0.5 Hz range as shown in Figure 4.7. This is called the Plucked method. This design contains two parts: first a mechanical

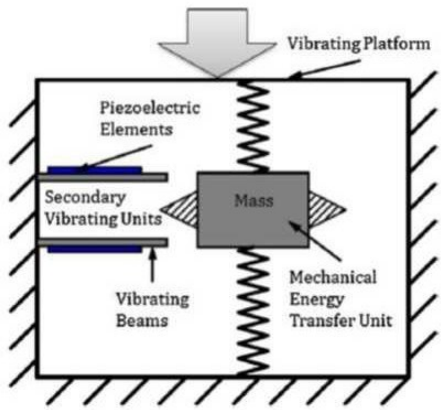


Figure 4.7: Schematic of an enhanced piezoelectric energy generator based on the two stage energy harvesting approach [65]

energy transfer unit which is linked with a vibration platform and next is the secondary vibration units which is composed of piezoelectric elements and vibrating beams. Due to the initial impact effects on the platform, the mass attached on the mechanical energy transfer units starts to vibrate at low frequency. This low energy vibration then is transferred and excites the piezoelectric beams as it passes over the secondary vibrating unit. So, the energy yields are strongly related to the time that piezoelectric elements are activated.

”If the piezoelectric elements are activated once per single footstep, the power generation (W) then can be calculated as a function of the number of pedestrians and the number of tiles that are stepped on by a single pedestrian along the pathway. The function is defined as follows:

$$W = M \times n \times E \times R \tag{4}$$

where M is the number of pedestrians; n represents the number of tiles that are activated is the electricity generated from single step; R is the enhancement rate when the plucked method is used to improve the harvesting efficiency" [47]. N in the above equation is a function of the size of the tile and their deployment method. Hence, the variations of n have to be considered by applying Equation 5 and Figure 4.8.

$$n = \frac{L_1}{L_T} \tag{5}$$

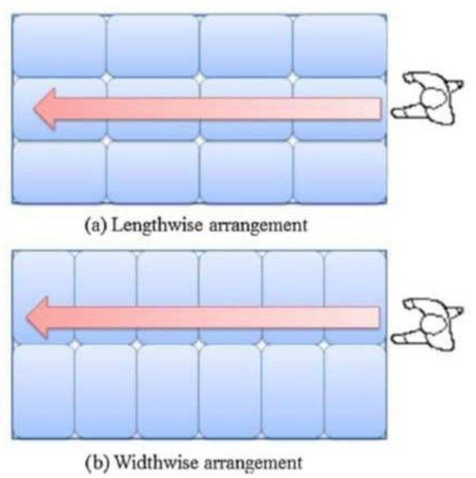


Figure 4.8: Two types of piezoelectric tile deployment [65].

According to these research results, 1.1 MWh/year can be harvested annually from pedestrian crossing energy. This model shows that the piezoelectric energy harvesters can save AUS $540 in the annual running costs and reduce 10 percent of greenhouse gas emissions by replacing the electricity from the power grid [47].

4.1.5 Power generation from pedestrian footstep

A company [58] has completed over 100 projects around the world, across various sectors including train stations, shopping centers, airports and public spaces. Figure 4.9 shows some projects which were performed by this company.

(a) Omer Train Station, Northern France . (b) Federation Square, Melbourne. (c) The Crystal, London.

Figure 4.9: Footstep energy generating sample projects [58].

This new technology captures energy from footsteps fooling on it and a combination of electromagnetic induction and flywheel energy storage technologies with capability of producing 7 watts of electricity from one person walking across a short space [58].

4.1.6 Dance floors

A similar project was performed in London by the Club4climate project which produces electricity with dancers jumping up and down which charges some batteries. This club produces 60% of the energy needed by the clubber's movement [20].

4.1.7 Piezo-harvesters embedded in rail-ways

The first try of installing piezoelectric IPEG pads on the rail track was done by Innowatchtech Inc [18]. an Israeli company. The experiment was conducted on the railway with ten-car train weight. Achieved results demonstrate that around 120 kWh could be produced which is enough to power light and signs, and other surpluses that can be routed to the grid (see Figure 4.11).

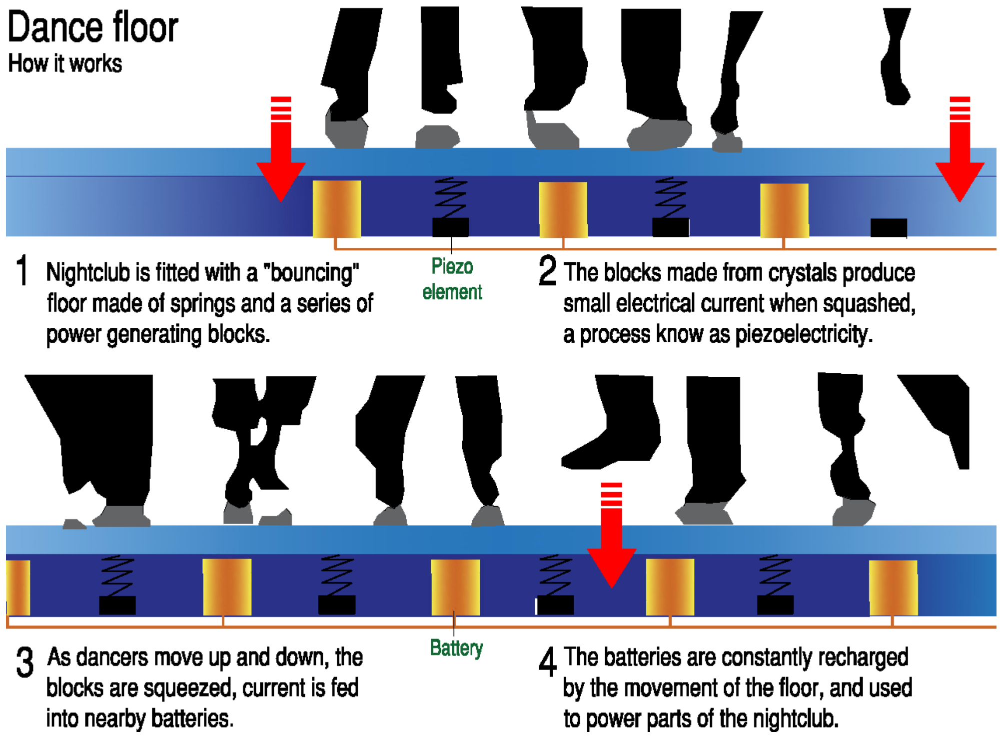
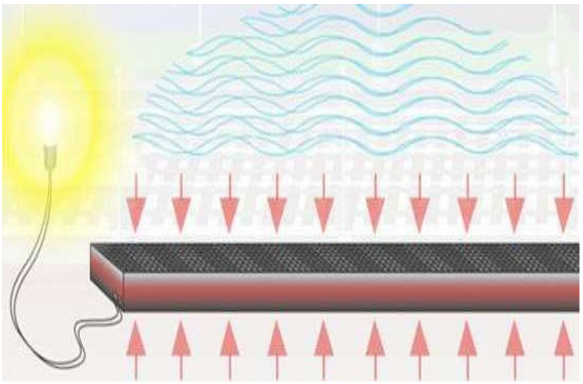


Figure 4.10: How a piezoelectric flooring system generates electricity through kinetic energy [20].

(a) Installing piezo IPEG pads.



(b) Piezo IPEG pads' function.

Figure 4.11: InnoWatch IPEG pads [18].

4.1.8 Piezo-smart roads

Transportation on highways and roads play a significant role in economy and society development. Currently, the speed of energy consumption is more than the speed of regenerating it. Therefore, to have more sustainable and reliable types of energy, it is required to think about some new technology to supply power. Almost all people need to use roads and highways very often such as taking buses or riding in cars. According to research, the transportation sector consumes almost one-third of the nation's energy [30]. Innowatch Inc. was the first company which worked on the

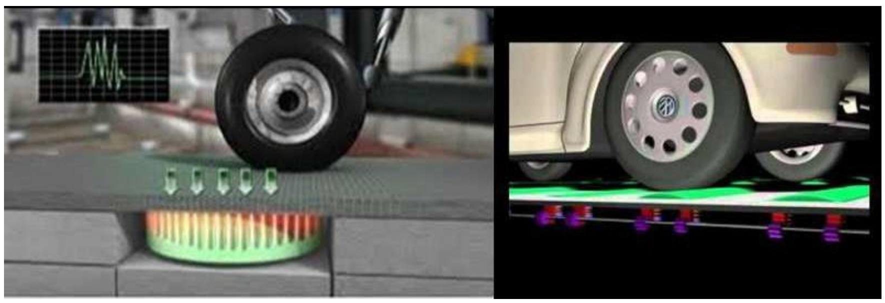


Figure 4.12: Smart-Road [30].

harnessing energy from the roads. According to Henderson [30], piezoelectric crystals embedded in the asphalt can generate up to 400 kilowatts of energy from a 1 kilometer stretch of generators along the dual carriageway (assuming 600 vehicles go through the road segment in an hour), enough energy to power 600-800 homes. The energy generating road offers a self-sustaining environment for the future.

4.2 LCA literature review

In tire industry, tire manufacturers are challenged to develop sustainable (economically and environmentally) products to participate in competitive markets with other manufacturers. Much research has been done to minimize the environmental impacts of this industry by citing ISO standards. Tire manufacturers are urged to improve steadily the performance of tires. On the other hand, they try to develop a product with minimum environmental impact. These two parts are mutually unique. LCA help to manufacturers to record all sustainable development aspects of tire during the life cycle of the tire. This approach provides consideration of all contributions of raw materials, energy use, distribution, use, treatment and re-use of the product. According to Backer and Gloeggler [8] the major environmental impact throughout a car's life cycle consists of the tire use phase with carbon dioxide emissions linked to the fuel consumption of the car, attributed to rolling resistance. This conclusion was also confirmed by SilkeKromer [73]. The North America manufacturers are slow to adopt LCA for their products, and therefore there are a few documents related to tire environmental impact assessment in comparison to Europe. There are differences in European and American life cycle assessments. One is related to material composition of tires. However, European average use is 40000 km for the tire life and the American average is 40000 miles. The other difference is between fuel use over the life cycle of the tire. The disposal route in the end of life of European is different with American. According to Reschner [67] a much larger percentage of tires are landfilled in Europe instead of incineration.

Raw materials used in the tire industry are documented in Simapro software, but, since energy requirements and emission change in different countries, other sources would be used as a source of inventory data. Herein, data published by Cobert [16] was used for baseline sources and data published by Ibn-Mohammed et al. [32] was used for piezoelectric material resources.

The other issue related to the tire LCA is end of life. Work has been done to increase the used tires instead of waste, and the landfilling method increases the environmental concerns among the public [9]. Therefore, new innovations in rubber shredding and incineration reduce the excessive scrap tires [55]. Morris [54] concluded that incineration consumes less energy than landfilling; even this method can recover energy from the waste material. For example, 1 kg of tire rubber contains 36 MJ of energy which is 4 times more than the same amount of coal [66]. Although open tire firing produces a large amount of carbon monoxides, particulates, sulfur oxides, nitrogen oxides, and volatile organic compounds. Open tire firing is not allowed. Standard and disposal methods of tires are always updated to provide the sustainability of the tire industry.

Chapter 5

Socio-economic impact of piezoelectric materials in cars

Climate change is one of the crucial problems, which the world is facing currently. With increasing usage of fossil fuels, levels of CO_2 and other levels of greenhouse gases are increasing with dangerous consequences including increasing global temperature. These current challenges of climate and energy require sustainability. Contemporary reliance on fossil fuels and emissions of CO2 to the atmosphere are not sustainable activities. CO_2 emissions growth demonstrates that this amount is beyond the atmospheric absorption capability.

All energy technologies have different amounts of environmental footprint. However, energy from renewable resources has less effect on climate change and environment pollution, because it has no combustion during the process. Therefore, generating energy from readily available resources is an advantage for decreasing climate change effects. New sources of renewable energy are becoming new topics for research. The major concern here is efficiency of storage systems because some of the renewable resources generate power only intermittently.

A sustainable system requires altering energy systems with low greenhouse emission systems. There are vast energy resources to meet our needs; however, the goal is lowering the cost and increasing reliability and the quality of sustainable systems, simultaneously to facilitate this transition. This is a huge challenge, but it can be undertaken with improvement in energy efficacy with deployment of a variety of technologies.

Among the numerous opportunities, in this research the piezoelectric effect has been studied. As discussed before, piezoelectricity is the interaction between crystalline materials, such as crystals and ceramics. The electrical charges are the result of an applied force or pressure through this interaction. This is the piezoelectric effect. In this research, we propose to place piezoelectric transducers on the outside surface of pneumatic tires that would use mechanical stresses from tire pressure and deformation and generate usable electric energy. This harvested energy can be transferred to an external battery for storage. This kind of technology is used in small scale now, but with further developments, this could be applied at larger scale and bring a lot of promise. Every day, hundreds of thousands of cars run through the city. The amount energy derived from the mass amount of cars is sufficient to provide power for several applications. This can decrease the amount of energy needed and in turn reduce the impact of carbon emissions.

With rapid improvement in piezoelectric technology, it would make sense that mass production of piezoelectric generators would be cost effectively. Installing piezoelectric in pneumatic tires, gives the opportunity to collect as much as energy as possible. This kind of renewable energy can provide electricity to car users and people of the city without harming the environment. This electricity can be used in vehicles or sent to an external transformer to wide spread use. The produced electricity can reduce the electrical cost and at the same time provide advantages to the environment.

Piezoelectric technology, currently, is meant to power small appliances such as tire pressure sensors, portable chargers for cell phones and laptops. However further development can open the ways to improve piezoelectric transducers for more efficient generators. Piezoelectric technology has great potential to provide the amount of energy, used on a daily basis. Implementing transducers, does not affect out regular habits. Car tires revolve in regular basis, so why not use this simple and self-powered technology for benefit and keep the earth healthy to have a brighter future.

Chapter 6

Methodology

6.1 Materials and methods

To generate electricity from running cars, the most suitable place must be chosen to put the piezoelectric materials. In the research performed by Makki and Pop-Iliew [48], piezoelectric materials were installed inside of the tire. The pressure inside of the tire is slightly less than the pressure outside of the tire surface. To claim this statement, imagine pressure represented with P_i and contact patch area with A, then force on the ground is $F_i = P_i \times A$. On the other hand, tires have some elasticity. Deformation of the tire because of weight creates an elastic force according to Hooke's law [24]. This force is F_e for tire. Therefore, the total force on the ground is:

$$F_g = F_e + P_i \times A \tag{6}$$

And the pressure of the ground is:

$$P_g = \frac{F_e}{A} + P_i \tag{7}$$

So, outside of the tire is a more appropriate candidate to install piezoelectric materials than the inside.

6.2 Methodology

The criteria to transit the car’s weight to the ground are defined by the contact patch which de- pends on the weight of the vehicle, and tire air pressure. When this weight is zero, the contact patch is a line. Increasing the load causes tire and side wall deformation and increases the area of the con- tact patch. With tire rotation, all different parts of the tire undergoes deformation at a frequency that is a function of the tire RPM. In this research, it is tried to simulate one standard car characteristic as a model and then scale it down to a prototype scale. Piezoelectric benders experience periodic deformation with tire revolution and generate a periodically charging and discharging.

As discussed before, piezoelectric materials produce charges when it is subjected to deformation

Ref. car	Chevrolet malibu					
	Curb weight	1400	kg	==	14000	N
Tire	205/70R15					
	R	16	in.	==	0.41	m
	P	2.6	m			
	Effective width	140	mm		measured	
	Contact patch length	145	mm		measured	
	contact patch pressure	0.17	MPa			
	Fequency	6.0	Hz	==	359	rpm
Model						
tire	r	4.5	in.	==	0.11	m
	p	0.72	m			
	effective width	35.00	mm			
	contact patch length	55.00	mm			
	contact patch pressure	0.17	Mpa			
	Frequency	6.0	Hz	==	359	rpm
required force	F	332	N			
scaled speed	V	15.5	km/h		4.3	m/s

Target velocity	V	
	55	km/h
	15.3	m/s

The target is keeping pressure and frequncy of the model same as the reference car.

Figure 6.1: Real and scaled down model specification.

at the contact area with the ground. This amount depends on the revolution per minute of tire or, in other words, the frequency. In this research, the goal is converting waste energy in cars to electricity which could be used at different parts of the vehicles. To achieve this, an actual car was simulated and scaled down in the laboratory.

The Horizon CT7.2 treadmill was used for this test. By considering that the maximum velocity of this treadmill is 10 mph, tire specifications and other conditions have been scaled down to simulate a model with a running car. Figure 6.1 presents the procedure of scaling and dimensional relation between an actual and prototype model. The Chevrolet Malibu was selected as the reference car and its specification was scaled down by a factor of 1/3.56 according to laboratory facilities. A spread sheet (Figure 6.1) was developed for this proposes to provide required speed and force. To achieve close results to the reality, it was decided to keep frequency and pressure constant underneath of the tire. The frequency of the piezo benders depends on RPM that is a function of velocity of vehicle. Here, because of limitation in the employed treadmill's speed, 10 mph equivalent to 55 km/h velocity of the reference model can be tested. Makki and Pop-Iliew [48] confirmed that the higher velocity is, the more the bender deforms, thus increasing the power output.

A steel frame with dimensions illustrated in Figure 6.2 was designed and constructed to transfer the load to the tire. The steel frame was made from a box profile with 50. The oval holes provided in the frame as shown in Figure 6.2c, gives the opportunity to balance the frame and apply load. It was impossible to rotate the pneumatic tire according to laboratory facilities so the relative motion law in physics was used. To simulate a vehicle's speed, it was supposed that the car was constant and the road is moving. The treadmill conveyer and its carpet play the road role in this experiment. Steel plates of three kg each, were used to apply the weight of the scaled down model to the frame. This weight transfers to the pneumatic tire using steel frame hanger and presses the wheel assembly to frame against the treadmill floor creating a tire contact patch. The pressure in the contact patch can be adjusted to simulate different contact patches size. Figure 6.3 presents the side view of the testing set up.

6.2.1 Piezoelectric element selection

Some materials like quartz, biological materials like bone, DNA, and various proteins have piezoelectric properties. At first, it was designed to use a virus as the piezo material. This choice is in the nature and could not damage the environment which is one of the goals of this research (sustainable development). Then, because of health and safety issues, it was changed to PZT. The PZT is described in previous chapters.

In this research four main criteria were considered to choose the piezoelectric materials.

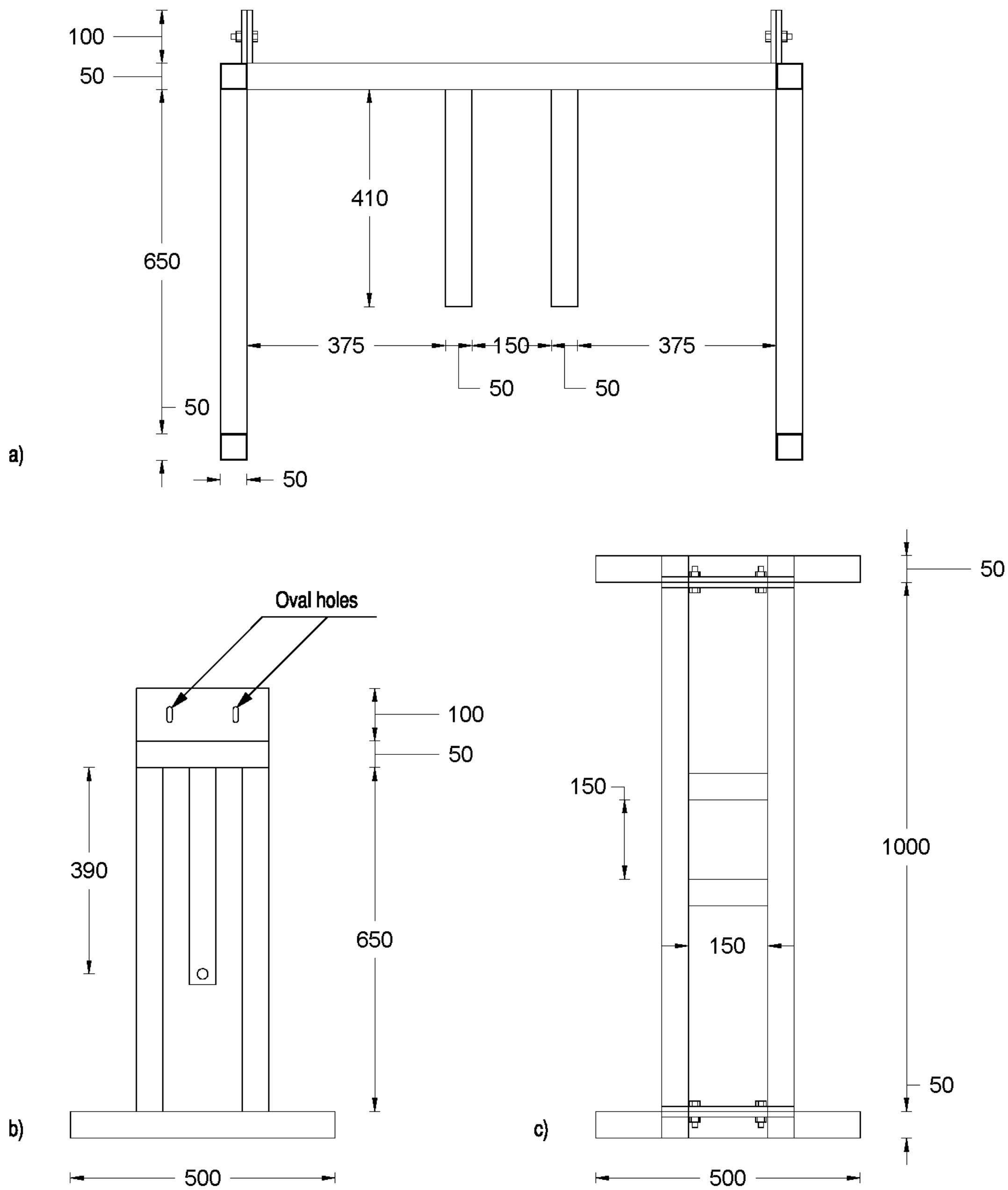


Figure 6.2: Dimensions of the steel frame: a) front view; b) side view; and c) top view.

- The piezoelectric material could deform without damage with tire revolution.

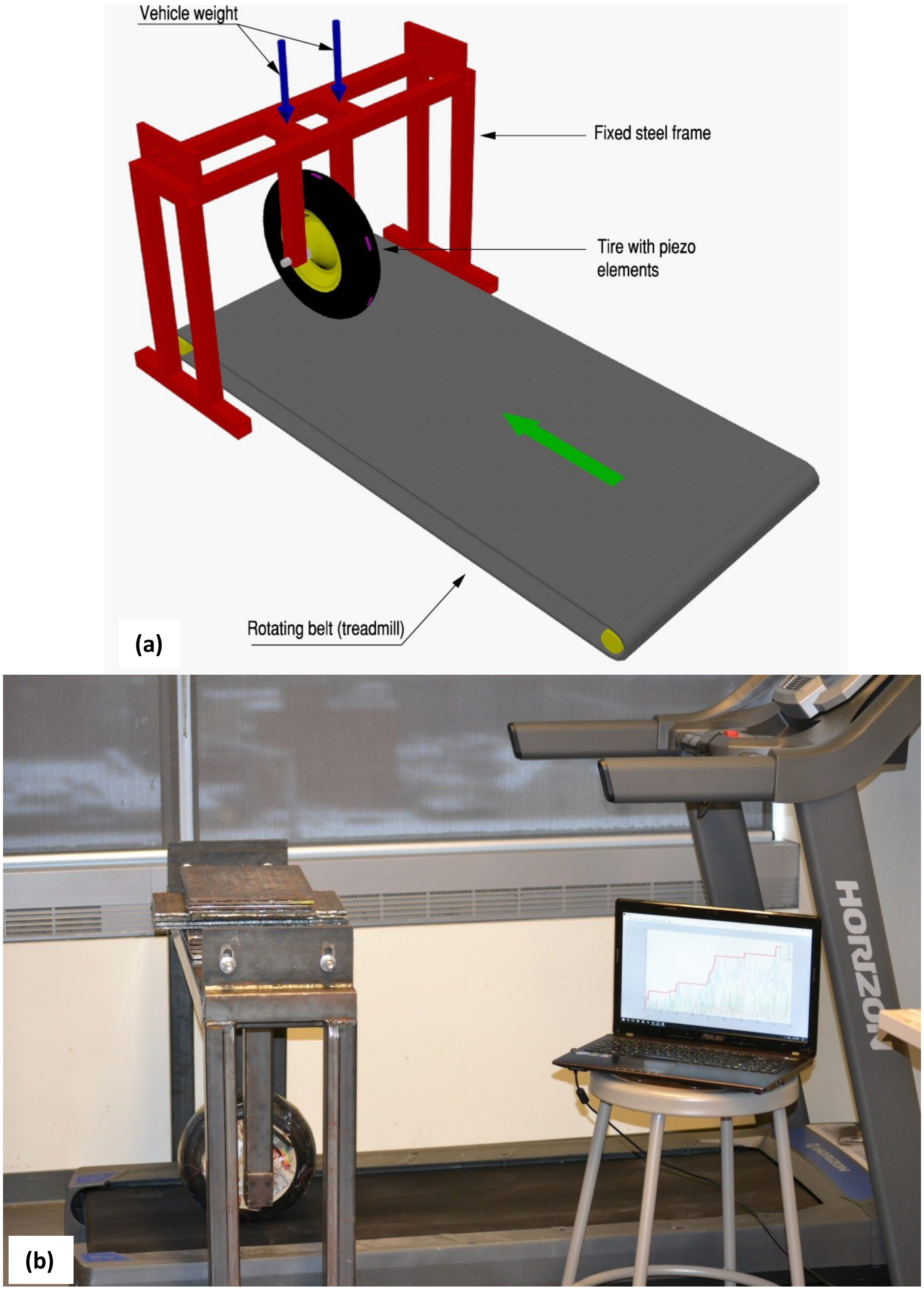


Figure 6.3: A 3D view of the test set up (a, b).

- Piezoelectric output is a function of voltage constant g_{33}, charge constant d_{33}, and piezoelectric dimensions.
- Cost.
- Environment friendly, lead-free piezoelectric elements.

Sufficient bendability of the element is of the most important aspects to match the cyclic deformation of the tire, which is 540 million cycle for a tire life of 100,000 km [48].
The other substitution for piezoelectric elements is polyvinylidene fluoride (PVDF) elements which have higher flexibility but, their cost is high and piezoelectric charges are low. Therefore, it is not a good candidate for this purpose.

Circular piezoelectric elements with a depth of 0.23 mm including a brass plate were chosen which help them to increase their bendability. These elements have been used before for power generation in the shoe sole during walking motion [45]. Piezoelectric elements produced by CUI INC NO. CEB-44D06 model were employed in the tests. The mechanical characteristics of the used piezoelectric elements are explained in Appendix C.

6.2.2 Adhesive selection

At first a Parmatex weatherstrip adhesive was selected to bond piezoelectric elements to the tire. This was a better choice because of flexibility, excellent adhesion to rubber and metal. However, to simplify changing the piezoelectric, 5 cm strip bonders were used. These strips facilitated the work to change the piezo element for each speed.

6.2.3 Piezoelectric arrangement

Figures 6.4 and 6.5 show the layout of piezoelectric elements in five pairs and connects with the control circuit. The tire was 23 cm in diameter; therefore just 10 piezoelectric elements are used for this experiment. On the other hand, piezoelectric elements require a breakout two by two, and wooden pad dimension would not allow using more than five which is used in this experiment.

The produced power amount is a function of piezoelectric materials which are connected in parallel to each other. Later, in discussion section, it will be shown why these elements were in parallel not in series. All piezoelectric pairs were connected in parallel to each other and all of them, then, were connected to the breakout board. The function of the breakout board is described latterly. Piezo elements are attached to the tire symmetrically. Therefore, charge and discharge time for all of them is equal.

Tire surface was sanded with sandpaper to remove all roughness, then, one rubber tube was bonded to the tire with the Parmatex weatherstrip adhesive. Creating a rubber based patch allowed easy assembly for attaching and removing the piezoelectric without contributing towards power generation.

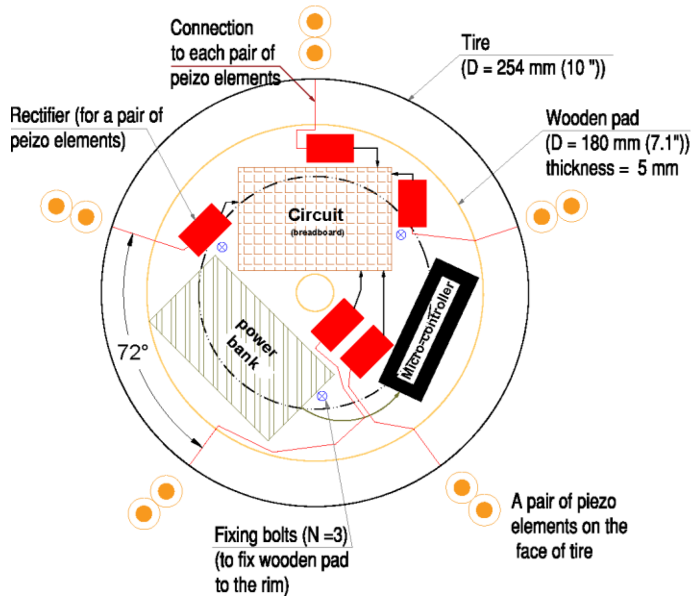


Figure 6.4: Location of piezo elements and circuit arrangement.

Figure 6.5: Photo of the mounted piezo elements and control circuit.

The piezo elements are capable of bending more in a concave manner i.e. with the ceramic on the inside of curvature rather than on the outside (convex) [48]. Figure 6.6 shows the concave and convex deformation of PZT elements. As said before, to bond the piezoelectric elements to the

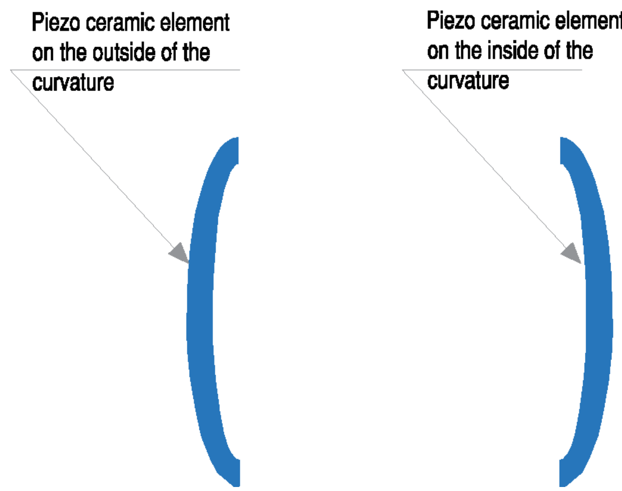


Figure 6.6: Different deformations of piezo elements.

rubber, an adhesive bond was used to increase bendability of piezoelectric materials and feasibility of assembly of them and prevent PZT layer damage. This technique ensures optimal concave defor- mation while significantly reducing convex deformation. Figure 6.5 shows how the piezo elements are adhered to the tire.

6.3 Control and Data acquisition

A data acquisition system was used to measure harvested voltage. The DAQ system in this experiment consisted of a micro controller or MCU , one power supply, and one breadboard to install voltage division circuit. The MCU is a Mini Arduino company's micro controller with an open source electronics platform which can read the input and change it to output. The MCU requires a power supply to work and generate output. Although it is possible to use general electricity to feed the micro-controller in order to establish wireless connection; but, if ,for any reason, the current disconnected, Arduino sending data would be interrupted to laptop or PC. Therefore, it was decided to use an external power supply to ensure an integral current. A circuit mounted on the wooden pad which is described before, include one board, five breakout board, one mini Arduino, and one power supply. The breakout board and Ardunio specifications are shown in Appendix C and D. Figure 6.7 shows a schematic plan of the test fabricated circuit and its connection with the data acquisition system.

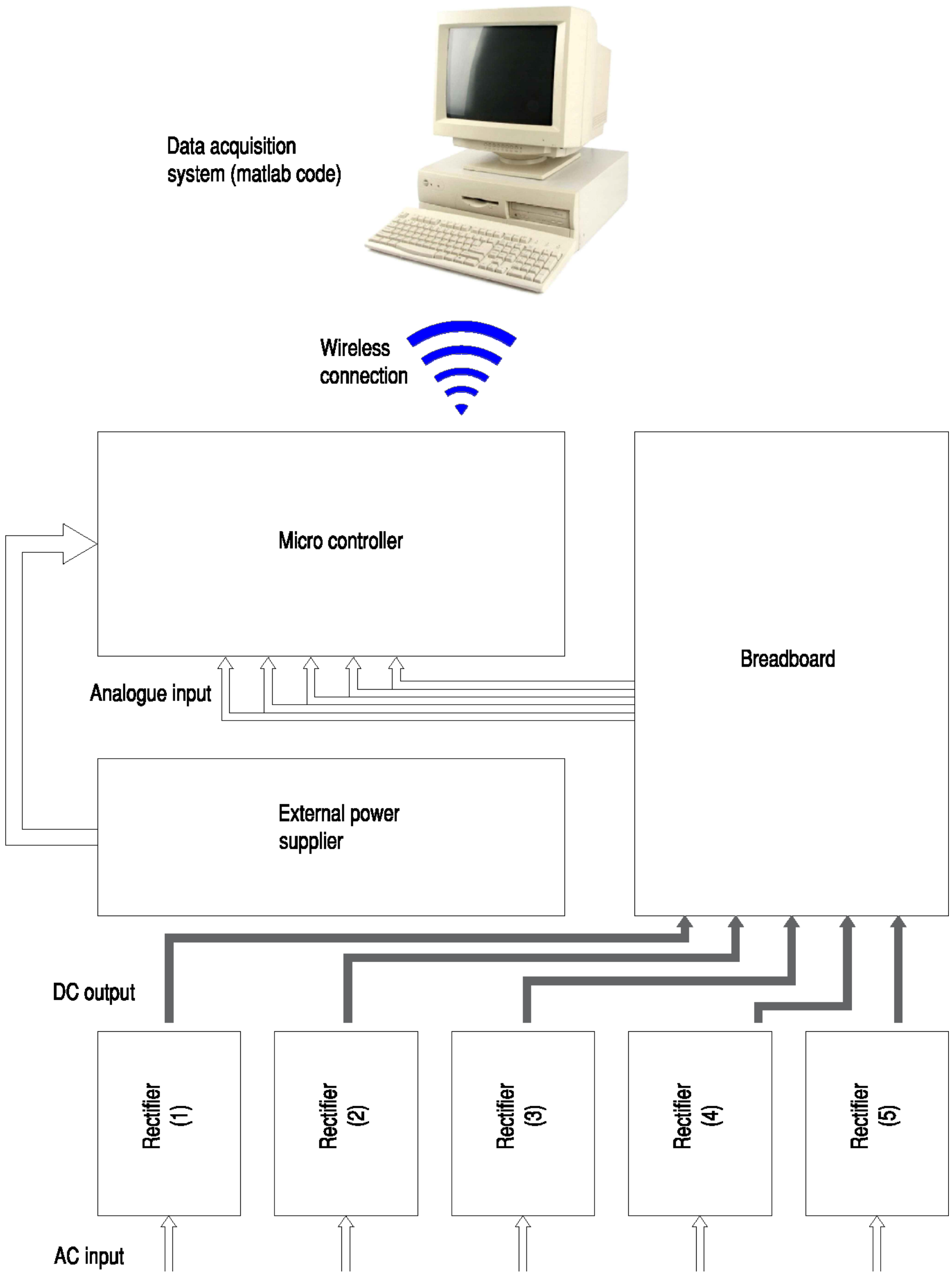


Figure 6.7: Test circuits and connection to DAQ center.

Input voltage to the Arduino micro-controller should be less than 5 volts but, according to the piezoelectric data sheet, peak voltage for piezoelectric materials can reach up to 10 volts which is over the Arduino input voltage. To solve this, $10\,\Omega$ and $2\,\Omega$ resistors were used to decrease this amount to one per 6 of input voltage (input voltage/6). The voltage division circuit is mounted on a breadboard located in the wooden pad of the pneumatic tire. To reverse this output voltage, a program in MATLAB was written to convert this amount to the voltage lower factor. This program is shown in Appendix A.

6.4 Tests

Three different components were performed in this experiment: weight, speed, and piezoelectric elements connection. First experiment was undertaken for two different weights (24 kg and 48 kg) in the laboratory to review the effect of weight on the energy harvesting. To do this, after attaching of piezoelectric elements, a 24 kg weight was located on the frame and then the treadmill was run. In the second one, the 24 kg weight was changed to 48 kg and the test was repeated. The results of both experiments were sent to the laptop by the DAQ system which was described before. The second experiment was run to decide the connection of piezoelectric to get more output. At first, one pair of piezoelectric elements were connected in series to each other and test was run with different speeds and results were achieved. Then, previous piezoelectric elements were removed and replaced with new ones. But this time, a pair of piezoelectric was connected in parallel and the test was repeated for it. During the tests, piezoelectric materials were changed to avoid fatigue effects on the piezo elements and ensure that all piezo materials are sound. In the third test which was the main experiment of this research, 5 different tests with different speeds were run to examine the effect of speed on the generating energy. In each step, all piezoelectric elements were replaced with new ones to do each experiment using fresh conditions. More discussions are in next chapter to evaluate the effect of weight and speed of vehicle on the final results.

6.5 LCA phases

6.5.1 Goals and scope of the LCA study

This study was intended to perform environmental analysis of a piezo-tire, as indicated before. This could be intended for tire users, environmental regulators, and suppliers to make their choice in terms of desires. A specific comparison of two different types of tires will be performed here: i) tire with piezoelectric materials; an ii) common pneumatic tires. As shown before, piezoelectric materials generate electricity by pressure. Therefore this would decrease the amount of energy which is required to run a car. The amount of energy produced by piezoelectric materials is considered as avoided product in LCA studies. As it is important for car customers be informed about the environmental impact of their used products, such studies help them to make wise decisions related to their choice. Piezoelectric materials are completely new and need to be developed more to achieve industry satisfaction for this use. This is only one solution to fuel efficient tires. Life cycle assessment of these two products depicts which stages of the life cycle of the piezo-tire and common tire are environmentally harmful. Tire raw production and manufacturing methods are confidential for some companies and this issue affects the project scopes. Specific techniques and processes are crucial for some companies due to competitive advantages, so it is not possible to obtain some data specific to a particular company [12]. In this study, the average production process of a large number of companies is used to decrease the limitation of data in case of confidentiality. This will limit the accuracy of results, but it will provide a good estimate of environmental impact of products.
Similar to other LCA studies, the functional unit of this analysis was a Chevrolet Malibu tire with a hub which was developed with piezoelectric materials on it. Because of time limitation in collecting data, a previous tire LCA in the United States was used [16]. Therefore, it is assumed that all steps of these functional units are included. All of the energy and materials except for natural rubber production is assumed from the United States. The natural rubber is produced in Southeast Asia. Energy mix percentages are derived through the US Energy Information [19]. Also, it is assumed that the tires always remain properly inflated with good care. When it is appropriate, the Simapro database was used for all material inputs and outputs to air, water, and land. In this report, the IMPACT 2002+ method is used as a primary assessment tool, and then TRACI 2.1 was used

for validation of results. One fundamental difference between these two methods is that IMPACT 2002+ use mid/endpoint approach and TRACI 2.1 is the midpoint impact assessment model.

Assessment methodology in this study

TRACI

This method was developed by EPA to reduction and assessment of chemical and other environmental impacts. Figure 6.8 presents the structure of the TRACI impact assessment method. This

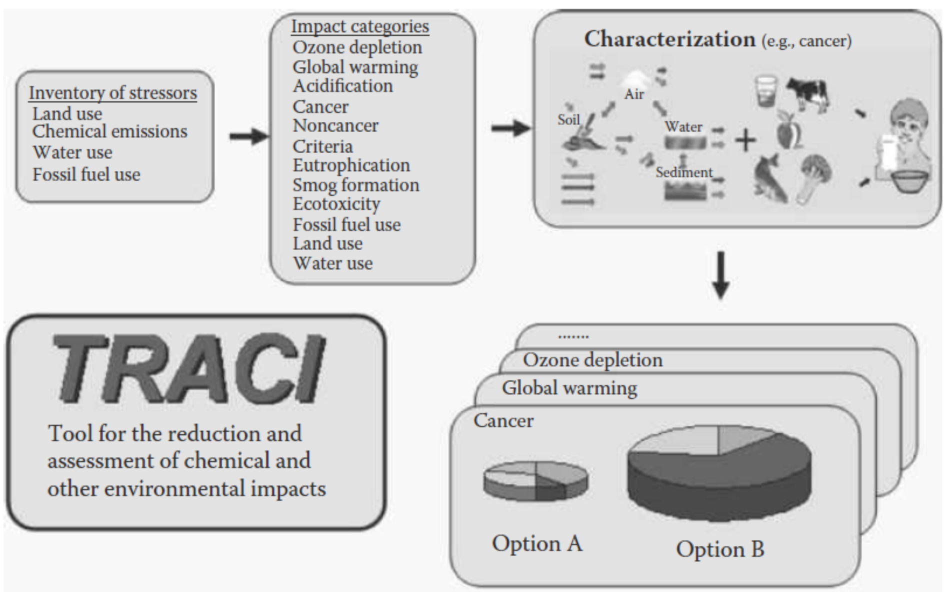


Figure 6.8: Structure of TRACI impact assessment method [22].

method characterizes the potential effects, under U.S. conditions, for the following midpoint impact categories: ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, eco-toxicity, human particulate effects, human carcinogenic effects, human non-carcinogenic effects, and fossil fuel depletion [37].

IMPACT2002+

This method provides the impact assessment at the midpoint and damage levels. The IMPACT 2002+ methodology links all types of life cycle inventory results (elementary flows and other interventions) via 14 point categories at midpoint to four damage categories. Figure 6.9 shows the midpoints and damage categories indicators. Jolliet et al. [36] presents that a midpoint indicator characterizes the elementary flows and other environmental interventions that contribute to the same impact. The midpoint term indicates that this point is located somewhere between LCI results and endpoint.

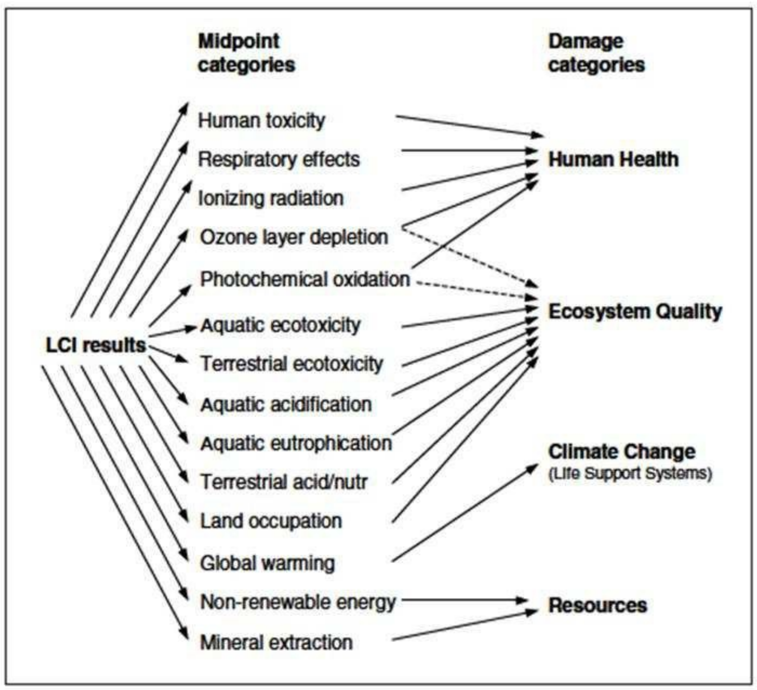


Figure 6.9: General structure of the UNEP-SETAC impact assessment framework [36].

Geographical boundary

This study uses American data when possible. Some raw materials are needed to produce a tire; therefore, the required data for inventory will come from the place that materials are produced. In the case of raw materials that are produced in other countries, the inventory data of required input and outputs is from the material country and their impacts to the US will be considered. For example, the natural rubber which is produced in the Southeast Asia is transported to US. This is inaccurate to assume that this raw material is produced in the US to ignore the transportation emissions. American methods are used for assessment. It is also assumed that piezoelectric materials are produced in the same place of the tires. Piezoelectric materials are newly developed; therefore there is little information about emissions of these products and LCA assessment. This part adds some uncertainty and assumptions to the LCA analysis which influence the accuracy of the assessment. We will not consider third party usage after the waste treatment step. Table 6.1 presents the functional units and reference flows of this study.

Table 6.1: Functional units and reference flows for two different scenarios.

System	Functional unit (Service offered)	Functional unit	Key parameters(Linking reference flows to FU)
One Piezo-Tire	Facilitates the car performance	60 pieces of piezoelectric units + one tire	1 kM run of tire
One tire	Facilitates the car performance	One tire	1 kM run of tire

6.5.2 Inventory Analysis

Inventory analysis is the next phase in LCA after the first phase definition. As indicated before, in this phase the inventory of the material extraction and their emission crossing the system boundary were quantified. Two methods are currently used to calculate the inventory: the process based approach and the input/output (I/O) approach [37]. The first one combines the reference flows and emission and extractions of unit process in the system. The other calculates the emissions and extraction on the basis of economic flows generated by service. Four subcategories of the entire life cycle are created in order to organize the large amount of inventory data: Production of raw material and manufacturing, use, and the end of life. To have a better evaluation of environmental impact of the entire tire production process, the production of raw materials and the manufacturing process are combined. All inventory data are derived from external sources and SimaPro packages (version

8.3) when data is limited.

Production Phase

Production of Raw Materials

- **Natural rubber** products are made with an initial source of latex drained from rubber trees or Hevea brasiliensis. These trees are farmed in Amazonian regions, but since the 20th century they are cultivated in Southeast Asia [74]. More information about the latex and its maintenance condition to prevent early coagulation can be found in Adhikati and Maiti [1]. There are different kinds of synthetic rubber produced today which dominate the market. In this analysis, it is assumed that all synthetic rubber used in tires is styrene-butadiene rubber (SBR) [16].

- **Carbon black** is a virtually pure element carbon in the form of dust or fine particles which is produced by the incomplete combustion of gaseous or liquid hydrocarbons under controlled condition.

- **Silica** or SiO_2 is found naturally from different sources including industrial sand, gravel, quartz crystal to improve rubber characteristics by increasing traction and reducing rolling resistance [80].

- **Sulfur** aids the vulcanization process and helps to maintain desired flexibility and durability of the tire. Currently about 75% of the total element sulfur is comprised of sulfur manufactured by the Claus process [72].

- **Zinc oxide** is a white powder and insoluble in water which is used in small amount in tire to protect rubber from degrading and increase the rubber cure.

- **Aromatic oils** are used in tires to improve the physical properties of rubber. This component is highly viscous liquid that improves flexibility and durability and is produced as by-products of refining crude oil.

- **Stearic acid** is a saturated fatty acid that is used in the tire industry as a rubber softener that is produced from animal fat [46].

- **Coated wires** reinforce the rubber and decrease its wearing. In fact, coated wires are comprises of steel wires with brass and zinc. Since the steel wires cannot bond to rubber directly, they are coated with brass and zinc.

- **Textile** is used to reinforce the tires. Nylon and polyester are two types of textiles. In this study, both of them are used in tire manufacturing in the 50:50 ratios.

- **Steel** is manufactured by chemical reduction of iron ore through a basic oxygen furnace or an electrical are furnace [13].

- **Polyurethane** is used in conjunction with rubber to keep the rolling resistance to a minimum.

- **Lead-free piezoelectric** is fabricated using sodium carbonate (Na_2CO_3), niobium pentoxide (Nb_2O_5) and potassium carbonate (K_2CO_3). These materials are distributed as 0.12%, 99.53% and 0.35% ratios, respectively [32].

Table 6.2 describes the material composition of functional unit (P205/45R17) which is analyzed through the life cycle.

Table 6.2: P205/45R17 tire material composition [16].

	Car gas	Tread	Total tire	Hub
Raw material	Wt%	Wt%	Wt%	Wt%
Synthetic rubber	15.78	41.72	24.17	0
Natural rubber	24.56	3.53	18.21	0
Carbon black	23.40	9.54	19.00	0
Silica	0.80	28.07	9.65	0
Sulfur	1.60	0.80	1.28	0
ZnO	1.83	0.91	1.58	0
Oil	4.02	10.64	6.12	0
Stearic acid	0.87	1.47	0.96	0
Recycled rubber	0.60	0	0.50	0
Coated wires	17.2	0	11.4	0
Textiles	7.0	0	4.7	0
Steel	0	0	0	100
Totals%	100	100	100	100
Weight (kg)	7.25	2.75	10.0	4.0

Production phase

- The common procedure of construction of the tire involves the assembling and then vulcanizing the components of a tire. Because of confidentiality, details of production process are different for manufacturers and they have not released their specific process. This simplified process is presented in Figure 6.10. This is out of the scope of this study to transport raw materials to a tire manufacturing facility. Consequently, it is assumed the raw materials are produced near the manufacturing plant. Tire production can be found in detail in PRe Consultants [62].

- Manufacturing route for fabricating lead-free piezoelectric includes batch weighing of components, ball milling of the mixture for 24 hours, drying of the slurry at $90^{\circ}C$ for 24 hours, calcining at $850^{\circ}C$ for 6 hours, ball milling again for 24 hours to ensure homogeneity of mixture, drying at $90^{\circ}C$ for 24 hours, sintering at high temperature for 3 hours and matching into different geometries [32]. Total primary energy consumed to manufacturing this component consist of thermal energy and electrical energy. For ball milling and sintering use the maximum electrical is 82% and thermal energy is 43%.

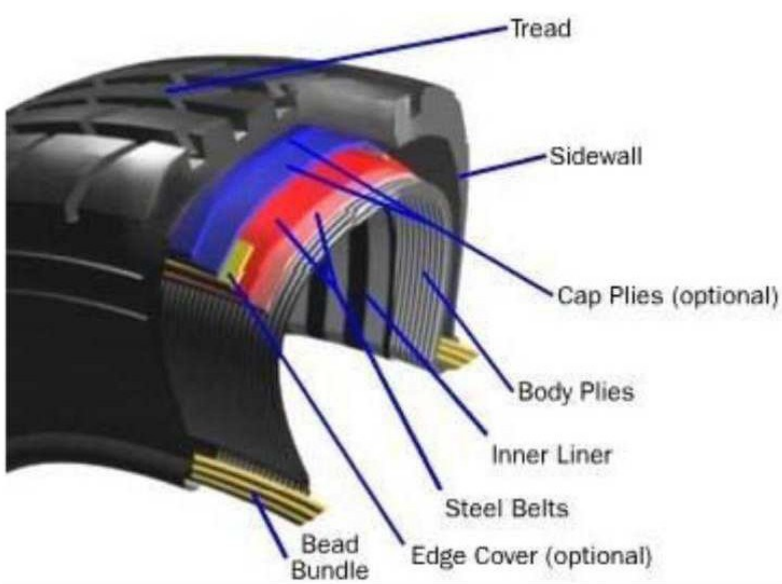


Figure 6.10: Tire component breakdown [56].

Distribution

- The transport of raw materials is not considered in the production of both systems. However, the required fuel to distribute tires to repair shops and the dealer is analyzed. The distribution of tires from production site to the retail point is done by a mixture of 28 and 16 ton trucks, delivery vans and ships [7].

Usage phase

- **Fuel consumption**: The amount of fuel consumed by a car is an important part of a tire life cycle assessment. Although the amount of fuel depends on the car efficiency, but the whole fuel is not used by wheels. So a certain percentage of the fuel fed to the car should be allocated to the wheels and used in this analysis. Total average fuel use for the tire P205/70R15 is 101 L in the lifespan of 42000 miles (67200 kM) [16].

- **Gasoline Emission**: It is necessary to develop the environmental profile of the producing gasoline in life cycle assessments. The production, storage and transport of crude oil and gasoline must be considered in this analysis. Table 6.3 includes the emission from combustion of gasoline [21]. The overall inventory data of gasoline used in the usage phase of each wheel comes from combining these emissions with the gasoline production inventory.

- **Tire debris**: During normal use of tire, the tread of tire wears due to the friction contact with road surfaces and this debris can become an environmental problem with tire use in the form of airborne or respiratory problems, or by accumulation on the water or on the ground. Normally, the tire loses about 10-20% of its weight during its usage phase [70].

Table 6.3: Emissions from combustion of gasoline [21].

Emission to air	Mass(kg)/kg of gas	Mass (kg)/L of gas
Sulfur dioxide	0.000494	0.000366
Nitrogen oxides	0.022147	0.016389
Carbon dioxide	3.407155	2.521295
Carbon monoxide	0.098807	0.073117
VOC, volatile organic compounds	0.014140	0.010464
Soot	0.000239	0.000177
Dinitrogen monoxide	0.000681	0.000504

End of life

- **Processing routes**: The rubber manufacturing associates have documented that there is four main processing techniques including i)Tire derived fuel (TDF); ii) Civil engineering uses; iii) landfill; and iv) ground rubber used in other processes [16]. Scrap tires are incinerated and used as fuel, ground into crumb rubber or thrown away intact [68]. According to last mentioned resource, tire burning produce 30% of the energy required for new tire producing and crumb rubber quantifies a noticeable amount of energy.

- **Tire recycling**: This term defines a group of methods which are implemented to reuse tire materials. Almost 18% of scrap tires can be recycled by exporting, stamping, agricultural, baled and grinding methods [67]. Among these methods, the first four can be ignored because of less impact on the life cycle. More details of tire recycling can be found in Myhre at al. [55].

- **Landfilling**: The main environmental problems raise from landfilling are land use, emission of methane and leaching toxic substance to surface and ground water. There are two methods of landfilling: controlled and uncontrolled. In this study, the overall inventory mix of the process is used.

- **Rubber derived fuel**: Tires have higher heat values due to organic components, so one option for discarded tires is to use them as fuel [55]. In this study controlled combustion source have been considered to control the quantity of air emission. Current devices are efficient for TDF and the overall environmental impact of TDF should be close to zero because avoided products negate the overall negative effects.

- **Retreading**: There are more than 1900 retreading facilities in North America [34]. This process has decreased because of low prices of new tire. The environmental impact of retreading will not be included in this analysis.

6.5.3 Life cycle impact assessment

The inventory collected data requires assembling in an organized manner to compare different products and their emission to assess their impact portion of each one in the life cycle assessment. In order to more accurately compare products, different impact assessment methods can be used to weight the environmental factors. There are different methods of assessment such as IMPACT 2002+, TRACI 2.1 and etc. The environmental impact methods slightly differ with each other, but, a single value (Pt or Eco point units) is mostly used with impact assessment creators to provide a scale to determine environmental impact assessment of different methods in a comparable manner. The life cycle impact assessment methods model the impact pathways of different substances to link, as accurately as possible, each inventory data to its potential environmental damage based on these pathways (Figure 6.11). These methods represent positive and negative scores.

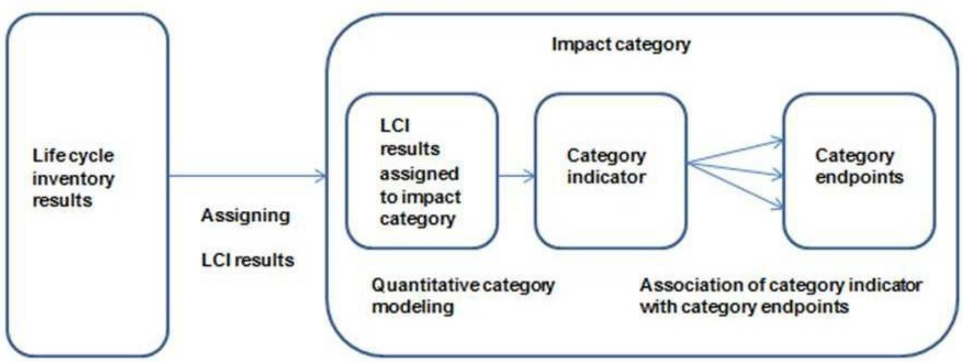


Figure 6.11: Impact assessment scheme to link inventory results with category end point or damage to areas of protection [37].

A negative score means a benefit to the environment like consumption of CO_2 from tree which has a positive impact on the environment and global warming. In contrast, negative score has adverse impact on the environment. Some processes contain both impact categories. As discussed before, there are two scenarios in this study. It is aimed to find the amount of the impacts by each product to determine which scenario is better.

Chapter 7

Results and discussion

In this research, the electrical response of a connection among multiple piezoelectric elements was investigated. A key difference in the results between a series connection and a parallel connection of the piezo elements has been achieved. A higher voltage can be obtained from a serial piezoelectric stack while higher power can be generated from a parallel one [77]. Piezoelectric harvesters, in addition to the advantage of being smaller and lighter, have three times higher energy density as compared to electrostatic and electromagnetic [61] Owing to these advantages, a piezoelectric energy generator has great potential in several applications. The recent advent of extremely low power electrical and mechanical devices, such as in vivo sensors, embedded MEMS devices and distributed network nodes, makes piezoelectric harvesters attractive and competitive where remote power is required [63].To harvest these energies effectively, piezoelectric stacks by connecting electrically several piezoelectric elements in series or in parallel are regularly utilized. In this research, the scope was harvesting power in running vehicles. Every day, a large amount of cars move on the roads. There is a significant waste energies that with new technology can be derived and used for different parts of vehicles or stored for other purposes. As described in the literature review section, some research has investigated numerically and practically. Here, the contribution is to consider and compare these piezo benders to work effectively on the inside of the tire or the outside.

In Chapter 6 it was demonstrated that the external surface of tires has much potential to generate power compared to inside. Figure 7.1 shows the vibration mode of piezoelectric under the pneumatic tire.

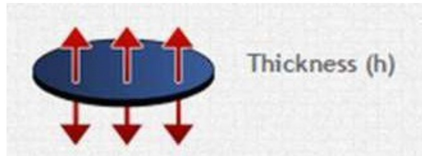


Figure 7.1: Mode of vibration displacement [4].

The rpm or revolution per minute is a metric for frequency of rotation.

$$rpm = \frac{V}{r \times 2\pi} \tag{8}$$

in which V is speed and $\mathbf{r}$ denotes the radius. According to this formula, for a constant r, the rpm increases with speed. As noted already, to simulate the set up with a real model, frequency and pressure under the contact patch was kept constant. The rpm in the test was 356 which gives a frequency of 6 hz. Figure 7.2 shows the effects of different speeds on the generated voltage. According to Figure 7.2, with increasing speed, the generated voltage and following power will increase. But, for high speeds, more time is required for charging the piezoelectric. At a threshold of 16 km/h, the generated voltage is less than other speeds. In other words, the output has a direct relationship with speed. Larger tires have a larger contact patch areas, and then can accommodate more piezoelectric to harvest more output. This state can be described as the acceleration time of car. At this time, the amount of energy increases with accelerating the car. It is discussed before that piezoelectric materials could not harvest energy in the static mode. When a car is stopped, there is no speed and revolution; therefore, the energy is zero. Hence the following relationships were achieved: power is a function of surface area, and the RPM. The other factors which affect the output include:

- Thickness of piezoelectric materials;
- Charge constant of piezoelectric material (d_{33}) and voltage constant (g_{33})

Some other experiments (Figures 7.2 to 7.4) were performed for different speeds (3.2,6.4,9.6,12.8,16 km/h) to determine how the speed affects the results. As obvious in Figure 7.4, the output voltage increases with rpm. Although, there are some errors because of the experimental conditions and simulation with real models. The demonstrated amount is related to cumulative voltage regardless of the impact of time. Also, these amounts are for five pairs of arrays of piezoelectric elements. Increasing the amount of piezo elements has a direct effect on output, more piezoelectric elements, and more output.

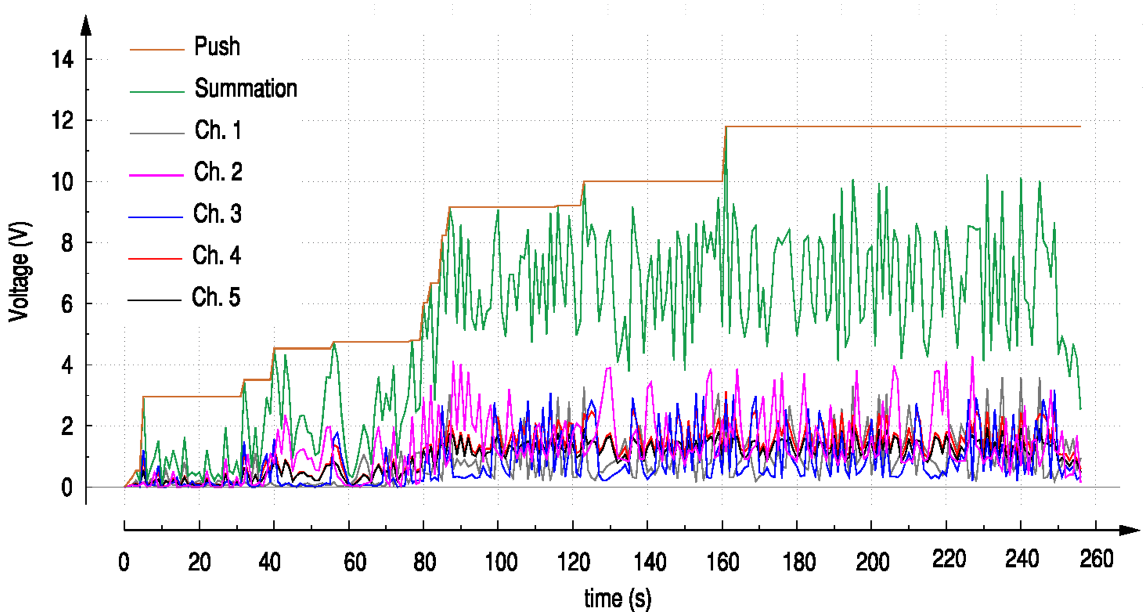


Figure 7.2: Voltage vs time at 12.8 km/h (8 mph).

Increasing the velocity from 2 mph to 4 mph resulted in 80 percent growth of the output voltage, while doubling the speed for the second time (8 mph) increased the output voltage just nine percent. It means that in higher speeds the time is not enough to complete 1 cycle of a charge-discharge in piezo materials. The reason is rooted back in the visco-elastic characteristic of the tire's material that release deformations with low rate.

As discussed earlier, piezoelectric materials have two vibration modes: radial and thickness. When a tire rotates, piezoelectric elements are bent prior to placement in contact with the patch area and are flattened out in the contact patch area and are bent again as it exits from that area. The contact patch area depends on the tire diameter and air pressure in the tire and weight on it.

Figure 7.5 proves that tire loading increases the piezoelectric output. Therefore, heavy vehicles could produce more power. Less air pressure decreases the tire loading effect and consequently the piezoelectric output. Piezoelectric output also depends upon the amount of piezoelectric materials placed under the contact patch and deflects at the same time of one set of elements which connect to each other. Anil and Sreekanth [2] showed that the mechanical energy stored in the piezoelectric discs increases linearly with the applied force and thickness of piezoelectric material. Anil and Sreekanth [2] also proved that the output voltage increases linearly with the input force, thickness and the capacitance of the piezoelectric device, and decreases with the increase of the area of the piezoelectric disc. An experiment was performed to determine how the piezo elements produce more power. Before attaching all piezoelectric materials, two different experiments is done to find in which situation piezoelectric could generate more voltage. For this reason, one experiment is run with two piezoelectric which were connected in series and in the second experiment these elements were linked in parallel.

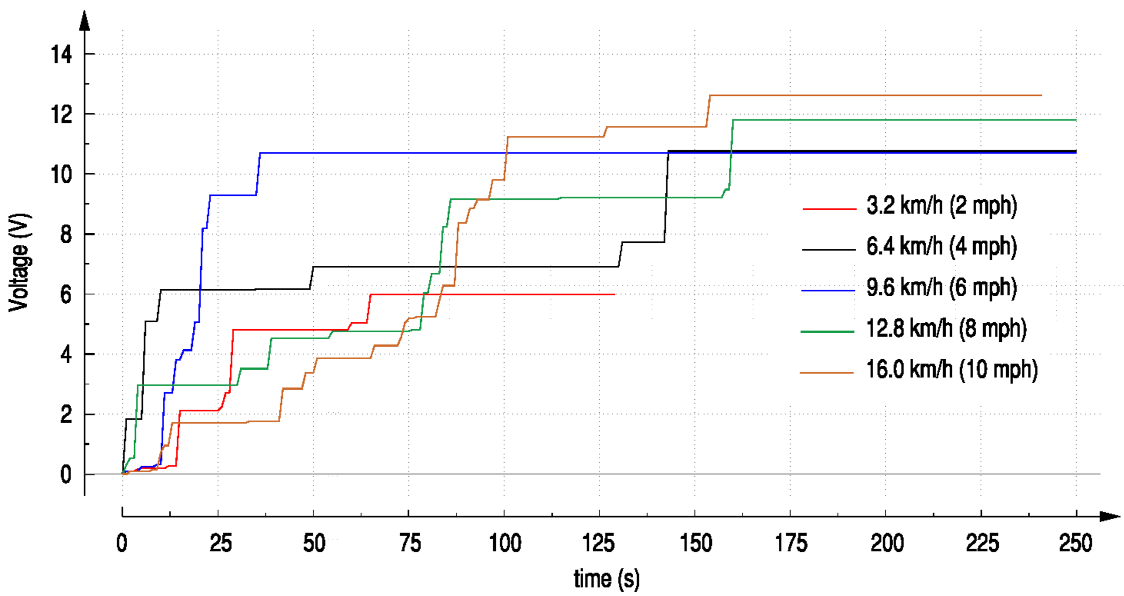


Figure 7.3: Test results for different speeds.

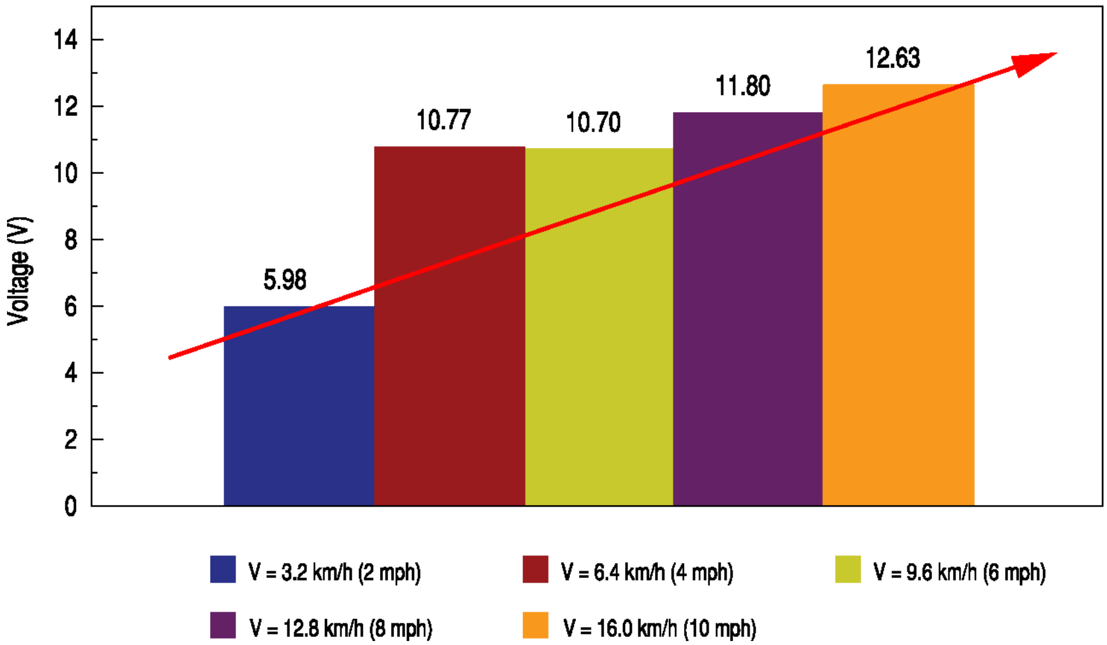


Figure 7.4: Comparison of final output for different speeds.

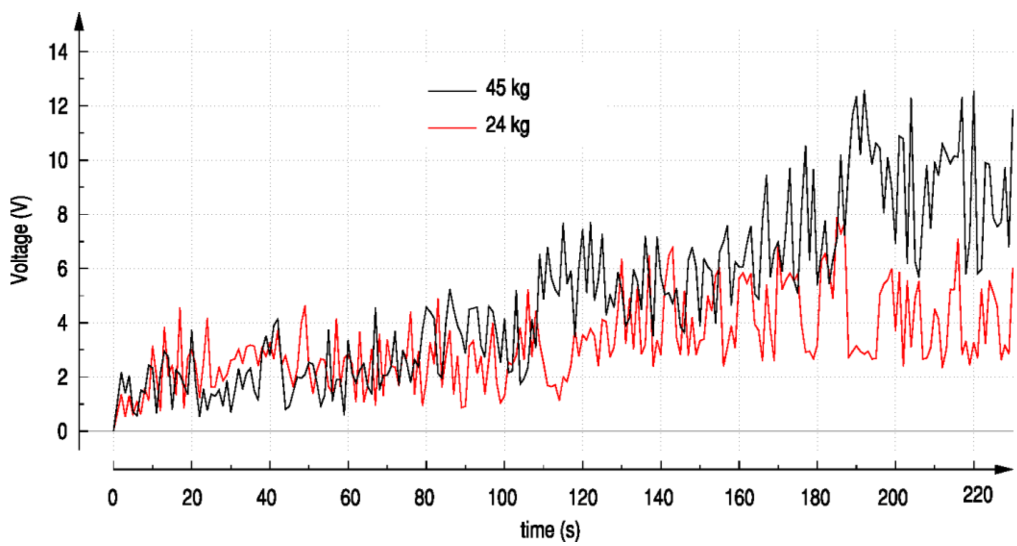


Figure 7.5: Weight impact on final results.

Figure 7.6 illustrate these two experiments. The results show that the amount of voltage in parallel is more than series. Therefore, the next step was to bond all piezoelectric materials in parallel to get the maximum output.

7.1 Output calculations

Since the vehicle weight is 1400 kg and it is supposed that the weight is distributed equally between tires, the load on each tire was calculated to be 350 kg (3433.5 N). As it is mentioned earlier, pressure and frequency were constant. Therefore, according to Figure 6.1, force is 332 N for the scaled down model and contact patch area A:

$$A = \frac{Force\ on\ each\ wheel}{Pressure\ under\ tire} = \frac{332}{0.17} = 1952.94\, mm^2 \tag{9}$$

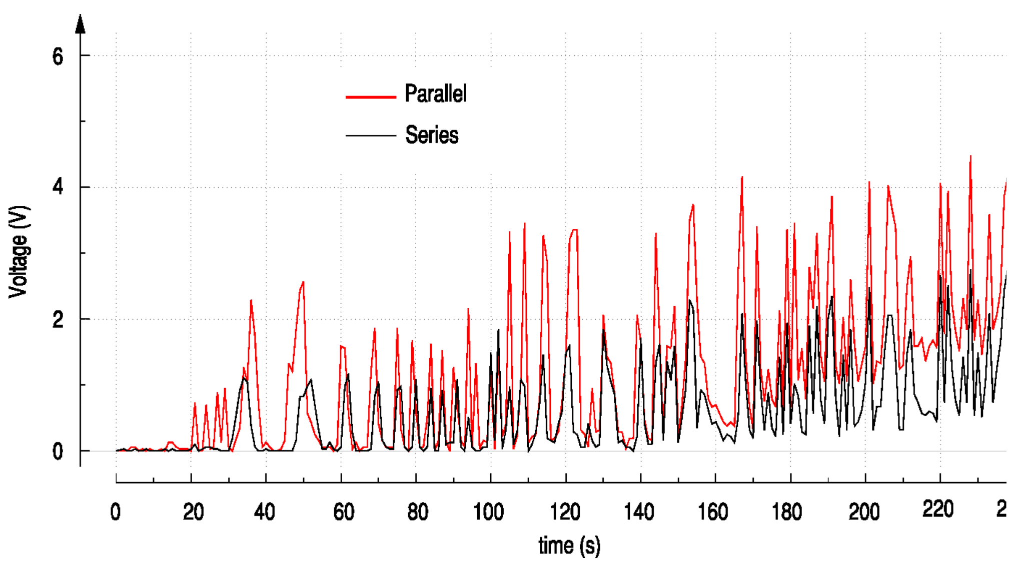


Figure 7.6: Series vs parallel connection to the element.

By considering the tire width, the contact patch length is 55 mm. This area is sufficient for two piezoelectric elements in two arrays.

$$Charge\ density = \mathrm{d}_{33} \times \sigma = 350 \times 10^{-12} \times 170000 = 0.0595\ \mathrm{m}\ \frac{\mathrm{C}}{\mathrm{m}^2} \tag{10}$$

where σ is the mechanical stress in the piezoelectric element, t is piezoelectric thickness and d33 represents the charge coefficient which is descried earlier.

$$Charge\ per\ each\ piezo\ elemnt = Charge\ density \times area\ of\ each\ piezoelemnt \tag{11}$$

$$Charge\ per\ each\ piezo\ elements = 0.0595 \times \pi \times 0.012^2 = 0.027\ \mu C\ or\ \frac{\mu A}{s}$$

$$Power\ output = V \times I = 1.29 \times 0.027 = 0.035\ \mu W/s \tag{12}$$

This amount is the output power for one piezo element in the scaled model in the pneumatic tire. A real model tire is 205/70R15. To find out how much power would one Chevrolet Malibu generate, the model needs to be scaled up to the reference vehicle. In Figure 6.1, all specifications of this car are shown. Assuming a 20 mm gap between the elements, and the tire circumference and width, the numbers of elements which can be placed are:

$$Number\ of\ elemnts\ on\ each\ wheel = \frac{Circumference}{Diameter + gap\ between\ elemnts} = \tag{13}$$

56 approximately

The reference tire width was 250 mm, which provides enough room to place 4 piezo elements in a row. Average voltage in the scaled down tire was 1.29/piezo element. Now, if all 4 piezo elements are connected parallel, the voltage output adds up to 1.29 × 4 = 5.16, and power output is 0.18 mW. For one complete rotation, the amount of power generated in total is equal to 0.18 × 56 = 10.11 mW/s. This amount of output depends on how to connect the other piezo elements to each other. Assuming that the vehicle runs at a speed of 90 km/h, and then the number of rotations per second is calculated with RPM equation which is shown above. This amount can be increased with different models of connection between piezoelectric in circumference or rectifiers to add up thetotal voltage.

$$RPM(90\frac{km}{h}) = \frac{V}{r \times 2\pi} = 9.7\ \frac{round}{s} \tag{14}$$

Therefore, the output power for each wheel in per second is 9.7 × 10.11 = 98.1. If this vehicle runs for one hour, then the amount of energy can be harvested is equal to 98.1 × 3600 = 0.35 W for each tire and 1.4 W for the whole car. This amount of energy is low for this time development of piezoelectric materials, but, this is a sufficient proof of future work for this new technology to run abroad electronics. Energy harvested from piezo benders depends on RPM and weight of vehicle. Different sizes of vehicles can produce different amounts of power. This method is sufficient for heavy vehicles with small diameters. Because according to pressure formula (P =F/A), by increasing F and decreasing A, this results in higher pressure and more power generation. Each piezoelectric element experiences two different modes: first, when the piezoelectric element places underneath of load which named open-circuit mode, and second is the bending situation before and after the contact patch. Open-circuit voltage amount can be achieved from this formula:

$$v = \frac{g_{33} \times F \times h}{\pi \times r^2} \tag{15}$$

in which:

$\mathbf{r}$ = out diameter of piezoelectric;

h = thickness of piezoelectric;

g_{33} = voltage constant.

For the piezo elements used in this study, the factors $\mathbf{r}$ and h, are 40 mm and 23 mm, respectively. The voltage constant g_{33} is 25×10^{-3} V.mm/N,

$$V = 25 \times (10)\text{^}(-3) \times 332 \times 0.23 \;/\; (\pi \times r\text{^}2\;) = 1.3 \;\; V$$

The amount of power produced because of revolution of tire calculated before:

$$P1 = 0.35 \text{ w} \tag{16}$$

and power at open-circuit situation is:

$$P2 = V \times I \times n = 1.3 \times 0.027 \times 56 = 1.96 \text{ w} \tag{17}$$

where n denotes the number of piezo element. Finally, the total power is:

$$P = P1 + P2 = 1.96 + 0.35 = 2.315 \text{ w} \tag{18}$$

In comparison to previous study, it seems that putting the piezoelectric elements outside of the tire could generate more power than inside of the tire.

Makki et al. [48] harvested 2.3 w per 160 stacks and 834 rpm versus in this study, 2.315 w of power is achieved for 56 elements and 356 rpm. This amount of power is not too much to competitive with current renewable energy. But, it is an itiative to more research.

As indicated before, the generated power has a direct relation with the number of piezoelectric cells used. Therefore, in comparison to the number of piezoelectric elements used in both work, this method generates more power compared to the reference work [48]. On the other hand, access to the outside of the tire, is easier than inside of the tire. Consequently, the outside of the tire is a good candidate to consider the validity of generating waste energy from cars. Although, this process has its advantages and disadvantages namely, tearing piezoelectric materials. This work is a realization of prototype model and has some errors. The purpose of study was to consider this kind of waste energy for the future.

7.2 LCA discussion

7.2.1 Interpretation

In this report, the interpretation phase is devoted to contribution analysis, quality control and sensitivity analysis.

Contribution Analysis

Contribution analysis is an important tool to understanding of uncertainty of results of a life cycle assessment [25]. This analysis is a step in interpreting the results to identify the major source (if any) of impacts by category. In other words, this step determines which process plays a significant role in environmental assessment.

After launching the analysis for IMPACT 2002+ modeling for the piezo-tire, the graph of the midpoint characterization (problems) is generated (Figure 7.7).

In Figure 7.7, the analysis makes it possible to conclude that all problem categories have the majority of the impacts caused by the production and use phase of the system.

To determine the damage impact to the environment, clicking on the damage assessment tab and then on the part of the graph where the impact is greatest, the exact impact score of the phase is selected according to the category (Figure 7.8). It is necessary to mount the scroll bar at the top so that the processes appear in descending order (from the most damaging at least).

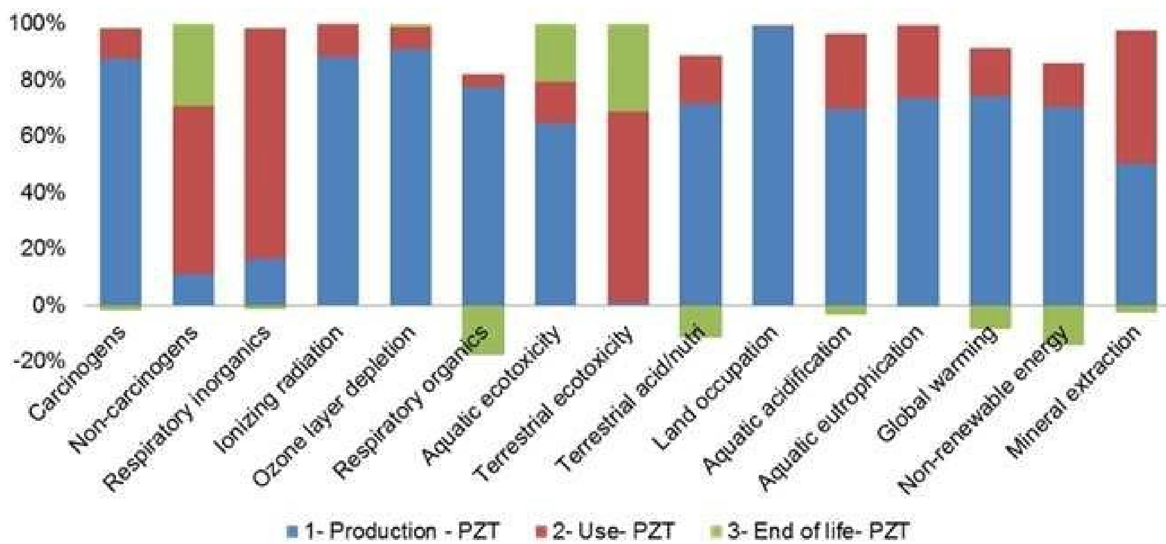


Figure 7.7: Characterization analysis of the piezo-tire with IMPACT 2002+

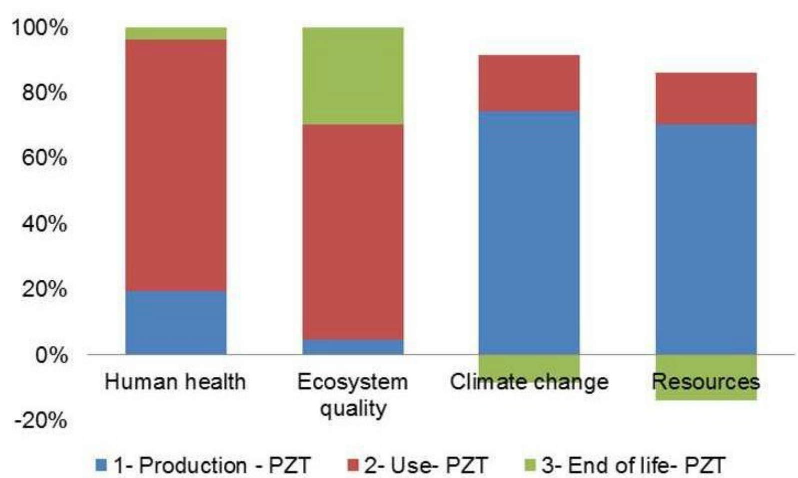


Figure 7.8: Damage assessment analysis of the piezo-tire with IMPACT 2002+

This process must be repeated for all damage categories to find out which substance has the biggest contributor of the life cycle assessment. Tables 7.1 and 7.2 allow to visualize the contributing substance and process. Tread debris in human health and ecosystem categories, textile in climate change category and carbon black in resource category are the most impacting process.

Comparing Tables 7.1 and 7.2 reveals that although lead-free piezoelectric energy production is low, it has a positive impact on the environment. Piezo-tire energy harvested is considered as avoided product which could save the energy and then be environmentally friendly.

Table 7.1: Contribution of different LCA phases in the damage assessment- Tire with PZT

Damage Categories	Life Cycle Step	Process	Substance
Human Health	Use-76.9	Tread debris	Rubber
Ecosystem Quality	Use-65.5%	Tread debris	Rubber
Climate Change	Production-81.4%	Textile	Nylon and polyester
Resources	Production-81.9%	Carbon black	Hydrocarbons

Table 7.2: Contribution of different LCA phases in the damage assessment- Tire without PZT

Damage Categories	Life Cycle Step	Process	Substance
Human Health	Use-83%	Tread debris	Rubber
Ecosystem Quality	Use-65.7%	Tread debris	Rubber
Climate Change	Production-99.8%	Textile	Nylon and polyester
Resources	Production-99.7%	Carbon black	Hydrocarbons

Comparing Tables 7.3 and 7.4 demonstrate that niobium pentoxide is mostly the outweighing material in lead-free piezoelectric manufacturing. The reason is niobium is a transition metal with a considerably high primary energy utilization and embodied foot print. The niobium extraction requires highly intense energy. DALY is abbreviation of disability-adjusted life year and refers to the number of years lost due to illness, disability or early death. This unit is a measure of overall disease burden.

Table 7.3: Damage category and impact of the piezo-tire

Damage Category	Unit	Impact
Human health	DALY	0.00101
Ecosystem Quality	PDF $\times$ m^2 $\times$ yr	464
Climate Change	kg CO_2 eq	65.3
Resources	MJ primary	870

Table 7.4: Damage category and impact of the common tire

Damage Category	Unit	Impact
Human health	DALY	0.00
Ecosystem Quality	PDF $\times$ m^2 $\times$ yr	457
Climate Change	kg CO_2 eq	20.8
Resources	MJ primary	150

Quality Control

The main point of quality control is to verify the consistency of the results and look into unexpected results [37]. The unexpected and surprising results should be considered to learn new things and explain inconsistency. Energy consumption and CO_2 emissions comparing is one way to check the consistency of inventory results. This comparison should be done for each phase and for the entire functional unit. To do this, the CO_2 emission and non-renewable energy usages should be calculated by ”IPCC 2013 GWP 100a” and ”cumulative energy demand”, respectively. Then, the ratio of CO_2 emission to non-renewable energy usage (g CO_2/MJ) is calculated for each life cycle stage. Ideally, this ratio should be between 0and100 to conclude that the study has quality data. Figure 7.9 is used to check the calculated ratio against the dominant processes and materials in orders of magnitude. This helps to analyst to take into account to major stages accurately. Tables 7.5 and 7.6 represent the result of the two systems (piezo tire and common tire). The gCO_2 eq/MJ ratio is between 0and100 and consequently this study has quality data.

Table 7.5: CO_2 emission ratio to non-renewable energy for the piezo-tire

Impact Category	Total	1.Production-PZT	2.Using-PZT	3.End of Life- PZT
g CO_2 eq	60130	52990	13890	-6750
Sum of Non-Renewable	865.05	847.66	186.05	-168.65
g CO_2 eq/MJ	69.510	62.513	74.66	40.02

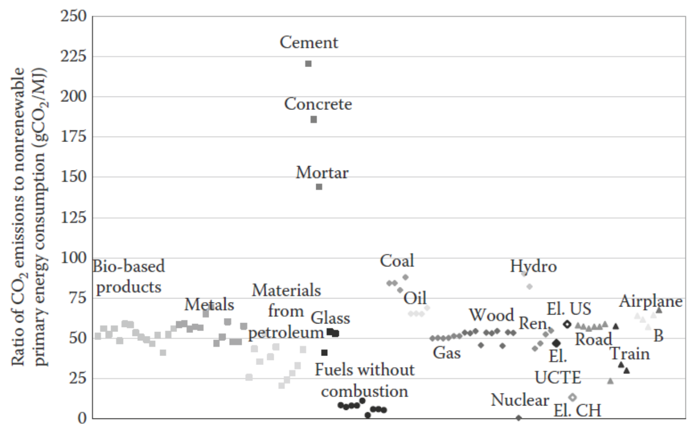


Figure 7.9: Ratios of fossil CO_2 emissions to consumption of non-renewable primary energy for different materials, energy systems, and means of transportation [37]

Table 7.6: CO_2 emission ratio to non-renewable energy for the common tire

Impact Category	Total	1.Production-PZT	2.Using-PZT	3.End of Life- PZT
g CO_2 eq Sum	12675	18894	54	-6273
of Non-Renewable	149.95	258.20	0.74	-108.99
g CO_2 eq/MJ	84.53	73.18	73.05	57.56

Sensitivity Analysis

The goal of a sensitivity analysis is to test the robustness of results and their sensitivity to data, assumptions, and models used. This analysis is a recommended step by the ISO standards (ISO 14040 & 14044, 2006) to observe the influence of the assumptions and choices made during the LCI and LCIA phases [51]. In this study, to provide sensitivity analysis, the piezoelectric materials amount is doubled to review the effects of environmental assessment. Regarding the results presented in Table 7.7, doubling the piezoelectric stacks, damage category scores is increased. For example the DALY score in the state of one layer of piezoelectric in production phase is 3.78 and this score for a double layer of piezoelectric materials is 4.83 which is less than twice the first situation. This condition gives better results for the usage phase. In this report, we had some uncertainties related to emission by piezoelectric materials. Certainly, this influences the final results. Although, as it was shown before, these materials are completely new to assess their environmental impacts. More research and experiments are required to fill the gap between inventory data and environmental impact assessment of piezoelectric materials.

Table 7.7: Sensitivity analysis of changing piezoelectric elements.

Damage Category	Unit	Production-PZT		Use-PZT		End of Life-PZT	
		Double	One	Double	One	Double	One
Human Health	mPt	4.83	3.78	16	14.9	0.717	0.717
Ecosystem Quality	mPt	1.81	1.59	22.4	22.2	10.2	10.1
Climate Change	mPt	7.27	5.92	2.71	1.39	-0.7	-0.68
Resources	mPt	6.83	5.59	2.47	1.24	-1.13	-1.11

Another sensitivity analysis is done for TRACI methods according to the United States stan- dards. Figures 7.10 and 7.11 illustrate the results of these two analyses. Although these two meth- ods have different impact categories, similar indicators such as human health (carcinogens and non-carcinogens), global warming and ozone depletion confirm that both methods have most environmental damage in the same phase. For example, the global warming phenomena happen for both methods at the production phase but human health damage is related to use phase of tires. More detailed results are required to ensure precision in the measurement and decrease uncertainty in the assessments.

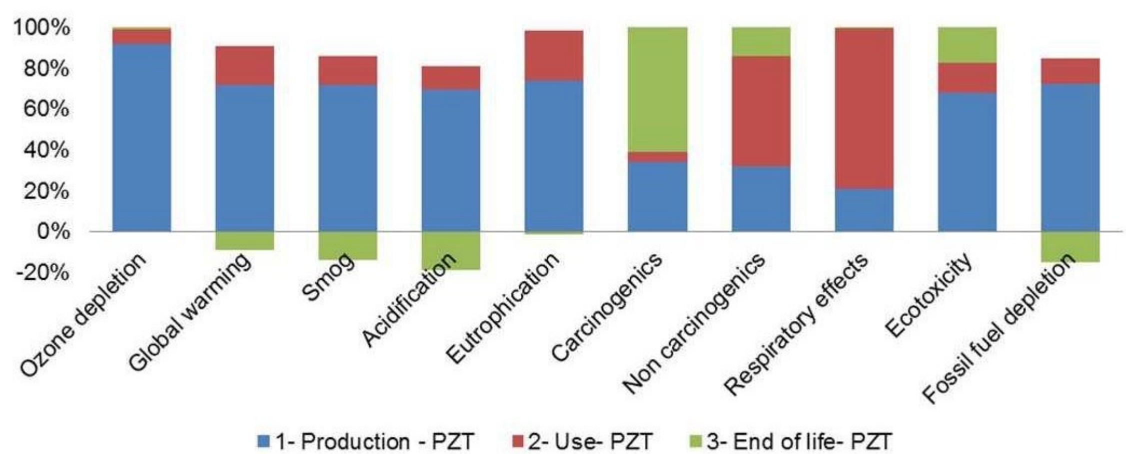


Figure 7.10: Analyzing LCA-PZT with TRACI 2.1

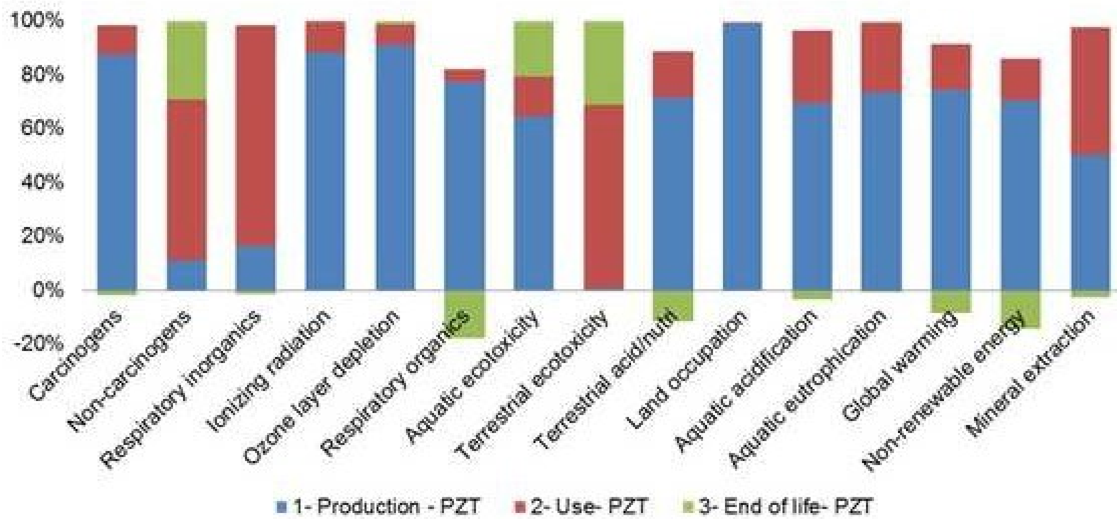


Figure 7.11: Analyzing LCA-PZT with IMPACT 2002+

Chapter 8

Conclusions and recommendations for future work

The aim of this research work is to utilize the advanced technology toward making power generation more sustainable and economical. In this research, a part of the lost energy through deformations of the tires was harvested using piezoelectric materials. The piezoelectric energy harvesting products are still not more competitive than other renewable energy harvesting techniques, such as solar and wind energies, this technology is of great interest in the development of waste energy harvesting ap- proaches. Therefore, it is reasonable to think about the large amount of energies which is wasted on the roads daily. The amount of energy generated by piezoelectric materials depends on the number of vehicles that is used.

In this thesis, the modeling and design of a piezoelectric energy harvester was investigated. The harvester circuit consists of five breakout boards, ten piezoelectric, a micro-controller, and one power supply which were all mounted on the tire. The proposed energy harvesting generated an inherent source of electricity due to the tire weight. When the tire rotates, the applied weights on the tire cause pressing and releasing (loading and unloading) of the piezoelectric elements and consequently produce a voltage inside piezoelectric elements. The focus of the project was on the development of a model to consider the potential of electricity generation of running vehicles. Experimental model that predict this potential has been developed and examined. The output voltage of the system is a function of tire RPM and weight of vehicle. The increase in the rotating speed makes the piezoelectric elements to generate electricity more frequently. Increasing the velocity from 2 mph to 4 mph resulted in 80 percent growth of the voltage, while doubling the speed for the second time (8 mph) increased the output voltage just nine percent. It means that in higher speeds the time is not enough to complete 1 cycle of charge-discharge in piezo materials. The reason is rooted back in visco-elastic characteristic of the tire's material that release deformations with low rate.

Then, experimental results were sent to the lap top by using a wireless micro-controller. A code developed in MATLAB records data to verify and compare these results with previous work has been done. Materials used for test is PZT which specifications described in Appendix A. Different piezoelectric elements were tested to achieve the best candidate to work in pressure with more flexibility. On the other hand, in the LCA part of this study it was found that a piezo tire contributes a slightly higher environmental load than common tires, but the fuel saving gives it an advantage in comparison to baseline tires. Due to the higher contribution of the use phase of tire in environmental damage, this technology could be considered for future research and development. This study is an initiative to think about that how can improve the tire characteristics to take advantage of harvesting waste energy in-use cars. It is obvious that piezoelectric material and similar ones which have this feature need to be studied and researched more to be able to use in industry. Regardless of how much electricity they are generating with current technology, materials with piezoelectric characterization can be found in nature. This study tries to give an idea about harvesting waste energy and then to consider each stage of the life cycle of both tires. It is a representative of current available data and thus requires more work in the future to update the LCA. Electricity generating tires is an idea that can be industrialized with improvement in the near future.

The technology is expected to make more contributions for the future exploitation and with further reduction in its cost, due to the rapid break through material developments. Design innovations as well as the manufacturing revolutions. The work presented here draws a solid starting line for the wide spread use of piezoelectric harvesters in the near future.

Consequently, the following recommendations are suggested for future work from the experience of work:

- There is a limitation in the selection of PZT elements because they are more fragile and damaged after a while. New developments in the PZT which have more potential to resist cyclic loads are required.
- In this study, all inventory data is taking from the state of the art work. However, piezoelectric materials are almost new and there are few studies about their LCA. Data collected by Ibn-Mohammeh et al. [32] was used for extraction and manufacturing lead-free piezoelectric. Some assumptions were taken whenever is required.

- The storage system for the generated power needs more investigation. Rechargeable batteries are an option.
- The generated power may be low to date. However it can be used for small parts of vehicles if stored. This application for small energy is not defined.
- The need for energy harvesting technology in the field of self-powered systems remains on emerging intelligent tire technology which captures waste energy and converts it to electricity by means of piezoelectric specifications.
- Improvement is required to apply this system to a wireless system.
- It is necessary to assess the emissions emitted during production, use and end of life process (land filling, recycling,) of the piezoelectric materials in the air, soil, and water in detail.

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Appendix A

Data Acquisition Code

It is a .m file created in Matlab.

```
clc;

clear all;

time_stamp = datestr(now,'yyyy-mm-dd-HH-MM-SS');
prompt = {'Enterrpm :','Enterweight(kg) :'};

dlg_title = ' Input';

num_lines = 1;
defaultans = {'2','24'};

answer = inputdlg(prompt,dlg_title,num_lines,defaultans);
mph = answer{1};
weight = answer{2};

fileID = fopen('data.txt','w');

i = 1;

figure hold on;

H = uicontrol('Style','PushButton', ...

'String', 'STOP', ...

'Callback', 'delete(gcbf)');

fact = 6.55/1024;

inpt1prev = 0;
```

```
inpt2prev = 0;
inpt3prev = 0;
inpt4prev = 0;
inpt5prev = 0;
totalprev = 0;
totalavprev = 0;
pickprev = 0;
ipre = 0;
fprintf(fileID,'%12.2f %6.2f %6.2f %6.2f %6.2f %6.2f %6.2f\n', 0, 0, 0, 0, 0, 0, 0);
while (ishandle(H))
data = urlread('http : //192.168.43.12/arduino/analog/2');
analogs = strsplit(data,',');
inpt0 = str2double(analogs1)fact;
inpt1 = str2double(analogs2)fact;
inpt2 = str2double(analogs3)fact;
inpt3 = str2double(analogs4)fact;
inpt4 = str2double(analogs5)fact;
inpt5 = str2double(analogs6)fact;
ginpt1 = [inpt1prev, inpt1];
ginpt2 = [inpt2prev, inpt2];
ginpt3 = [inpt3prev, inpt3];
ginpt4 = [inpt4prev, inpt4];
ginpt5 = [inpt5prev, inpt5];
total = [totalprev, (inpt1 + inpt2 + inpt3 + inpt4 + inpt5)];
sum = inpt1 + inpt2 + inpt3 + inpt4 + inpt5;
if sum ≤ pickprev
sum = pickprev; end
fprintf(fileID,'%12.2f %6.2f %6.2f %6.2f %6.2f %6.2f %6.2f\ n _
```

```
′,i0.01, inpt1, inpt2, inpt3, inpt4, inpt5, sum); pick = [pickprev, sum];
step = [ipre, i];

    plot(step, ginpt1, 'b');
hold on;
plot(step, ginpt2, 'k');
hold on;
plot(step, ginpt3, 'g');
hold on;
plot(step, ginpt4, 'c');
hold on;
plot(step, ginpt5, 'r');
hold on;
plot(step, total, 'b');
hold on;
plot(step, pick, 'r', 'LineWidth',3);
hold on;

    legend('A1', 'A2', 'A3', 'A4', 'A5', 'total');
hold on;
inpt1prev = inpt1;
inpt2prev = inpt2;
inpt3prev = inpt3;
inpt4prev = inpt4;
inpt5prev = inpt5;
totalprev = inpt1 + inpt2 + inpt3 + inpt4 + inpt5;
totalavprev = (inpt1 + inpt2 + inpt3 + inpt4 + inpt5 + totalavprev);
pickprev = sum;
ipre = i;
```

```
i = i + 1;
pause(0.01);
end
fclose(fileID);

    filename = strcat(time stamp,' ', mph,' mph ', weight,' kg',' .xlsx');
display '–DATA AQUISITION IS DONE!!!! LOOK FOR DATA INSIDE DAQs FOLDER–'
daq = load('data.txt');
xlswrite(['D : \Thesis\ARDUINO\graph\DAQs\' filename], daq);
time = daq(:, 1);
A1 = daq(:, 2);
A2 = daq(:, 3);
A3 = daq(:, 4);
A4 = daq(:, 5);
A5 = daq(:, 6);
plot(time, A1, 'b');
hold on;
plot(time, A2, 'k');
hold on;
plot(time, A3, 'g');
hold on;
plot(time, A4, 'c');
hold on;
plot(time, A5, 'r');
legend('A1', 'A2', 'A3', 'A4', 'A5');
```

Appendix B

Arduino Code

This code is adapted from Arduino examples.

```
#include <Bridge.h>
#include <YunServer.h>
#include <YunClient.h>
YunServer server;
void setup( ) {
Bridge startup
pinMode(13, OUTPUT);
digitalWrite(13, LOW);
Bridge.begin( );
digitalWrite(13, HIGH);
server.listenOnLocalhost( );
server.begin( );
}
void loop( ) {
YunClient client = server.accept( );
if (client) {
```

```
process(client);
client.stop( );
}
delay(50);
}
    void process(YunClient client) {
String command = client.readStringUntil('/'); if
(command == ''digital'') {
digitalCommand(client);
}
if (command == ''analog'') { analogCommand(client);
}
if (command == ''mode'') {
modeCommand(client);
}
}

    void digitalCommand(YunClient client) {
int pin, value;
pin = client.parseInt( );
if (client.read( ) ==' /') {
value = client.parseInt( );
digitalWrite(pin, value);
}
else {
value = digitalRead(pin);
}
    client.print(F("Pin D"));
client.print(pin);
```

```
client.print(F(" set to "));
client.println(value);
String key = "D";
key+ = pin;
Bridge.put(key, String(value));
}
    void analogCommand(YunClient client) {
int pin, value;
pin = client.parseInt( );
if (client.read( ) ==' /') {
value = client.parseInt( ); analogWrite(pin, value);
client.print(F("Pin D"));
client.print(pin);
client.print(F(" set to analog "));
client.println(value);
String key = "D";
key+ = pin;
Bridge.put(key, String(value));
}
else {
value = analogRead(A0);
client.println(value);


    value = analogRead(A1);
client.print(F(", "));
client.println(value);


    value = analogRead(A2);
client.print(F(", "));
```

```
client.println(value);

    value = analogRead(A3);
client.print(F(", "));
client.println(value);

    value = analogRead(A4);
client.print(F(", "));
client.println(value);

    value = analogRead(A5);
client.print(F(", "));
client.println(value);

    Stringkey = ''A'';
key+ = pin;
Bridge.put(key, String(value));
} }
    void modeCommand(YunClientclient) {
int pin;
pin = client.parseInt( );
if (client.read( ) ! =′ /′) {
client.println(F("error"));
return;
} String mode = client.readStringUntil(′\r′);
if (mode == ''input'') { pinMode(pin, INPUT);
client.print(F("Pin D"));
client.print(pin);
client.print(F(" configured as INPUT!"));
```

```
return;
} if (mode == ’’output’’) { pinMode(pin, OUTPUT);
client.print(F(”Pin D”));
client.print(pin);
client.print(F(” configured as OUTPUT!”));
return;
}
      client.print(F(”error: invalid mode ”));
client.print(mode);
}
```

Appendix C

CUI INC | **Part No: CEB-44D06** | **Date: 7/28/2006**
Description: piezo electric diaphragm | **Unit: mm** | **Page No: 1 of 4**

RoHS

Specifications

Maximum input voltage	20 Vp-p	
Resonant frequency	0.6 ± 0.3 KHz	see Measurement Methods
Resonant impedance	1000 Ω max.	see Measurement Methods
Electrostatic capacitance	70,000 ±30% pF	at 120 Hz / 1 V
Operating temperature	-20 ~ +70° C	
Storage temperature	-30 ~ +80° C	
Dimensions	ø44.0 x H0.23 mm	
Weight	5.10 g max.	
Material	Brass	
Terminal	Wire type	
DC resistance	20 M Ω min.	Fluke 45 rate: Fast Measurement time: 1 second (only for ≤ 20 mm test)
RoHS	yes	

Figure C.1: CEB-4406- Description

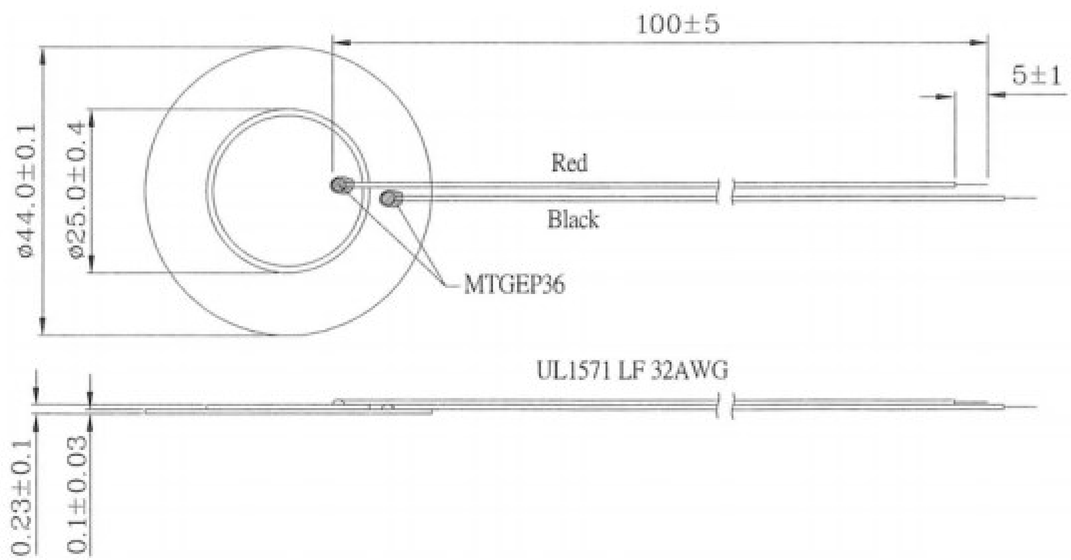


Figure C.2: CEB-4406-Apperance

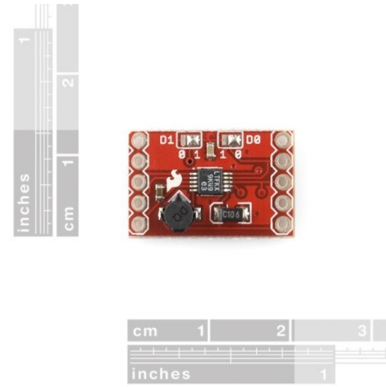
Appendix D

The breakout board (see Figure D.1) uses the LTC3588 from linear technologies. This board has a bridge-rectified input and direct input for piezo elements and DC sources, respectively. This breakout has four-output pin for different voltages (1.8V, 2.5V, 3.3V and 3.6V) with up to 100 mA output current and 3.3 V preconfigured voltage. The following have some features of this break out (SparkFun Electronics):

- 950 nA Input Quiescent Current (Output in Regulation - No Load);
- 450 nA Input Quiescent Current in UVLO\;
- 2.7 V to 20 V Input Operating Range;
- Integrated Low-Loss Full-Wave Bridge Rectifier Up to 100 mA of Output Current;
- Selectable Output Voltages of 1.8 V, 2.5 V, 3.3 V, 3.6 V;
- High Efficiency Integrated Hysteretic Buck DC/DC;
- Input Protective Shunt-Up to 25 mA Pull-Down at VIN $\geq$ 20 V;
- Wide Input Under Voltage Lockout (UVLO) Range;

A schematic plan of connection of this breakout illustrated below. The characteristic of LTC3588-1 also presented in detail in.

(a) LTC3588 breakout top view



(b) LTC3588 breakout dimension

Figure D.1: LTC3588 Breakout

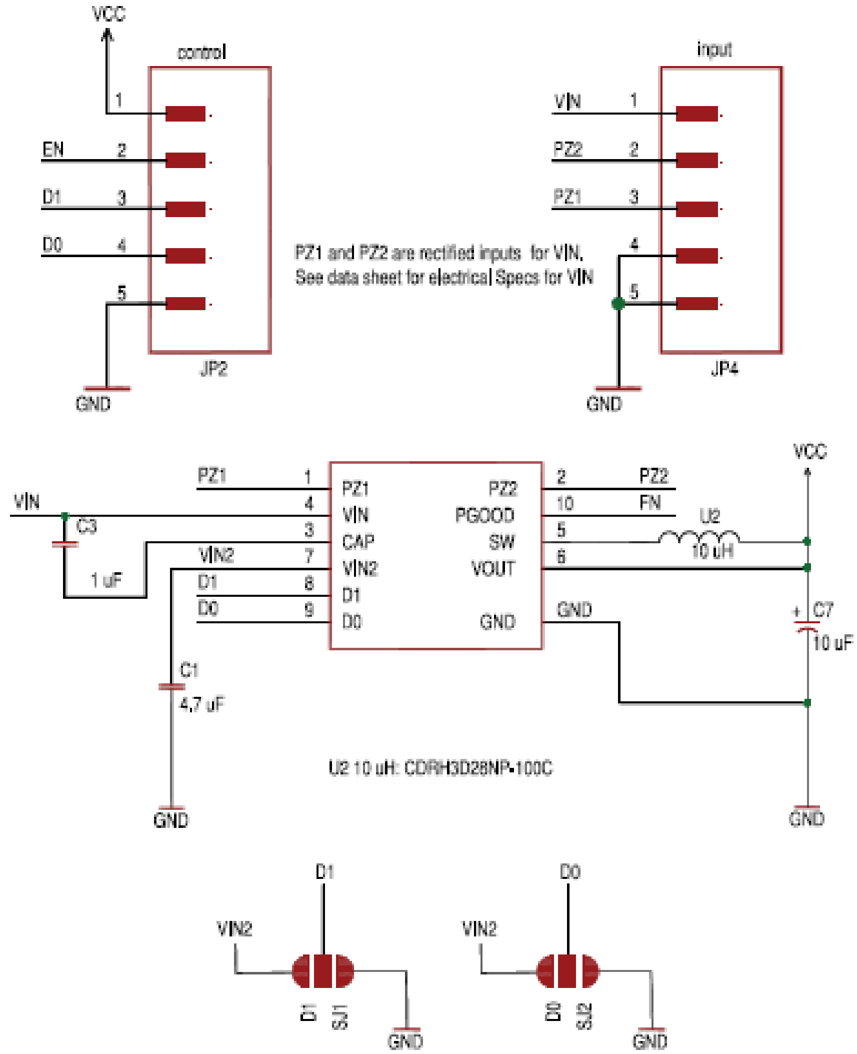


Figure D.2: LTC3588 breakout circuit.