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Automotive Energy Harvesting
A research study for a toll-road chip and energy harvesting system

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Abstract

On-Board Unit, a toll-road chip developed by Q-Free is battery powered today, with an expected lifetime of approximately five years. Anders Hagens patent from 2014 claims the On-Board Unit can be powered partly or fully by energy harvesting from vibrations in a vehicles windshield.

In this thesis, vibrations from three vehicle windshields are mapped and compared. Three energy harvester transducer types are investigated and compared. One will compare how the available windshield vibrations correlate with the selected energy harvester transducer type, and how much power can be delivered from the transducer.

The vibrations available in a vehicles windshield are in general small in amplitude and narrow-banded in frequency. The characteristic frequency of each vehicle varies slightly. The piezoelectric transducer chosen as the best approach is narrow-banded in frequency, and is dependent of exact impedance matching to enable full power delivery to a designated load. By utilizing the PZT piezoelectric material, a common model for a multiple of vehicle types is not a possible solution by now.

A piezoelectric transducer is able to deliver approximately 10 to 20 uW to its load when both the transducer and the load are optimally matched. These are ideal figures, and will not be able to reach in a real life implementation due to losses in the piezoelectric element, power conditioner, energy storage and similar.

**Keywords**: Energy harvesting, Automobiles, Toll-road chip, Vibration analysis, Piezoelectric, Frequency tuning.
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Glossary

**AC** Alternating Current. 25

**CSV** Comma Separated Values. 16, 19, 31

**DLPF** Digital Low-Pass Filter. 33

**FFT** Fast Fourier Transform. 15, 16, 18, 19, 37, 38, 45

**FWD** Front Wheel Drive. 37

**GEMC** Generalized Electromechanical Coupling Factor. 23

**ITS** Intelligent Traffic Systems. 1

**JSON** JavaScript Object Notation. 16

**MEMS** Microelectromechanical systems. 8

**MFC** Macro Fiber Composite. 61

**PSD** Power Spectral Density. 18, 19, 37, 38

**PZT** Lead Zirconate Titanate. III, 58, 60–62

**ROHS** Restrictions of Hazardous Substances. 58, 60

**RTC** Real Time Clock. 16

**RTOS** Real-Time Operating System. 57, 58

**RWD** Rear Wheel Drive. 37
**SDOF**  Single Degree Of Freedom. 21

**Two’s Complement**  Positive and negative representation of a number. 19

**WSN**  Wireless Sensor Network. 1, 58

**Youngs Modulus**  Material stiffness. 9, 59
Chapter 1

Introduction

1.1 Background

Q-Free is a global supplier of class-leading Tolling, Parking, Traffic Management and Connected ITS / Connected Vehicle Solutions.

Anders Hagen at Q-Free was granted the patent On-Board Unit For Use In Vehicle Identification in 2014 (Hagen, 2014). The patent presents how an On-Board Unit assembled in a vehicle can be powered partly or fully by an energy harvester.

An On-Board unit is today used to uniquely identify a vehicle, for road tolling or other purposes. Today’s On-Board units are active, and powered by a lithium primary cell (3.6V, 350 - 900 mAh). In normal operation the battery lifetime is expected to be at least five years. Since it is not desirable to replace the battery during the On-Board Units lifetime, the battery lifetime represents a limitation in the system design. This applies even if battery changes are estimated as rarely as every 5 years.

In order for battery replacements to happen as rarely as possible, extensive work is done to enable the On-Board Unit to operate more efficiently. At the same time, the possibility of greater battery capacity in the device is investigated, or solutions where the device harvests its own energy. All this assuming that the physical size and weight of the On-Board Unit are not significantly altered.

There is a large growth in WSNs for a multiple of markets, such as smart buildings, health and lifestyle monitoring and automotive applications. With this comes an evident need for alternative power supply solutions, as these systems should be able to operate without any maintenance throughout their lifetime (Vullers et al., 2010).

Increasing the amount of batteries for use in sensor networks is not a satisfactory solution, as they contain potentially toxic materials (Kang et al., 2013). From an environmental standpoint utilizing self-propelled systems which harvest their own energy is desirable, especially if one can avoid the use of components that contain
potential environmental toxins such as lead, nickel and cobolt.

A solution where the On-Board Unit is self-supplied with energy, without affecting space and / or economy is desirable. A multiple of energy sources in the circumstances of the On-Board Unit are available, such as solar, thermal, vibrational, rotational and impulse sources.

For the scope of this master thesis, energy harvesting from the latter three energy sources will be covered.

1.2 Related work

Apart from energy analysis performed locally by Q-Free, little information exists for energy profiles at vehicle windscreens in todays literature. The main focus has been vibration energy harvesting from shock absorbers, wheel bearing and brake systems. Parthasarathy (2012) has conducted work on an energy harvesting sensor system for use on wheel assembly. As the sensor system is assembled parallel to a rotating wheel, it will possibly be exposed to more energy at motion compared to an energy harvesting system assembled inside a vehicle, due to damping. Thomas and Anderson (1979) assembled a vibration measurement system onside a series of transit-buses. Their goal was to verify whether or not the vibrations occurring from commute bus rides served a threat towards sensor systems present at the bus. Their main findings were vibrations present in the 10-15 Hz area, with varying amplitude. Even though this study cannot be said to be directly relevant towards energy harvesting in vehicles, some of the findings from the study are of particular interest. The frequency content, the damping from wheel bearings up towards bus chassis and floor, and how the vibrations correlate with the bus’ speed and road conditions are of particular interest.

1.3 Problem motivation

An On-Board Unit is in most cases located on the top of a vehicles windshield. Since energy harvesting is to take place locally in the unit, a mapping of the energy profile present at top of a vehicles windshield is needed. Different vehicles may have different vibration characteristics for their windscreens. This could be affected by the vehicle type, its vibration characteristics from engine and suspension, as well as road conditions and driving style. Physical placement of the On-Board Unit could also affect how an energy harvester operates. One must determine if there is a common point of reference to base an energy harvester solution upon.

From what is known of piezoelectric, electromagnetic and electrostatic transducers today is that some of them have a narrow frequency operating range, and that the direction and angle they operate at is affecting their efficiency.

The energy available from windscreen energy harvesting is expected to be negligible compared with the energy available at wheel bearing and brakes. Thus an
energy harvester solution located in a vehicles windscreen needs to attain optimum high efficiency, ranging from physical placement of transducer, through several energy conversions and towards energy storage and supply.

1.4 Project Objectives

- Identify the presence of vibration, rotation and impulse energy sources in the windscreen of a selection of vehicles. A measurement jig will need to be constructed. It should determine direction, frequency and amplitude contents of the three energy sources that exists in the windscreen in these vehicles.

- Identify characteristics of energy harvesters for the following transduction methods available on todays market:
  - Piezoelectric
  - Electrostatic
  - Electromagnetic

- Compare prior mentioned energy harvesters and determine which harvester solution that best fit with the energy present in a vehicles windscreen

- If necessary, simulate measured energy profiles and characteristic properties of energy harvesters, for example in Comsol Multiphysics. This to verify the behaviour of a given energy harvester with a known energy profile.

- Identify the typical power consumption of an On-Board Unit

- Determine if the available energy and the chosen energy harvester solution is sufficient to hold an On-Board Unit operative alone.

- Design, construct and function verify a prototype of an energy harvester solution, applicable for use with an On-Board Unit. An energy harvester prototype for On-Board Unit will likely contain these features:
  - Energy harvesting transducer
  - Rectifier circuit
  - Charge pump
  - Voltage regulator with impedance matching circuit
  - Power storage unit (Capacitor, battery)
  - Power management module

Selection of transducer will affect nearby component selection, since they have varying characteristics.

Function verification will likely be based by applying energy from known sources, such as an industrial vibrator. A function test in a vehicle is also desirable. To simplify any test setup, one would like to implement a load
with similar characteristics as the On-Board Unit. This applies if using the On-Board Unit as a real load would give an unrealistic workload for function testing.

- Compare the material cost of implementing an energy harvesting solution with a single battery driven approach

1.5 Project significance and value

The measurement data should serve as generalized data sets for vehicle behaviour, and possibly be used for other purposes later.

The prototype should serve as a proof of concept for the On-Board Unit patent mentioned earlier. One should be able to divide single elements from a successful implementation of the Energy Harvesting On-Board Unit prototype, to further generalization for use in other concepts.

1.6 Outline

The theory of the thesis work is described in chapter 2. This includes description of three types of energy harvester transducers and how the operating frequency is tuned.

Methods of operation for vibration measurements, signal processing and energy harvester modelling are all described in chapter 3.

The results from the vibration measurements are presented in chapter 4. Results from energy harvester modelling are also presented in chapter 4.

Discussion of chosen solutions for measurement system, data processing and results for energy harvester modelling are discussed in chapter 5. Concluding the work is also done in chapter 5.

The amount of measurement and analyzed data was too big to fit reasonably in the main section of the report. Parts of the data for vibration measurement and energy harvester modelling are located in section A.1 and section B.1.

1.7 Contributions

All work in this paper is solely done by the author himself. Sections where the author has obtained inspiration, or obtained help from others for understanding should be evident from the report.
Chapter 2

Theory

2.1 Electromagnetic Energy Harvester

The electromagnetic effect refers to Faraday’s law, and how the change of an electromagnetic field in cooperation with a closed circuit can generate an electromotive force. Electromagnetic generators mostly consists of permanent magnets to produce a magnetic field, and uses a coil as conductor. The movement of the coil compared to the magnets is what induces a voltage over the coil. The voltage is dependent upon the strength of the magnetic field, the motion velocity and the number of turns in the coil. Electromagnetic generators are mostly characterized by low voltage high current outputs (Kazmierski and Beeby, 2014).

According to Beeby et al. (2007), the coupling strength of micro-scale NeoDymium magnets is non-linear, and significantly lower than macro-scale NeoDymium magnets. This can possibly further increase its complexity in micro-scale energy harvester implementations.

A typical electromagnetic transducer setup is depicted in Figure 2.1.

![Figure 2.1: Electromagnetic Energy Harvester (Kazmierski and Beeby, 2014)](image-url)
2.2 Electrostatic Energy Harvester

The electrostatic generator is based upon electrostatics, and how changing the capacitance by mechanical vibrations can induce a charge which moves between two electric dipoles. Electrostatic generators can be classified in three types, which are depicted in Figure 2.2 (Kazmierski and Beeby, 2014).

![Electrostatic generators: (a) in-plane overlap; (b) in-plane gap closing; and (c) out-of-plane gap closing](image)

**Figure 2.2:** Electrostatic generators: (a) in-plane overlap; (b) in-plane gap closing; and (c) out-of-plane gap closing (Kazmierski and Beeby, 2014)

A circuit representation of an electrostatic generator is depicted in Figure 2.3. The electrostatic generator is represented by the $C_v$ component in Figure 2.3, while the other components are support and load. The electrostatic generator also needs an external charge to operate, represented by $V_{in}$. Kazmierski and Beeby (2014) tells that electrostatic generators are realizable in MEMS versions, and hence small-scale implementations. However, their need of an initial voltage to operate, as well as their high output impedance makes them not applicable to operate solely as a power supply.
### 2.3 Piezoelectricity

#### 2.3.1 The piezoelectric effect

The piezoelectric effect refers to a change in the electric field of a crystalline material when mechanical stress is applied. The change of electric field is due to the non-centric-symmetric crystal structure of the material. By placing the center ion slightly off center, each related unit cell is turned into an electric dipole. By poling each unit cell, the dipoles are manipulated to orient in slightly the same direction, shown in Figure 2.5 b. When mechanical stress is applied to the material, the position of each center element in all of the unit cells is shifted in the same direction, maximizing the force of the generated electric field. (Multiphysics-Cyclopedia, NKb) This process is reversible, meaning that applying an electric field to a certain material can generate a mechanical deformation. (Multiphysics-Cyclopedia, NKa) Figure 2.4 depicts the electric field in a piezoelectric Quartz lattice at three situations, where the electric field changes according to the force applied to the material.

![Piezoelectric Effect in Quartz](image)

**Figure 2.4:** Piezoelectric characteristic (Tires, Unknown)
2.3.2 The piezoelectric transducer

The crystal orientation is together with material selection the key components in piezoelectric transducer design. The best known material for piezoelectric energy harvesting is lead zirconate titanate (PZT), due to its high piezoelectric constant (Hudak and Amatucci, 2008). Figure 2.5 a depicts how the crystal can be oriented to absorb force in either longitudinal or transverse direction (31 and 33 mode respectively). Figure 2.5 c shows a piezoelectric cantilever beam sensor, operating in 31 mode with a weight placed on the freely moving part of the crystal, maximizing the impact of the applied force and hence also the electric field.

![Figure 2.5: a) Longitudinal and transverse stress absorption b) Polarization scheme for crystals c) Piezoelectric cantilever beam](image)

Piezoelectric transducers are available as both single- and multilayer constructions. The construction of the transducer will often be dependent of the absorption direction. The classical construction method is a protective coating for single- or multilayer constructions, and wires to connect the transducer to a rectifier, power conditioner and charge system. Such constructions are often found both as harvesting systems implanted in shoe soles, and actuators found in fire alarm buzzers. Piezoelectric transducers can also be constructed as MEMS devices, offering energy harvesting, rectification and voltage controller, integrated in one single chip. With a significantly smaller chip size than the earlier mentioned setup, they are well suited for use in areas where size matters.

Vocca and Cottone (2014) claims that the available power is significantly higher for a 33-mode absorption system compared to a 31-mode system, due to the possible strain and coupling coefficients of the 33-mode system. On the other hand, the 33-mode system is best suited for high frequency operations, while a 31-mode system easier can produce an electric charge after being suppressed to strain at lower frequencies. Conventional MEMS devices are mostly constructed as 31 mode harvesters, with a piezoelectric layer placed between the top and bottom electrode. The voltage generated from this system is proportional to the piezoelectric constant,
applied stress and the thickness of the piezoelectric layer. Kim et al. (2012) claims that with today’s technology both the piezoelectric constant and acceleration in a typical 31 mode use case is too low to generate a satisfactory voltage for a rectifying circuit.

Future advancements in piezoelectric technology will eventually enable the use of 31-mode piezoelectric materials with higher material constants. Piezoelectric materials of this kind will help realizing future 31-mode MEMS harvester solutions (Kim et al., 2012).

2.4 Frequency tuning

The efficiency for most of the transducers mentioned above is strongly frequency dependent, and one will most likely need to tune the resonance frequency of a commercially available transducer down to a desired level, to meet the desired frequency found in vibration measurements. Frequency tuning for the three transducers discussed above will be application specific, but in general these statements can be made:

- Tuning procedure should be represented by a minimal quisquent current
- Frequency range and frequency resolution should not be affected by tuning
- A high Q-factor should be attained, to ensure minimum system damping and to attain maximum output power

Frequency tuning can be accomplished by either adjusting the electrical load or by changing the mechanical properties of the transducer. For simulation purposes, the load applied to the transducer will be a power conditioner, further explained in section 3.4. As the load characteristics of the power conditioner is somewhat unknown, one will focus on adjusting the resonance frequency by changing the mechanical properties of the transducer.

In general, the resonance frequency of a mechanical resonator is

\[ f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{Y \times w \times b^3}{4 \times b^3 (m + 0.24m_c)}} \] (2.1)

A typical mechanical resonator, here a piezoelectric cantilever beam, is depicted in Figure 2.6. The parameters listed in Equation 2.1 are similar to the ones depicted in Figure 2.6. The Y parameter is Young’s Modulus. Since parameter k, the spring constant is material dependent, little effort can be made to manipulate the material itself. The spring stiffness can be manipulated by adding external springs in parallel to the resonators spring, in such a way that it lowers the total spring stiffness.

\[ f_{\text{res}} = \frac{1}{2\pi} \sqrt{\frac{k_{\text{eff}}}{m}} = \frac{1}{2\pi} \sqrt{\frac{k_m + k_a}{m}} \] (2.2)

Manipulating either the cantilever length or the total mass of the system is the most feasible approach to achieve resonance frequency tuning. Changing the
position of the cantilever mass could also be a possible approach to further tune the resonance frequency of a mechanical resonator, but will not be a priority by now due to time restrictions (Kazmierski and Beeby, 2014).

Figure 2.6: Cantilever beam frequency tuning (Kazmierski and Beeby, 2014)

2.4.1 Frequency resolution

This section explains the frequency width of piezoelectric energy harvesters, and how the quality factor affects the frequency width and the possible harvestable power.

Figure 2.7 depicts the normalized harvestable power as a function of excitation frequency, considering various quality factors. A high quality factor coincides with the highest possible output power, but the most narrow frequency width, meaning that the excitation frequency has to perfectly match the harvesters resonance frequency (Hehn and Manoli, 2015a).

As the normalized harvestable power is dependent of the relationship between the excited frequency and the resonant frequency, \( \frac{\omega}{\omega_0} \), the frequency width will be narrowed down until an infinitely narrow value as the resonance frequency is lowered down towards 10-15 Hz. The frequency width and possible output power will be dependent of the systems Q-factor.
2.5 Vibration occurrence

The Hagen (2014) patent that originated with this idea suggests to tune the resonance frequency of an energy harvester towards a given wheel or engine frequency present in a vehicle. One can consider that different vehicles likely will have different vibration sources, which results that the vibrations available in the windscreen change in both amplitude and frequency for different vehicle manufacturers.

Irvine (2019) has conducted experiments to determine the frequency content in a vehicle while driving. An accelerometer was assembled in the console of a vehicle, which drove in a constant speed on a highway. The results tells that there are frequency components near DC-level (1 to 1.5 Hz), which relate to the vehicles suspension system, known as Spring-Mass Frequencies. The measurements also reveal that there are frequencies present in the 15 Hz area, similar to those mentioned by Hagen (2014). Irvine (2019) claims the frequencies in the 15 Hz area, as well as their 2nd harmonics are related to tire imbalance. If one considers that the vibrations from wheel imbalance are transferred via the suspension to the entire vehicle chassis, one can also consider that these vibrations will at least be partly present in the windshield of a vehicle.

The frequency for tire imbalance is calculated in Equation 2.3:

\[
f = \frac{\text{Speed}[\text{km/h}] \times 10.94\left[\frac{\text{in/s}}{\text{km/h}}\right]}{\pi \times \left(\text{Rim diameter}[\text{in}] + 2 \times \frac{\text{Tire width}[\text{mm}] \times \text{profile}[:%]}{25.4[\text{mm/in}]}\right)} \tag{2.3}
\]

Equation 2.3 is deduced by the author, with inspiration from Irvine (2019). The tire imbalance frequency is dependent upon the relationship between speed and wheel circumference. The wheels circumference is decided by the rim size and height of the tire. The tire height is a percentage of the tire width, and the percent
value is called profile in the tires specification. These values are all printed on the sidewall of a tire, and they will vary with respect to the chosen tire model. To represent the tire height on both top and bottom side of the rim, the tire height section of the equation is multiplied by two. (Goodyear, NK). A typical tire letter indication is given below:

- Tire width/Profile.Construction Method.Rim size.

With Equation 2.3 available, it is desirable to calculate change in frequency as a function of wheel size, and as a function of speed.

If one considers the measurements conducted on the Volvo V70, measurements were conducted with both summer and winter tires. A vehicles tire dimension is restricted by a document given by Vegdirektoratet (1995). A standardized tire and rim dimension is given by the vehicles registration document. Vegdirektoratet (1995) indicates that a drift of the rolling circumference of up to 5% from standard is legal, which directly relates to the tire and rim dimension of a vehicle.

For the Volvo V70, the following tire dimensions were driven with during the test period:

- **Summer tires**: 235/35R19
- **Winter tires**: 205/55R16

The summer tire dimension represent the extreme of what is legal to drive with on the particular car, and calculating the frequency at each tire dimension will be a good indication of how the frequency changes with different tire and rim sizes. To simplify calculations, both calculations below will be conducted with a constant speed of 80 km/h.

**Summer tires**

\[
\begin{align*}
  f &= \frac{80[km/h] \times 10.94[in/s/km/h]}{\pi \times (19[in] + 2 \times \frac{235[mm]}{25.4[mm/in]} \times 35[\%])} \\
  &= 10.94 \ Hz
\end{align*}
\]  

(2.4)

**Winter tires**

\[
\begin{align*}
  f &= \frac{80[km/h] \times 10.94[in/s/km/h]}{\pi \times (16[in] + 2 \times \frac{205[mm]}{25.4[mm/in]} \times 55[\%])} \\
  &= 11.19 \ Hz
\end{align*}
\]  

(2.5)

From the calculations above, one sees that the tire imbalance frequency is expected to change with approximately 0.25 Hz when the car is driven at a constant speed of 80 km/h.

As most of the measurements will be conducted with winter tires, it is most feasible to see the frequency drift as a function of speed for the winter tire setup. A simulation of the vibration characteristic is depicted in Figure 2.8.
2.5. Vibration occurrence

Figure 2.8: Vibration frequency vs vehicle speed for a Volvo V70 - winter tires
Chapter 3

Method

3.1 Measurement system

As stated in section 1.4, a measurement system is needed to identify the presence of vibrations in a vehicle’s windshield.

Initial research revealed several measurement systems available for remote vibration measurements, such as the Midé Slam Stick system. However, due to the price of the measurement system it was desired to use a more cost-effective alternative. It was decided to develop a system based on a MEMS accelerometer and a Raspberry Pi.

3.1.1 Measurement system requirements

Anders Hagens patent (Hagen, 2014) claims there are acceleration values in the 10-15 Hz range in the windshield of the vehicle where he has conducted initial tests upon. The measurement system constructed by this study should ideally achieve similar results.

Midé claims their SlamStick C to be best suited for measurement operations beneath 500 Hz (Midé, 2017). Its sample rate is configurable from 12.5 Hz to 3.2 kHz per channel. When it is uncertain whether frequency components over 15 Hz exist in the measurement spectrum, and at the same time a precise reconstruction of measured signals is desired, one wants to attain as high sample rate as possible. Since the MPU6000’s upper sample rate is 1 kHz, it is desirable to reach this limit for the sampled data.

Data processing

The sampled data is supposed to be processed in Matlab or similar tools, for FFT analysis and energy harvester modelling. Thus it is desired to be able to export
Chapter 3. Method

acceleration data from the measurement platform to a computer in a single file format, such as CSV, JSON or similar.

Midé has developed their very own measurement software to cooperate with the Slam Stick dataloggers. Midé’s example software for vibration analysis in Matlab is used for FFT analysis in this paper. The software can be found at Midé’s web page (Midé, NK).

Windshield assembly strategies

An On-Board Unit will ideally be assembled in a vehicle’s front windshield, attached with some sort of adhesive. Hence it is desirable to assemble the measurement system similar as an On-Board Unit would be, to ensure real and credible measurement results.

The solution was to 3D-print a holder specifically designed for the accelerometer used in test setup. This was then assembled with double sided tape in the windshield of the actual vehicles used in the test sequence. An accelerometer for industrial use is mostly assembled with stud mounts, to ensure sufficient adhesive properties towards the material it is assembled to. In this case, since the accelerometer is being assembled towards glass, stud or spike mount is not a viable option. Poff (2010) has compared adhesive and stud assembly for industrial grade accelerometers in automotive applications, and compared the sensor output from a specific test setup. Their results indicates that the accelerometer response is similar for both assembly techniques. Thus, one can safely assemble an accelerometer setup with double-sided tape, as long as the tape is newly cut and the windscreen is sufficiently clean.

3.1.2 Realized measurement system

The finalized measurement system consists of the following items:

- Mikroelektronika MPU IMU click, with MPU6000 accelerometer
- Raspberry Pi 3 Model B
- DS3231 RTC
- Custom push-button control board
- Custom accelerometer holder

The workflow of the measurement system is depicted in Figure 3.1. The assembled measurement system is depicted in Figure 3.2.
3.1. Measurement system

Figure 3.1: Flowchart Python script
3.2 Signal Processing

The accelerometer data is sampled at various time scopes, ranging from the authors daily commute ride of approximately 15 minutes, until longer rides upon 1 hour in two different taxis.

Hanly (Uknown) has written the Midè handbook for Shock and Vibration Testing, which gives a brief introduction on how to configure a measurement system and to process the data for further analysis.

The guide from Hanly (Uknown) also contains real-life measurement examples, along with scripts for data analysis, such as FFT, Power Spectral Density (PSD) and spectogram analysis. The scripts given by Hanly (Uknown) are used in varying degree to process data coming from the measurement system, for use in FFT, PSD and spectrogram analysis.

3.2.1 Signal Pre-processing

A system design error that is further described and discussed in subsection 5.1.1 led to selecting a sample rate of 615 Hz for the measurement system.

From Hanly (Uknown) it is taken that an oversampling of 10 times the desired measured signal frequency should be sufficient. If the highest available signal is in the area 15-20 Hz, a sample rate of 615 Hz should be sufficient. The number of frequency bins attained by an FFT analysis is equal to half the sample length, N/2. To achieve similar processing between the various vehicles and journeys, a common sample length is desired.

The standard sample length for the processing is set to \( N = 2^{20} \) samples. With a sample rate of 615 Hz this represents a sample length of approximately 28 minutes.
To achieve this length, data sets for shorter journeys are zero padded up to the desired length, while longer data sets are cut down to the desired length.

In order to simplify the data management of the measuring system, it is chosen to process as little data as possible locally. The data coming from the measurement system’s CSV file is a time code per three-axis accelerometer reading, as well as a two-byte ADC value per axis representing the accelerometer signal. This data must be pre-processed in order to run further analysis.

Several scripts have been developed in Matlab to process the time-code and accelerometer data. The time code data is remapped and a new time series starting from time $t=0$ is created with basis in the original time signal.

The accelerometer ADC data is converted into Two’s Complement, and scaled according to the accelerometers set sensitivity. For these measurements, the sensitivity have been set to 2G, to enhance the best possible resolution of the measured data.

### 3.2.2 FFT analysis

A standard signal FFT extracts the frequency components of a signal with finite length. The signal amplitude and frequency is extracted, and shown to give the user a perspective of the vibrational components present in his measurement system. The FFT is best suited for finite length signals, preferably with non-varying frequencies during the measurement time. The resolution for the frequency bins of the FFT is dependent of the sample length, and it is hence best practice to acquire a satisfactory sample length. On the other hand, with long sample length and environments where frequency components may vary over time, frequency drifting could be experienced. In such situations it would be beneficial to verify the behaviour with a PSD analysis instead (Hanly, 2016).

### 3.2.3 PSD analysis

A PSD analysis is an FFT periodgram analysis. It can be calculated in three separate ways (Irvine, 2019). In the most computational effective method, the amplitude of the FFT is multiplied with its complex conjugate and normalized according to its frequency bin width. The (Midé, NK) examples, which this work will be based upon uses the Matlab function Spectrogram to perform these analysis. With this procedure, a trustworthy frequency representation for samples with possibly varying length, and where frequency content varies over time can be given. Since the vibration profile of an automobiles windshield is somewhat unknown, a PSD analysis will most likely prove beneficial (Hanly, 2016).

### 3.2.4 The Pwelch method

With measurements performed in noisy environments, the actual FFT data could be buried in noise. For measurements like this, Pwelch’s method can be utilized. Pwelch is a periodgram just as the PSD analysis, but it uses window functions to get rid of white noise in the measurement data. The filter width, overlap and resolution
will require some trial and error before success, but could potentially reproduce essential frequency components which are not buried in white noise (Schmid, 2012).

### 3.2.5 Spectrogram analysis

A spectrogram analysis illustrates how frequencies and their respective amplitudes change in a measurement environment over time. Can be used as a verification for whether certain vibration frequency components are present in the measurement environment in a longer time scale (Hanly, 2016).

### 3.2.6 Measurement and signal processing scripts

The scripts used to measure acceleration data are developed by the author, and the scripts used for processing and energy harvester modelling are developed with inspiration from Midè (NK). These scripts can be found at the authors private Github-account (Haugen, 2019).

### 3.3 Energy Harvester Modelling

#### 3.3.1 Transducer selection

As described in section 1.4, three transduction methods from mechanical energy to electrical energy are desirable to compare. Selection of transduction mechanism will most likely be dependent of use case. The Hagen (2014) patent states that all the transduction mechanisms mentioned in section 1.4 are possible candidates to enhance the battery lifetime of an On-Board Unit. In order to make the On-Board Unit self sustainable, a solution with no battery cells present was desired by the author. This means that the modeling work will be performed with piezoelectric and/or electromagnetic generators, since electrostatic generators require an external power source to operate.

Exploring online stores has verified there are less piezoelectric and electromagnetic energy harvesters commercially available than initially thought. The electromagnetic energy harvesters available are too big in physical volume to be assembled in a vehicle windscreen. Beeby et al. (2007) claims the coupling strength of micro-scale NeoDymium magnets to be non-linear, and significantly lower than macro-scale NeoDymium magnets. Decreasing the size of an electromagnetic energy harvester would possibly make it useless due to the lack of magnetic field strength, and is most likely the reason why there are a low number of implementations for microscale electromagnetic generators. For these reasons, piezoelectrics is chosen as transduction mechanism.

The best solution for a commercially available piezoelectric element is the Midè S129. Its datasheet tells it has a resonance frequency of 49 Hz with a load of 18 kohms, which is far from the expected vibration frequency of 10-15 Hz. Since the resonance frequency of a piezoelement is dependent of the load attached to
3.3. Energy Harvester Modelling

it, one should also determine its characteristics for no-load and power-conditioner attached.

Frequency tuning as shown in section 2.4 will need to be performed to bring the piezoelectric beam down to the desired frequency. It is desired to utilize the piezo element in 31 mode, since it is the transduction method that best will utilize the vibrations in a vehicle’s windshield, even though 33 mode harvesters have higher piezoelectric constants, mentioned in subsection 2.3.2.

3.3.2 Mechanical model

Both piezoelectric and electromagnetic transducers can be mechanically modelled as mass-spring-damper systems. This simplifies them to be represented in simulation softwares such as Matlab and similar. For this specific case, a SDOF piezoelectric harvester will need to be modeled. Hehn and Manoli (2015b) explains the principle of piezoelectric elements from their material constants, into mechanical modeling and further to electrical modeling. A typical mass-spring-damper model for a piezoelectric energy harvester is depicted in Figure 3.3.

![Figure 3.3: SDOF Piezo model (Hehn and Manoli, 2015b)](image)

- \( z(t) \): Travel distance for piezoelectric element
- \( m \): Mass of the harvester
- \( k \): Spring stiffness. Represents the harvester’s oscillation response
- \( d \): Damping factor. Represents mechanical damping on the system due to friction, air resistance and similar. Hard to calculate for simulation purpose due to its application specific configuration.
- \( F_e \): Additional electric damping from transducer, given when load is connected, such as power conditioner.
- Interface circuit: Load connected to the transducer, such as power condition circuit.
From the listing above, the damping factor cannot be accurately determined for multiple use cases. Most likely the system will be under-damped, meaning a damping factor between 0 and 1. To enhance efficiency and reduce losses the system is best suited with a damping factor that goes towards 0. One will then have to add the factor for electrical damping as well, as shown by Hehn and Manoli (2015b).

Hehn and Manoli (2015a) has conducted experiments to model a piezoelectric element from Midè, the V22B transducer. They suggest three methods to determine piezoelectric parameters, which all involve an electric model of an energy harvester (lumped model):

- Finite Element Analysis
- Extracting piezoelectric parameters based upon datasheet values. Often proven to be problematic, since datasheets often are given for one specific use case, and sometimes wrongly describes the measurement procedure (Hehn and Manoli, 2015a)
- Extracting parameters from a series of response analysis, such as open circuit and short circuit voltage analysis. The frequencies found at half power bandwidth are used to determine quality factor, and further to determine damping parameters.

### 3.3.3 Electrical model

A mechanical model of an energy harvester is of interest to understand its physical parameters. To attain a model which can be utilized in simulations with load, an electrical equivalent is desired.

A typical electrical model of a piezoelectric transducer is depicted in Figure 3.4. The various properties of the piezoelectric beam and their representations are explained in Table 3.1.

![Figure 3.4: Piezo element - electrical model (Hehn and Manoli, 2015b)](image)
3.3. Energy Harvester Modelling

<table>
<thead>
<tr>
<th>Element</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration source</td>
<td>$V_m = ma/GEMC$</td>
</tr>
<tr>
<td>Mass</td>
<td>$L_m = m/GEMC^2$</td>
</tr>
<tr>
<td>Parasitic damping</td>
<td>$R_m = d/GEMC^2$</td>
</tr>
<tr>
<td>Piezo stiffness</td>
<td>$C_m = GEMC^2/k$</td>
</tr>
</tbody>
</table>

Table 3.1: Piezo element - Electrical model - Parameters

GEMC - Generalized Electromechanical Coupling Factor

The coupling between mechanical and electrical domain is represented by a Generalized Electromechanical Coupling Factor, GEMC. GEMC describes the relationship between the energy applied to a transducer and the energy harvested from a transducer. A piezoelectric transducer possesses elastic, dielectric and piezoelectric properties, which all affect a piezoelectric transducers ability to transfer energy. The three properties mentioned above are all handled by the GEMC factor. These properties are also dependent upon the boundary conditions of a piezoelectric element, and one cannot determine a generic GEMC factor for multiple use cases (Lamberti et al., 2002).

The GEMC factor utilized for these measurements is defined in Equation 3.1. The variables are all material specific, and the GEMC factor will vary with the actual piezoelectric element chosen. The piezoelectric element chosen to conduct tests upon is Midé S129, and the manufacturers datasheet is considered to get material constants. Heln and Manoli (2015a) claims this to be a non desired procedure, but it is the best possible solution due to time restrictions and lack of a piezoelectric element to conduct response analysis upon, described by subsection 3.3.2. Grønbech (2017) conducted response analysis to determine system parameters for a piezo element for energy harvesting wireless circuits.

Yun et al. (2011) has calculated the mechanical-electrical conversion efficiency for a PMG27 electromagnetic harvester. Their estimation tells that the mechanical-electrical efficiency is approximately 20 percent for their generator in their specific use case. Since their use case is human-powered motion energy harvesting by electromagnetics, one cannot say that a factor of 20 percent is correct for a piezoelectric windshield harvester implementation, but their study shows the complexity in determining such parameters.

The calculated GEMC factor is shown in Equation 3.2.

The system damping factor is also dependent of mass, resonance frequency and quality factor, shown in Equation 3.3 (Halvorsen et al., 2013).

$$GEMC^2 = k_{31,S129}^2 \times K_{S129} \times C_{S129}$$ \hspace{1cm} (3.1)

- $k_{31,S129}^2$ – (Coupling Coefficient)
- $K_{S129}$ – (Piezo Stiffness)
- $C_{S129}$ – (Piezo Capacitance)
Chapter 3. Method

\[ GEMC = \sqrt{0.37^2 \times 261[N/m] \times 22 \times 10^{-9}[F]} = 886.605 \times 10^{-6} \tag{3.2} \]

\[ d = \frac{\text{mass} \times \omega_0}{Q_m} \tag{3.3} \]

Voltage source

The voltage source is supposed to be a vibration signal input, and one needs to manipulate the attained datasets to fit with the characteristics of the voltage source depicted in Figure 3.4. This can be done by adding a voltage-controlled voltage source in the simulation software LTSpice, or by Matlab calculations. An implementation of a voltage controlled voltage source is depicted in Figure 3.5. For simplicity, the coupling factor will be calculated by Matlab, meaning that the entire dataset can be represented by a single voltage source, as in Figure 3.4. The Coupling element will be calculated and named as a Voltage correction factor. Its calculation is shown in Equation 3.4. With this calculation, the voltage source will represent the entire work that the measured vibration signal and corresponding added mass will do towards a piezoelectric energy harvester at certain frequencies.

![Piezoelectric model - Voltage controlled voltage source](image)

\[ V_m = \text{Accel. Signal}[G] \times \text{Voltage. Correction. Factor}[\frac{kg \times 9.81 m/s^2}{GEMC}] = \frac{m \times a}{GEMC} \tag{3.4} \]

3.3.4 Power estimate / Performance

Maximizing the power output from a piezoelectric element is dependent of the excited force towards the harvester, the harvesters mechanical damping and matching of load impedance. As Equation 3.5 shows, one needs to ensure a low mechanical damping and high excited force at the transducer to keep the available harvestable power from the transducer at top. This is also directly relevant towards the systems Q-factor, shown by Equation 3.3 (Hehn and Manoli, 2015b).

\[ P_{im} = \frac{(ma')^2}{8d} \tag{3.5} \]
3.4 Power conditioning

Hehn and Manoli (2015b) generalizes how maximum power extraction is performed for a piezoelectric element versus its load. In general, the maximum power available from a piezoelectric element is achieved when the load impedance is equally matched to the harvester impedance. The calculated estimates here must be said to be ideal, and one will most likely not reach this power level in a real life implementation due to load matching complexity.

An idealized impedance matched load for a piezoelectric harvester is depicted in Figure 3.6. The model is inspired by Hehn and Manoli (2015b).

To determine the maximum average power from the Midé S129 piezo element, simulations will be performed with ideally matched load for each vehicle. LTSpice, the chosen simulation software will calculate the average power over the load resistor $R_{\text{mc}}$ during the simulation time. This will not represent an entirely realized energy harvester circuit, from piezo element to output of a power conditioner. The purpose of a power conditioner is further described in section 3.4. Because a power conditioner impedance characteristics are complex, and because such characteristics could not be found for the desired power conditioner, one will only estimate the maximum attainable power from the piezo element at an ideally matched impedance, as shown in Figure 3.6.

![Figure 3.6: Piezoelectric model - Ideal load match](image)

3.4 Power conditioning

Since the power generated by piezoelectric elements is AC, a power conditioning circuit is needed to rectify and further conditioning of the power coming from the transducer. Sometimes a booster circuit is needed before the conditioner circuit, to ensure that the voltage coming from the piezoelectric element or any other energy harvesting transducer is in the applicable input area of the conditioner.

A well known conditioner circuit is the BQ 25505 from Texas Instruments (BQ25505 datasheet, 2019). It is a boost regulator topology, which gives an output voltage higher than the input voltage. This chip requires a DC input voltage, hence an external rectifier circuit is needed. Its datasheet also specifies that the maximum input voltage is 5.1 volts. With Piezo actuators that are able to provide up to 20 volts to an input some sort of clamping circuit will be needed.

To utilize both Buck and Boost topologies, a conditioner circuit such as Linear Technology LTC3129 could be used (LTC3129 datasheet, 2013). With externally added Schottky diodes for rectification and voltage clamping, this conditioner could operate with piezo elements, and has a quiescent current of 1.3 uA.
Chapter 3. Method

Another option is the LTC3330 Buck-Boost converter (LTC3330 datasheet, 2013). With an integrated rectifier circuit it is also applicable for use in energy harvester applications. This converter has a buck converter for the energy harvesting input, meaning that a voltage over the desired output voltage is needed to successfully operate. The primary cell input has a Buck-Boost regulator, and is hence more suited for energy harvesting with battery backup systems.

A conditioner circuit well known for use with piezoelectric harvesting elements is the LTC 3588 from Analog Devices (LTC3588 datasheet, 2010). It is depicted in Figure 3.7. Among its most characteristic features is pin selectable output voltage, Buck DC/DC converter and a quiescent current of 950 nA when regulating power with no load. In a typical use case the conditioners output voltage is connected to a capacitor. Storing any energy to a super-capacitor, battery or similar would require an additional charging circuit.

The LTC3588 seem to have the lowest quiescent current for no-load regulation. Since it is also mentioned by the supplier of the desired piezoelectric element, Midé, it is the desired power conditioner for use in the simulations. An LTSpice model is also available, and it can easily be implemented in simulations to act as a power conditioner, and give a relation of the power output available for a realized energy harvesting system.

The realized model of a piezoelectric energy harvester and power conditioner is further described in section 3.5. The LTC3588 is configured according to the LTC3588 datasheet, and configured for a piezoelectric low voltage input (LTC3588 datasheet, 2010). This is depicted in Figure 3.7.

Figure 3.7: LTC3588 Power Conditioner - Low Voltage Input Operation (LTC3588 datasheet, 2010)
3.5 Realizing a model of Piezo element and power conditioner

Described in the first three subsections of section 3.3, there are multiple transduction mechanisms available for energy harvesting, as well as a multiple of strategies to model them. Adding power conditioning to an overall model increases the complexity even more.

To gain an overall system description for both piezo element and power conditioner in one single chain of simulations, an electrical model of a piezo element is desired. Since an electrical model of the LTC3588 power conditioner exists in the simulation software LTSpice, LTSpice is chosen as the main simulation software. The piezo element will be represented by an electrical model, described in subsection 3.3.3. The actual model used for simulation purpose for all vehicles is depicted in Figure B.1.

Matlab is chosen to pre-process the acceleration signal from the vehicles mentioned earlier. Since no initial calibration of the measurement system has been performed, a mean value calculation and subtraction is performed to remove any static gravitational acceleration components. The resonance frequency of the given vehicle is calculated, and the data set amplitude is manipulated, as explained in subsection 3.3.3.

After manipulating the data set, the piezo element is configured for the specific resonance frequency, as shown in section 2.4. This is done by changing the tip mass, which also affects the system damping. This affects the selection of inductor and resistor value for the electrical model. The data set is imported and processed by the model, where one will be able to see the output voltage and power from piezo element and power conditioner based on the vibrations the vehicle is exposed to.

3.5.1 Power Conditioner - Load calculation

The power conditioner is in need of a load to represent the characteristics of the On-Board Unit. The typical load characteristics of the On-Board Unit is depicted in Table 3.2 (Hagen, 2014).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Condition</th>
<th>Power consumption</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>On</td>
<td>10(\mu)W</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transmit</td>
<td>10mW</td>
<td>20 mSec (approx)</td>
</tr>
</tbody>
</table>

Table 3.2: Power Conditioner - Load calculation

For simplicity in simulations, a static resistive load of 100k\(\Omega\) is chosen. With an output voltage from power conditioner of 1.8 volts this load will represent a max
power draw from the conditioner of

\[ P = \frac{U_{LTC3588}^2}{R_{Load}} = \frac{1.8V^2}{100k\Omega} = 32.4\mu W \]

This will be an approximation of the average power draw from the On-Board Unit. The approximation does not fully represent the power consumption of an On-Board Unit, but it is the most feasible approach by now. More thorough load simulations will need a customized test setup, which will be more time consuming and increase the overall complexity.
3.6 Measurement system verification

The measurement system is supposed to capture sensor data with somewhat unknown content, and a verification of the measurement systems frequency response is desired.

An industrial vibrator was desired to conduct vibration verification measurements to the measurement system. However, when no industrial vibrator was present, the final solution was to assemble the measurement system on a 12 inch subwoofer. The verification setup is depicted in Figure 3.8.

![Accelerometer measurement verification jig](image)

Figure 3.8: Accelerometer measurement verification jig

- Panasonic T25pl03a6 12 inch subwoofer
- XLS 400w amplifier
- TTi TG2511 signal generator
- Agilent DSO-X2002A oscilloscope

Frequency characteristics for subwoofers in most online stores tells that they operate from approximately 20 Hz upwards to 2.3 kHz, such as the Pioneer TSA300D4. Hence it will not be possible to verify acceleration values down to 10 Hz.

One were not able to find a datasheet for the subwoofer mentioned in the list above, hence its lower operating area could not be determined. The measurement system was verified with several measurement series, where the frequency of the signal generator was held constant and moved successively up and down between the different series. The results from measurement system verification can be found in subsection 4.1.1.
Chapter 3. Method
Chapter 4

Results

4.1 Measurement system

4.1.1 Measurement system verification

This section describes the results from the measurement system verification, further described in section 3.6.

Time accuracy

A sample-rate drift in the measurement system occurred during the development period. The measurement system is based upon Raspbian and Python, and a few effects further discussed in subsection 5.1.1 occurred. The configured sample rate is 615 Hz, which means a time period of

\[ t_{\text{sample}} = \frac{1}{\text{samplefreq}} = \frac{1}{615\text{Hz}} = 1.6 \text{ ms} \]

The sample rates influence on the measurement system is depicted in Figure 4.1, which shows the time difference between each sample. From Figure 4.1c one sees distinct time periods between 1.55 to 1.7 ms, which correlates well with a sample time period of 1.6 ms. As data is written to the CSV file one sees a time period of approximately 20 ms, depicted in Figure 4.1b. This means that writing measurement data to the CSV file takes approximately 20 ms. This procedure occurs once every second, since data is written to the CSV file when 615 samples are collected. The entire sample scale and corresponding time difference is depicted in Figure 4.1a. The data set used for this display is from the Mercedes W212, driver 1. Since the same measurement system have been used for all vehicles, one should expect similar results for all vehicles.
Chapter 4. Results

(a) Measurement system - Time between samples - Complete dataset

(b) Measurement system - Time between samples - Write to file vs sampling

(c) Measurement system - Time between samples - Data sampling

Figure 4.1: Measurement system verification - Time drift
4.1. Measurement system

Frequency accuracy

The systems frequency accuracy has been verified as described in section 3.6. Measurement series with frequencies from 20 Hz up until 4 kHz have been conducted, but a limited amount of the measurement series are shown here. The frequencies from the signal generator applied to the measurement system and shown in the verification process are 20 Hz, 70 Hz, 450 Hz and 1 kHz.

For the 20 Hz signal, one sees from Figure 4.2b that the FFT contains frequency components in the 20 Hz area. Sidelobes have occurred for the FFT. Sidelobes typically occur either because of a non-integral number of cycles in the test setup, or non-linearities derived from operation in signal generator and/or amplifier. Since the top priority of this test is to verify the location of the main lobe, one will not go into detail regarding side lobes.

Increasing the signal frequency to 70 Hz causes the signal to drift slightly towards 68 Hz, as shown in Figure 4.3. This drift is most likely due to the non consistent sample rate, further discussed in subsection 5.1.1. Since the desired signal frequency should be in the area of 10-15 Hz, any smaller drift for higher frequency components shall not affect measurements conducted by the measurement system.

As the measurement systems sample rate is 615 Hz, one should expect it to faithfully represent vibration signals up towards 300 Hz, similar to what the Shannon Nyquist theorem say (Olshausen, 2010). The accelerometers datasheet claims there is a DLPF implemented, and that it is configured with a cut-off frequency of 260 Hz initially. This means that all vibration signals over 260 Hz should be cut off by the accelerometers DLPF. One had expected the 450 Hz signal to give a flat frequency response, since it is outside the measurement range and handled by the filter.

The measurement system is not operating entirely correctly, since aliasing has occurred, depicted in Figure 4.4a. If one compares the 450 Hz and 1 kHz signal depicted in Figure 4.4b, one sees that aliasing apparently does not occur for the 1 kHz signal. This reference measurement was also conducted with higher frequencies at non $2\pi$ intervals, none of them which showed any signs of aliasing.

According to the data-sheet of the accelerometer, the frequency response for the DLPF is given for a sample rate of 1 kHz. Since the realized measurement system is configured to a sample rate of 615 Hz, the filter preferences will not be correct. With given configuration, it appears that one has an area that does not have a sufficiently high sampling frequency, but is also not covered by the implemented low-pass filter. This is an unfortunate feature of the measurement system. On the basis of the actual measurements conducted in vehicle, this effect seems to have affected minor sections of the measurements.
Chapter 4. Results

(a) Measurement system verification - FFT of 20 Hz signal

(b) Measurement system verification - FFT of 20 Hz signal - zoomed

Figure 4.2: Measurement system verification - 20 Hz input signal
Figure 4.3: Measurement system verification - 70 Hz input signal
Chapter 4. Results

(a) Measurement system verification - FFT of 450 Hz signal

(b) Measurement system verification - FFT of 1 kHz signal

Figure 4.4: Measurement system verification - 450 Hz and 1 kHz input signal
4.2 Accelerometer measurements

The following section describes the results obtained from accelerometer measurements in three different vehicles. The accelerometer used in test setup measures in three directions, and tests has been conducted for several journeys for all of the test vehicles. Given this parameter, the amount of data is too comprehensive to display in the main section of the report. The data presented here represents the measurements conducted on the Volvo V70. Measurement data for the other vehicles are present in section A.1.

The data presented here and in the appendices represents only a fraction of the actually measured data, but the data sets are selected to represent an average for each vehicle.

The Pwelch method, mentioned in subsection 3.2.4 was tried simultaneously with PSD analysis to enhance any noise properties that could be present in the data sets. Initial testing of the Pwelch method showed that the desired vibration signal was filtered away, since the desired vibrations appear to be narrow-banded in frequency spectrum and have low amplitude. Several different filter and window sizes were tried, all of which yielded almost equal results. Since the measurement results appear to be somewhat equal over several datasets, one assumes that there is no larger noise component in the measuring system. It should therefore be sufficient to use only FFT, PSD and Spectrogram analysis.

The vehicles used for vibration measurements are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Vehicle brand</th>
<th>Year</th>
<th>Transmission</th>
<th>FWD/RWD</th>
<th>Effect [hp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volvo V70</td>
<td>2006</td>
<td>Manual</td>
<td>FWD</td>
<td>163</td>
</tr>
<tr>
<td>Mercedes W213</td>
<td>2018</td>
<td>Automatic</td>
<td>RWD</td>
<td>190</td>
</tr>
<tr>
<td>Mercedes W212</td>
<td>2016</td>
<td>Automatic</td>
<td>RWD</td>
<td>170</td>
</tr>
</tbody>
</table>

Table 4.1: Measurement Vehicles

In general, all the vehicles have certain dominant frequencies in each axis, with some variations due to vehicle brand, further discussed in subsection 4.2.2.

For all of the vehicles, the Y axis FFT analysis seems to best represent the frequency components mentioned by Irvine (2019), also mentioned in section 2.5. Components in the 1.5 Hz and 10 to 15 Hz area are present, as well as some higher order frequency components.

If one considers the PSD analysis, all the distinct frequencies mentioned in the FFT analysis are also present here. These distinct frequencies remains the highest logarithmic power level compared with any higher order distinct frequencies.

If the FFT and PSD analysis are compared with the spectrogram analysis, one sees that the frequency components designated to have higher power in both FFT and PSD appear to be continuously present throughout the measurement period. The higher order frequency components are most likely harmonic oscillations given by the base frequency.

The frequency width is limited by the FFT and spectrogram analysis, and it is not possible to distinguish frequencies in the lower range. On the basis of the
analysis done in section 2.5 one cannot determine which speed a vehicle held in a
given moment in the spectrogram analysis.

The highest frequency component in the lower order of the y-axis FFT analysis
is the most dominant from the given data set, and thus most likely represents the
average speed of the trip.

If one compares the FFT and PSD analysis for X, Y and Z axis for all vehi-
cles, one sees a consistent pattern of high power vibrations in the lower frequency
spectrum for both X and Y axis. The Z axis measurements for all vehicles appear
to have some higher order frequency components. Since the measurement system
has shown non linear behaviour for higher order frequency components, including
aliasing, one chooses to disregard any measurements from the Z axis for further
work with the energy harvester implementation. No literature has been found to
explain how vibrations with these frequencies occur either.
4.2. Accelerometer measurements

4.2.1 Volvo V70

FFT analysis

(a) FFT Volvo V70 drive - X axis

(b) FFT Volvo V70 drive - Y axis

Figure 4.5: FFT results - Volvo V70 - X,Y,Z axis
(e) FFT Volvo V70 drive - Z axis

**Figure 4.5:** FFT results - Volvo V70 - X,Y,Z axis
4.2. Accelerometer measurements

PSD analysis

(a) PSD Volvo V70 drive - X axis

(b) PSD - Volvo V70 - Y axis

Figure 4.6: PSD results - Volvo V70 - X,Y,Z axis
(c) PSD - Volvo V70 - Z axis

Figure 4.6: PSD results - Volvo V70 - X,Y,Z axis
4.2. Accelerometer measurements

Spectrogram analysis

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrogram_v70_x_axis.png}
\caption{Spectrogram Volvo V70 - X axis}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{spectrogram_v70_y_axis.png}
\caption{Spectrogram - Volvo V70 - Y axis}
\end{figure}

\textbf{Figure 4.7}: Spectrogram results - Volvo V70 - X,Y,Z axis
Chapter 4. Results

Figure 4.7: Spectrogram results - Volvo V70 - X,Y,Z axis

(e) Spectrogram - Volvo V70 - Z axis
4.2.2 Comparison - Dominant frequencies

This section compares the dominant frequencies found for each vehicle, and discusses the relation between them.

Dominant frequencies found for all the vehicles are depicted in Table 4.2.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Dominant frequency 1 [Hz]</th>
<th>Amplitude 1 [g]</th>
<th>Dominant frequency 2 [Hz]</th>
<th>Amplitude 2 [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>10-15</td>
<td>1.0 * 10^{-4}</td>
<td>85-90</td>
<td>0.8 * 10^{-4}</td>
</tr>
<tr>
<td>Y</td>
<td>10-12</td>
<td>2.0 * 10^{-4}</td>
<td>60-65</td>
<td>0.5 * 10^{-4}</td>
</tr>
<tr>
<td>Vehicle: Volvo V70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>10-15</td>
<td>1.4 * 10^{-4}</td>
<td>75-80</td>
<td>3.4 * 10^{-5}</td>
</tr>
<tr>
<td>Y</td>
<td>10-15</td>
<td>1.0 * 10^{-4}</td>
<td>75-80</td>
<td>2.0 * 10^{-5}</td>
</tr>
<tr>
<td>Vehicle: Mercedes W213</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>10-15</td>
<td>1.0 * 10^{-4}</td>
<td>85-90</td>
<td>5.0 * 10^{-4}</td>
</tr>
<tr>
<td>Y</td>
<td>10-15</td>
<td>1.0 * 10^{-4}</td>
<td>5-10</td>
<td>1.5 * 10^{-4}</td>
</tr>
<tr>
<td>Vehicle: Mercedes W212 - Driver 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>10-15</td>
<td>2.25 * 10^{-4}</td>
<td>85-90</td>
<td>5.0 * 10^{-4}</td>
</tr>
<tr>
<td>Y</td>
<td>10-15</td>
<td>1.0 * 10^{-4}</td>
<td>5-10</td>
<td>1.4 * 10^{-4}</td>
</tr>
<tr>
<td>Vehicle: Mercedes W212 - Driver 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Acceleration - Dominant frequency comparison

Dominant frequency Y axis

From multiple measurement series conducted on all vehicles there seem to be vibrations in the lower frequency spectrum present for both X and Y axis for all vehicles. The frequency spectrum for Y axis for all test vehicles seems to be recurring, and it is chosen to compare the distinct frequencies from Y axis and how they relate.

A zoomed view from the FFT analysis for all the vehicles is depicted in Figure 4.8. It shows how the 1.5 Hz frequency component is present in all vehicles, and how the frequency in the 5-15 area changes according to car type.

Figure 4.8a depicts a frequency component with top value in the 11-13 Hz area, while Figure 4.8b has a flatter frequency characteristic, with tops at 7 and 14 Hz.

The FFT result of the Mercedes W213 is also slightly unequal to the results of the Mercedes W212, which is depicted in Figure 4.8c and Figure 4.8d. The characteristic frequency of the Mercedes W212 is 8-9 Hz, and seems to be similar for both drivers.
(a) FFT - Y axis - zoom - Volvo V70

(b) FFT - Y axis - zoom - Mercedes W213

(c) FFT - Y axis - zoom - Mercedes W212 - Driver 1

(d) FFT - Y axis - zoom - Mercedes W212 - Driver 2

**Figure 4.8:** FFT - Y axis - Zoomed - Measurement Vehicles
4.3 Energy Harvester modeling

The following section describes results from the energy harvester modeling. The datasets used for energy harvester modeling are all the same that was used for vibration analysis in section 4.2. The amount of data was surpassing what available simulation software could handle, and it was decided to simulate smaller time-scopes of the actual data sets, ranging from 200 to 400 seconds. Longer time-scopes of the actual simulations from all vehicles are given in section B.1.

The piezoelectric element used in the energy harvester is depicted in Figure B.1. It is configured to be at resonance with the parameters depicted in Table 4.3 for each vehicle. The calculations performed to achieve these component values are described in Table 3.1.

<table>
<thead>
<tr>
<th>Resonance Freq [Hz]</th>
<th>Added mass [g]</th>
<th>( L_{mc} [\text{H}] )</th>
<th>( R_m [\Omega] )</th>
<th>Voltage correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle: Volvo V70</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.5</td>
<td>42</td>
<td>( 5.346 \times 10^4 )</td>
<td>( 7.022 \times 10^4 )</td>
<td>( 4.650 \times 10^4 )</td>
</tr>
<tr>
<td>Vehicle: Mercedes W213</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07.02</td>
<td>134</td>
<td>( 1.706 \times 10^5 )</td>
<td>( 1.254 \times 10^5 )</td>
<td>( 1.484 \times 10^5 )</td>
</tr>
<tr>
<td>14.02</td>
<td>33.6</td>
<td>( 4.275 \times 10^4 )</td>
<td>( 6.279 \times 10^4 )</td>
<td>( 3.718 \times 10^4 )</td>
</tr>
<tr>
<td>Vehicle: Mercedes W212 - Driver 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.59</td>
<td>89.5</td>
<td>( 1.139 \times 10^5 )</td>
<td>( 1.025 \times 10^5 )</td>
<td>( 9.913 \times 10^2 )</td>
</tr>
<tr>
<td>Vehicle: Mercedes W212 - Driver 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.59</td>
<td>89.5</td>
<td>( 1.139 \times 10^5 )</td>
<td>( 1.025 \times 10^5 )</td>
<td>( 9.913 \times 10^2 )</td>
</tr>
</tbody>
</table>

Table 4.3: Resonance Frequency tuning - All Vehicles

The following description applies for Figure 4.9 and Figure 4.10, as well as the similar pictures in section B.1. In general, the behaviour of \( I(R_{load}) \) for figure A tells how the power conditioner switches the output voltage on and off, as its input voltage goes below its threshold. The switching activity will be dependent upon how well the resonance frequency between the harvester and vehicle is matched. The initial frequency tuning of 14.02 Hz for the Mercedes W213 seem to have failed, which is depicted in Figure 4.11b. There are no time periods over a few seconds where the power conditioner appears to be active.

Figure B depicts the relationship between the mechanical acceleration signal and the piezo voltage that will be present at the input of a power conditioner or similar. The voltage difference between the acceleration signal and piezo voltage relates to piezoelectric losses, due to damping and frequency tuning.

Figure C depicts the piezo voltage mentioned in Figure B, and its relationship to the output voltage from the power conditioner. In general one sees that when the piezo voltage drops below a certain threshold, or when the frequency appears to change due to change in speed or similar, the output voltage from the power conditioner will also drop.

Figure D depicts the output current and power from the power conditioner.
Chapter 4. Results

The output current and power follows the output voltage of power conditioner, depicted in Figure C.

Note: The datasets do not contain any information about the vehicles speed at any given time, and one cannot say with full certainty that the drift in frequency and amplitude at the piezo side is related to change in speed. One will need to correlate the vibration data with a speed logger simultaneously, and find a relation for how the vibration frequency changes with speed, as Irvine (2019) claims it will do.
4.3. Energy Harvester modeling

4.3.1 Volvo V70

(a) Energy harvester modeling - Volvo V70 - 12.54 Hz resonance - 900 seconds

(b) Energy harvester modeling - Volvo V70 - 12.54 Hz resonance - Acceleration signal vs piezo signal - 100 seconds

Figure 4.9: Energy harvester modeling - Volvo V70 - 12.54 Hz resonance
(c) Energy harvester modeling - Volvo V70 - 12.54 Hz resonance - Piezo voltage vs LTC output voltage - 100 seconds

(d) Energy harvester modeling - Volvo V70 - 12.54 Hz resonance - LTC3588 output current and power - 100 seconds

**Figure 4.9:** Energy harvester modeling - Volvo V70 - 12.54 Hz resonance
4.3. Energy Harvester modeling

4.3.2 Mercedes W213

(a) Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance

(b) Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance - Acceleration signal vs piezo signal

Figure 4.10: Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance
(c) Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance - Piezo voltage vs LTC output voltage

(d) Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance - LTC3588 output current and power

**Figure 4.10:** Energy harvester modeling - Mercedes W213 - 07.02 Hz resonance
4.3. Energy Harvester modeling

Frequency tuning complexity

Given in Table 4.3, and depicted in Figure 4.8b, the frequency spectrum of the Mercedes W213 appears to be flat in the area of 7-15 Hz. Initially it was selected to tune the energy harvester for an upper resonance frequency of 14.05 Hz, as the higher frequency band tuning represents less system damping. Simulations of the optimized energy harvester proved that resonance tunings of both 14.05 Hz and 14.45 Hz were not successful. This is depicted in Figure 4.11. One sees how the output power of the power conditioner has a higher number of transitions and apparently no longer period of being constantly active for Figure 4.11b and Figure 4.11c compared with the output power depicted in Figure 4.11a.

At last a frequency tuning of 07.02 Hz was proven successful. This serves a bit problematic, since the two frequency peaks have the same amplitude and as the lowest frequency has the highest damping. Most likely this is due to that the 07.02 Hz frequency has the highest occurrence in the dataset, but this cannot be exactly verified, since the frequency bins are too wide to detect distinct frequencies in the spectrogram analysis.

![Energy harvester modeling - Mercedes W213 - Resonance 07.02 Hz - Full scope](image)

(a) Energy harvester modeling - Mercedes W213 - Resonance 07.02 Hz - Full scope

![Energy harvester modeling - Mercedes W213 - Resonance 14.02 Hz - Full scope](image)

(b) Energy harvester modeling - Mercedes W213 - Resonance 14.02 Hz - Full scope

![Energy harvester modeling - Mercedes W213 - Resonance 14.45 Hz - Full scope](image)

(c) Energy harvester modeling - Mercedes W213 - Resonance 14.45 Hz - Full scope

**Figure 4.11:** Energy harvester modeling - Mercedes W213 - Frequency tuning
4.4 Power estimates

To estimate maximum power available from the piezo element for the different vehicles, the power conditioner will be replaced with a load ideally tuned for the resonance frequency of each vehicle. This is described in subsection 3.3.4.

A simulation of mean power calculation with ideal load for the Volvo V70 is depicted in Figure 4.12. The piezo element and load is tuned for a resonance frequency of 12.54 Hz.

![Piezo element power estimation - Ideally matched load - Volvo V70](image)

**Figure 4.12:** Piezo element power estimation - Ideally matched load - Volvo V70

An artifact that occurred during the idealized power simulations is that the mean power seems to be higher over the load resistance compared with the piezo internal resistance. The maximum power transfer theorem states that the power over the load cannot be higher than the internal power, and the results from this section cannot be said to be fully correct. This artifact could be occurring because a different number of digits have been used to determine component values for the piezo element and load. This means that the impedance match is not truly ideal, but the component values and power levels given in Table 4.4 are so close to being ideal that one can use them as an approximation.

From Table 4.4 one sees how the average power over the load ranges from 3.8775\( \mu \text{W} \) for the apparently falsely tuned Mercedes W213, until 20.118\( \mu \text{W} \) for the Mercedes W212. One also sees the difference in average power for the Mercedes W213 at the two different resonance frequencies. Since the only physically changed parameter with the system is adding mass, as described in section 2.4, it is apparent that the vibration amplitude in cooperation with the mass increases the average maximum power level from the piezo element, even if the system damping increases.
4.5. Cost

Since a final system implementation is price dependent, section 1.4 says that a price comparison for a piezoelectric and pure battery powered solution is desired. Note: General R&D companies will most likely hold purchase deals with other suppliers for large component quantities, and a real life implementation will most likely result in another price. The calculation below is only to be considered as a guide, especially since cost for additional PCB design is not considered. All prices given in Table 4.5, except battery, is for buying a quantity of 100 items per component.

<table>
<thead>
<tr>
<th>Component</th>
<th>Price [USD]</th>
<th>Store</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Piezoelectric energy harvester</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midè S129-H5FR-1803YB</td>
<td>24.60</td>
<td>piezo.com</td>
<td>Piezoelement</td>
</tr>
<tr>
<td>LTC3588</td>
<td>4.8</td>
<td>mouser.com</td>
<td>Power conditioner</td>
</tr>
<tr>
<td>Panasonic 10SVPS10M</td>
<td>1</td>
<td>mouser.com</td>
<td>Output capacitor</td>
</tr>
<tr>
<td>Panasonic CBC3225T100MRV</td>
<td>0.2</td>
<td>mouser.com</td>
<td>Capacitor</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>31.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Battery driven solution</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tadiran TL-5101/SBP</td>
<td>6.4</td>
<td>mouser.com</td>
<td>Battery</td>
</tr>
</tbody>
</table>

Table 4.5: Price comparison - Piezoelectric harvester vs battery
Chapter 4. Results
5.1 Discussion

5.1.1 Measurement system

It was experienced during the development period that the sample rate of the measurement system drifted at occasional times. This is because of the software configuration of the measurement system. Raspbian is not an RTOS, and the python script running the measurement code will not have exclusively access to the system clock, which means that all operations performed by Raspbian is put in some sort of queue.

The consequence of this was in the first instance that the desired sample rate of 1 kHz was not achieved, and one rather went down to 615 Hz as it seemed that the measuring system was operating sufficiently.

Secondly, the setup for writing measurement data to file caused the python script to spend longer time between two samples at the time data was written to the file. This is an unfortunate effect, and there has been little information to find about the consequences for the sample-data due to this. After consulting with Håkon Grønning, associate professor at NTNU, it seems that the small drift from approximately 1.6 ms can represent a smaller stationary deviation. The larger deviation that occurs when writing to file will hopefully be insignificant if one does not have frequency components in the upper frequency area.

To verify if the frequency spectrum is legal, the matlab function resample has been used for some data sets. It resamples data sets sampled at a non-consistent rate, and interpolates the missing data points. The result shows that the frequency spectrum is similar for the original and the resampled data set, and it can thus be concluded that the sample rate drift did not play any major role in this case. Effort were made to enhance the performance of the measurement system, such as implementing multiprocessing in Python. This could have solved the drift issue, but due to the authors lack of experience with Python these attempts failed. In
Chapter 5. Discussions & Conclusions

retrospect, one should have used an RTOS platform initially, to avoid these potential timing critical issues. The work was started but not completed due to time restrictions.

Not performing any initial calibration is also an unpleasant feature, since one does not have any relation to the static acceleration component and must trust the mean value computation to be real. In retrospect, an initial calibration before each measurement trip should have been implemented. Due to lack of time and experience in these kind of measurement systems, the calibration procedure was not implemented.

5.1.2 Signal Processing

One were uncertain whether the approaches presented in section 3.2 were sufficient to extract frequency components from the measured data, and the relation between them, especially when the characteristics of both the vibration signal and any surrounding noise were unknown. As measurements took by, it became evident that the signal processing algorithms chosen were sufficient to gain a realistic representation of the measured signal. Together with the system verification procedure shown in subsection 4.1.1 one is certain that the results depicted from the measurement system are reliable, except for the data sets with potential aliasing.

5.1.3 Transducer selection

A piezoelectric transducer consisting of the PZT material was the best commercially available material to base the particular energy harvesting solution upon. As the PZT material contains lead, it cannot be said to fully comply with the environmental needs for futuristic WSNs, mentioned in section 1.1. Even though its high lead content, the PZT material is still ROHS approved, since it is the best option available on todays market(Reach, 2015). Awaiting new future materials will hopefully increase the frequency bandwidth, power extraction capabilities and environmental demands for low toxins.

5.1.4 Modeling

Determining system parameters

The system parameters were determined by considering the specific piezoelements datasheet, shown in section 3.5. This was claimed to be an unreliable method to determine system parameters, shown in subsection 3.3.2. Since the system parameters are likely to change dependent upon use case, the system parameters should ideally have been extracted by the help of response analysis, similar to Grønbech (2017).
5.1.5 Simulations

Load simulations

The loads simulated and presented in this report are quite narrow, and does likely not represent the load of a realized On-Board Unit, or any third party sensor system. Simplified load simulations were chosen when modeling the piezoelectric element itself was proven to be a complex task, but also due to time restrictions. The results from section 4.4 claims that an optimally tuned piezo element only will be able to deliver power up towards $20\mu W$ to an ideally matched load. It is apparent that simulations with a $100\,k\Omega$ resistor load is too much for the energy harvester system to handle, since the resistor will draw $32.4\mu W$ of power. If such a system was to be realized as a proof of concept, further load simulations with more complex and time varying loads should have been performed.

Frequency tuning

Frequency tuning strategies were tested throughout the simulation period, to tune the piezoelectric element to a desired frequency and increase efficiency. One were only able to tune the frequency of the harvester towards one specific test vehicles characteristic frequency for each simulation. This approach can not be implemented in a realized system for multiple vehicle brands, because of narrow frequency width. Section 2.4 tells how the frequency of a piezoelectric element can be tuned by changing the material properties. If one were supposed to have a more wideband vibration energy harvesting system, adaptive frequency tuning by either lowering the $q$-factor or by adding secondary spring systems could be a feasible approach, shown by Kazmierski and Beeby (2014). In a realized system, the secondary spring system could be an electromagnetic or electrostatic energy harvester. However, the latter approach will be in need of an active system for frequency tuning, which adds additional current consumption to the total system.

Another feasible tuning procedure is to add multiple piezoelectric transducers with separately tuned frequencies in parallel, enhancing the system bandwidth. However, this gives extra system overhead, as multiple transducers and power conditioners gets implemented, and the total system cost will increase even more.

Energy harvester realization

The results above depicts the frequency dependence of a piezoelectric energy harvester, and how adding mass changes its resonance frequency. According to the calculations performed in section 4.3, a mass of 42 grams would need to be added to the piezoelectric beam to reach a resonance frequency of 12.5 Hz, and even more mass would be needed to reach lower resonance frequencies, since the relation is non-linear.

One might imagine that a mass of between 40 and 100 grams attached to a piezoelectric beam may be too much for the material to handle, since after all it is 5.5 cm long. The materials ability to handle such masses is defined by its Youngs Modulus, mentioned in the specific material data sheet (Piezoelectric Material
Properties, 2019). Due to time restrictions, one has not calculated the material’s ability to handle masses of such kind, which should be done prior to a system realization.

5.1.6 Social

The overall results depicts how an energy harvester could have solved the need to power equipment assembled in vibrating components of vehicles. Environmental friendly components and production facilities are requirements present for new technology today. These requirements are occurring because some of the components are known to contain heavy metals. The modelled piezoelectric energy harvester used in this work is based on the PZT material, which contains lead. During the lifetime of an On-Board Unit one can ideally say that toxin batteries are replaced by one instance of lead for a piezoelectric energy harvester. However, to increase the overall environmental gain and stop using materials containing toxic chemicals, further research is needed. This is evident, since even the PZT material holds the ROHS environmental approval until better materials are present.

5.1.7 Ethics

Gathering data to base research upon is a strictly necessary measure in academic work. The data gathered for this work is mostly the authors personal commute trips, and as the data is processed by the author himself it does not represent any concerns regarding information security. The data gathered and processed for driver two is done under the consent of driver two. In a general manner, a real life implementation of the energy harvester solution presented above would require an initial calibration towards each vehicle. Data management from multiple vehicles could also raise several ethical issues. As a third party could analyze these data, the vehicles position during certain timeslots of the day can be estimated if one knows the initial position and the duration of the journey.


5.2 Further work

A realized prototype of an Energy Harvesting On-Board Unit will need further work to be able to supply enough energy to an On-Board Unit, from several types of vehicles with different vibration characteristics. The vibrations measured in the front windshield are said to occur from tire imbalance, mentioned in section 2.5. One does not know how vehicle engine characteristics affects these vibrations. Electric vehicles have been of special interest in Norway from 2010 and onwards, and a study of how the vibrations are affected by the engine characteristics would be of special interest. Two similar vehicles with similar characteristics but dissimilar engines, such as the Volkswagen diesel Golf and the electric Golf could be utilized for such a study.

Due to the piezoelectric materials frequency dependency it does not seem like it is able to operate towards a multiple of vehicles without unique tuning for each vehicle type. The three transducer types mentioned in chapter 2 were of special interest when the Hagen (2014) patent was written. A realized prototype with self-tuning properties, such as a piezoelectric and electrostatic combined harvester could be of interest. Recent research have also revealed other material types which can be of interest for energy harvesting, such as MFC and triboelectric energy harvesting. The MFC material is a spin-off from the PZT material, but does not have the same frequency dependency as the PZT material (Corp, NK). Triboelectric energy harvesting is based upon friction energy harvesting, and recently got its analytical model verified (Schweber, 2017). It is also said to be less frequency dependent than the PZT material. These two materials would be of special interest for a vibration based energy harvester with other transducer types than those mentioned in chapter 2.

The complexity of load matching for piezoelectric elements, and how it affects the output power is mentioned in subsection 3.3.4 and section 4.4. A microcontroller, or similar load connected to the piezo element and its power conditioner will represent load conditions other than those presented in this paper. Further work should take into account how pulse/pause-based load affects the load of the power conditioner and the piezo element, and how it affects the total power delivered by the piezo element. Determining power conditioner behaviour was initiated with inspiration from Blystad et al. (2010), but not completed due to time restrictions.
5.3 Conclusions

This study has presented a vibration measurement system, performed post processing of the acquired signals and modeled and simulated a piezoelectric energy harvesting system with the acquired signals as input force.

The measurement system and data is acquired from a series of journeys in three different vehicles. The vibration pattern behaves differently between the three vehicles, even vehicles of the same manufacturer but of different year models behave differently.

The frequency dependency of the PZT material is confirmed by simulations, where the acquired acceleration signal is given as input to the modeled piezo element. Mathematical calculations and modeling of piezo element confirms its complex behavior, which parameters that determine whether a given system enters resonance, and the efficiency of the given system.

Based on the vibration analysis and energy harvester modeling conducted by this study, a common model for a PZT based piezoelectric energy harvester that can operate towards a multiple of vehicles is not a viable option by now. This is mainly due to the PZT elements frequency dependency, and the cost of implementing multiple tuned transducers for one single On-Board Unit.

A real life implementation of this particular piezoelectric system would need an initial calibration towards each vehicle type. The system would still only be able to harvest energy enough to partially power the On-Board Unit. This system is ideal, and the systems Q factor will likely change in a real-life implementation. Other real-life outside parameters such as air friction could also affect the system parameters. The efficiency of a real-life implemented system would be even lower than described in this paper, and will need further research to be exactly determined.

Future energy harvesting systems for an On-Board Unit should be based on materials that are less frequency dependent, and hopefully contains less toxic materials.

A combination of transduction mechanisms is a viable option for a realized energy harvester, for example piezoelectrics and electrostatics. The overall system complexity and cost of a combined system is still higher than a solely battery powered On-Board Unit, and not covered in this paper. In general, a higher cost can be defended if the lifetime of the On-Board Unit increases and the use of toxic materials decreases.
Vibration Analysis

A.1 Vibration Analysis

A.1.1 Mercedes W213

The dataset used for vibration analysis in the Mercedes W213 is a 30 minute taxi trip, on a night shift with high activity.

FFT analysis

(a) FFT - Mercedes W213 - X axis

**Figure A.1:** FFT results - Mercedes W213 - X,Y,Z axis
Appendix A. Vibration Analysis

(b) FFT - Mercedes W213 - Y axis

(c) FFT - Mercedes W213 - Z axis

Figure A.1: FFT results - Mercedes W213 - X,Y,Z axis
A.1. Vibration Analysis

PSD analysis

![PSD analysis](image)

(a) PSD - Mercedes W213 - X axis

(b) PSD - Mercedes W213 - Y axis

**Figure A.2:** PSD results - Mercedes W213 - X,Y,Z axis
Appendix A. Vibration Analysis

(c) PSD - Mercedes W213 - Z axis

**Figure A.2:** PSD results - Mercedes W213 - X,Y,Z axis
A.1. Vibration Analysis

Spectrogram analysis

Figure A.3: Spectrogram results - Mercedes W213 - X,Y,Z axis
Appendix A. Vibration Analysis

Figure A.3: Spectrogram results - Mercedes W213 - X,Y,Z axis

(c) Spectrogram - Mercedes W213 - Z axis
A.1.2 Mercedes W212 - Driver 1

The dataset for vibration analysis in the Mercedes W212 for driver 1 is a 30 minute taxi trip, on a night shift with high activity.

**FFT analysis**

![FFT results - Mercedes W212 - Driver 1 - X,Y,Z axis](image)

(a) FFT - Mercedes W212 - Driver 1 - X axis

(b) FFT - Mercedes W212 - Driver 1 - Y axis

**Figure A.4:** FFT results - Mercedes W212 - Driver 1 - X,Y,Z axis
Appendix A. Vibration Analysis

Figure A.4: FFT results - Mercedes W212 - Driver 1 - X,Y,Z axis

(e) FFT - Mercedes W212 - Driver 1 - Z axis
A.1. Vibration Analysis

PSD analysis

(a) PSD - Mercedes W212 - Driver 1 - X axis

(b) PSD - Mercedes W212 - Driver 1 - Y axis

Figure A.5: PSD results - Mercedes W212 - Driver 1 - X,Y,Z axis
Appendix A. Vibration Analysis

Figure A.5: PSD results - Mercedes W212 - Driver 1 - X,Y,Z axis

(e) PSD - Mercedes W212 - Driver 1 - Z axis
A.1. Vibration Analysis

Spectrogram analysis

(a) Spectrogram - Mercedes W212 - Driver 1 - X axis

(b) Spectrogram - Mercedes W212 - Driver 1 - Y axis

Figure A.6: Spectrogram results - Mercedes W212 - Driver 1 - X,Y,Z axis
Appendix A. Vibration Analysis

Figure A.6: Spectrogram results - Mercedes W212 - Driver 1 - X,Y,Z axis

(e) Spectrogram - Mercedes W212 - Driver 1 - Z axis
A.1.3 Mercedes W212 - Driver 2

The dataset for vibration analysis in the Mercedes W212 for driver 2 is a 30 minute taxi trip, on a morning rush hour shift.

FFT analysis

Figure A.7: FFT results - Mercedes W212 - Driver 2 - X,Y,Z axis
(e) FFT - Mercedes W212 - Driver 2 - Z axis

Figure A.7: FFT results - Mercedes W212 - Driver 2 - X,Y,Z axis
A.1. Vibration Analysis

PSD analysis

Figure A.8: PSD results - Mercedes W212 - Driver 2 - X,Y,Z axis
Appendix A. Vibration Analysis

Figure A.8: PSD results - Mercedes W212 - Driver 2 - X,Y,Z axis

(e) PSD - Mercedes W212 - Driver 2 - Z axis
A.1. Vibration Analysis

Spectrogram analysis

(a) Spectrogram - Mercedes W212 - Driver 2 - X axis

(b) Spectrogram - Mercedes W212 - Driver 2 - Y axis

**Figure A.9:** Spectrogram results - Mercedes W212 - Driver 2 - X,Y,Z axis
Appendix A. Vibration Analysis

(c) Spectrogram - Mercedes W212 - Driver 2 - Z axis

Figure A.9: Spectrogram results - Mercedes W212 - Driver 2 - X,Y,Z axis
Energy harvester simulations

The following appendix depicts some of the full-scale energy harvester modelings that were performed initially, which are not placed in the report for readability reasons. To get a view of the overall efficiency and power levels they are located here.

B.1 Energy harvester simulations

B.1.1 Energy Harvester Model

This section depicts the acquired piezoelectric model and power conditioner that was used to conduct energy harvester simulations upon. It is depicted in Figure B.1.
Figure B.1: Piezo element and power conditioner - LTSpice model
B.1.2 Mercedes W212 / Driver 1

(a) Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance - Full scope

(b) Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance - Acceleration signal vs piezo signal

Figure B.2: Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance
Appendix B. Energy harvester simulations

(c) Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance - Piezo voltage vs LTC output voltage

(d) Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance - LTC3588 output current and power

Figure B.2: Energy harvester modeling - Mercedes W212 - Driver 1 - 8.59 Hz resonance
B.1. Energy harvester simulations

B.1.3 Mercedes W212 / Driver 2

(a) Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance - 200 seconds

(b) Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance - Acceleration signal vs piezo signal

Figure B.3: Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance
Appendix B. Energy harvester simulations

(c) Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance - Piezo voltage vs LTC output voltage

(d) Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance - LTC3588 output current and power

Figure B.3: Energy harvester modeling - Mercedes W212 - Driver 2 - 8.59 Hz resonance
B.1. Energy harvester simulations

B.1.4 Mercedes W212 on Volvo V70 harvester

The following section shows the output voltage and power from the dataset of Mercedes W212, Driver 1, optimized for the Volvo V70. One sees clearly how the excited frequency from the Mercedes W212 mismatches with the resonance frequency of the energy harvester, and how it affects the output power from the power conditioner. This is depicted in Figure B.4b.

(a) Energy harvester modeling - Mercedes W212 - Resonance 8.59 Hz

(b) Energy harvester modeling - Mercedes W212 - Resonance 8.59 Hz on Volvo V70 energy harvester - Resonance 12.54 Hz

Figure B.4: Energy harvester modeling - Generic model attempt
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