



Pavement health monitoring using IoT enabled in-road sensing

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Abstract

Continuous pavement health monitoring detects the early degradation of the pavement structure and extends the lifetime thereof by informing routine maintenance actions. Traditional pavement condition monitoring techniques are limited in this regard as their high cost restricts the frequent use thereof. Thus, a need exists for low-cost, high coverage, and continuous monitoring of the pavement structure. This paper presents a low-cost wireless self-powered in-road sensing device that frequently assesses the pavement's condition. Unlike traditional systems, the proposed solution combines a suite of different sensors to provide valuable insight into the factors that affect pavement health. Measurands such as the pavement deflection at the time of vehicular loading, temperature, humidity, and moisture content are captured at the upper layers of the pavement structure. In addition, the ability of accelerometers to accurately convert the acceleration of the pavement to elastic deflection and/or displacement upon loading is assessed.

Keywords: *Intelligent Transportation Systems, IoT, In-road Sensing, Condition Monitoring, Power Management.*

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Abbreviations

RTN – Road Traffic Noise

ANE – Anomalous Noise Event

GMM – Gaussian Mixture Model

ML – Machine Learning

WSN – Wireless Sensor Network

MPD – Mean Profile Depth

AP – Access Point

SQL – Structured Query Language

ANN – Artificial Neural Network

MLP – Multi-Layer Perceptron

SVM – Support Vector Machine

PoE – Power over Ethernet

NTP – Network Time Protocol

ITS – Intelligent Transportation System

IoT – Internet of Things

GWR – Geographically Weighted Regression

RTN – Road Traffic Noise

APCS – Automated Pavement Condition Survey

MDD – Multi-Depth Deflectometer

FWD – Falling Weight Deflectometer

HMV – Heavy Motor Vehicles

RRV – Road Rail Vehicle

1 Problem Statement

In this chapter the problem is identified, together with the context in which the problem exists. This is followed by a proposed solution together with the proposed objectives and benefits thereof. Finally, the research scope, deliverables, and methodology are discussed.

1.1 Introduction

Road networks are one of the most valuable assets of a country, allowing citizens or tourists to move from point A to B, between home and the workplace. This asset also underpins a country's economic development, and its usefulness is evident in the supply chain, connecting the various stakeholders as seen in Figure 1-1 below. From a simple demand to the end-product, logistics provide a link between the various sectors.

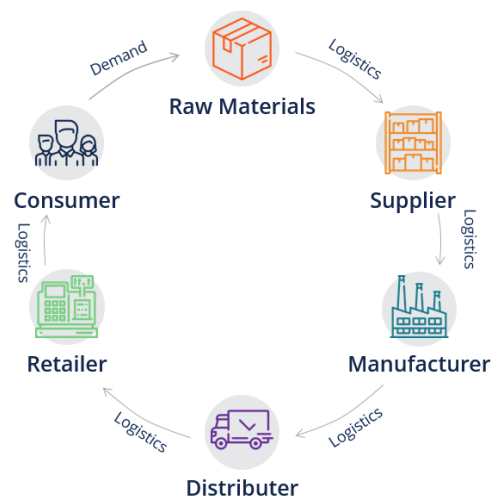


Figure 1-1: The supply chain [1]

Roadways are designed in accordance with standardized design methodologies; nevertheless, the road pavement infrastructure faces ongoing exposure to environmental factors and various traffic and environmental loads, leading to gradual structural degradation over time. Unroadworthy vehicles, suffering from excessive vibration levels, also abuse this vital asset. These vehicles not only place the lives of road users in danger but also limits the lifetime of the road infrastructure. This creates a need to monitor the health of the pavement infrastructure. An important aspect of health monitoring is the early detection of pavement degradation by continually monitoring the structural and functional pavement performance, allowing road agencies to address the problem with a significantly lower maintenance cost.

1.2 Problem definition

Pavement deterioration can infer significant costs for a road agency if left unmanaged. Excessive stresses applied to a poorly designed road can quickly lead to the formation of micro-cracks in the layers of the pavement structure. If left untreated, these micro-cracks lead to rutting and eventually form potholes. Furthermore, roadway deterioration is exacerbated by unroadworthy vehicles with excessive loading and faulty suspension systems. Consequently, corrective maintenance actions are required to achieve the designed lifetime of the road, but it requires a significant investment. According to the South African National Treasury, major repairs on roads can cost up to R3.5 million per kilometer [2]. It is therefore of great importance to maximize the lifetime of roadways, which can only be done by using preventative maintenance solutions and identifying stress formation early on. As mentioned previously, current solutions which utilize the Automated Pavement Condition Survey (APCS), Multi-Depth Deflectometer (MDD), and Falling Weight Deflectometer (FWD) cannot effectively meet this need. Therefore, there is a need to monitor the health of the roadways with an emphasis on increasing the frequency and coverage of these assessments and at the same time lowering their cost.

1.3 Proposed solution

The proposed solution uses an in-road sensor unit, embedded in the top few layers of the pavement structure, to monitor the effect of the environment on the pavement structure. This sensor unit will be used to measure certain environmental features, including but not limited to the pavement's elastic deflection and/or displacement, temperature, humidity, and moisture content. The data to be processed and transmitted wirelessly to an IoT gateway. By using inferential sensing techniques, the current state of the pavement, i.e., pavement layer stiffness's, (i.e. elastic moduli of layers) can be determined and used to predict the long-term performance of the pavement structure. Furthermore, multiple sensor units could be distributed in a section of pavement to ensure that the spatial variability of the pavement is accounted for and to effectively monitor the entire contribution of a passing vehicle on the health of the road. Secondary features, such as vehicle classification and unroadworthy vehicle identification could also be achievable with this concept. To increase the coverage of pavement assessments, a sensor network is to be formed in which thousands of sensor units are distributed over an area and connected to a central network that processes, evaluates, and stores the information. This network is known as a Wireless Sensor Network (WSN). What makes the proposed solution distinctly different from current solutions, is its ability to provide a low-cost and low-power alternative. The sensor unit to utilize energy harvesting techniques to eliminate the need for lengthy power cables and unnecessary routing. Together with low-cost components, the sensor unit may be a feasible option for a road agency looking to deploy a large-scale network of sensors.

1.4 Project aim and objectives

1.4.1 Primary objective

The main objective of this study is to investigate the feasibility of an in-road sensor unit to monitor the long-term performance of the pavement structure. Consequently, the techniques to measure the elastic deflection and/or displacement of the pavement structure as a vehicle passes over it, needs to be

investigated. The sensing techniques need to conform to the limitations of the system with regards to the cost, power supply, communication technology, and the physical environment. This requires the deployment of a small-scale sensor network in a real-world setting under real-world conditions. Furthermore, the processing techniques, used to extract certain features and infer certain performance indicators from real-world signals, need to be investigated. To deliver a system that is deployable in a practical setting requires a system-level design, which not only focuses on the development of a single sensor unit but acknowledges that it is only a single node in a vast network of sensors. As a result, the focus is to be directed to the network design, which includes the gateway-to-server communication link and data storage options. The following questions should be answered at the end of the study:

- How does the utilization of a low-cost, wireless, self-powered in-road sensing device enhance the frequency and accuracy of pavement condition assessments compared to traditional monitoring techniques?
- What are the challenges and limitations of using accelerometers to convert pavement acceleration to elastic deflection and/or displacement for assessing pavement health, and how can these limitations be addressed or minimized?
- Can the system accurately measure the state and behaviour of the pavement structure in real-world conditions?

1.4.2 Secondary objective

The secondary objective of this study is to investigate the potential of the system to detect and classify passing vehicles. The impact that different vehicle classes have on the road surface can then be determined. Furthermore, when classification is possible, unroadworthy vehicle detection is also possible. If connected with existing automatic numberplate recognition (ANPR) data, traffic authorities can identify and act against the traffic offender. The following research questions address the secondary objectives.

- Is vehicle detection and classification possible with the current solution?
- Can the system be integrated with existing traffic monitoring solutions?

1.5 Anticipated benefits

The solution would provide the following benefits:

- Determine the remaining useful life of a roadway. The in-road sensor needs to determine certain pavement performance indicators by means of pavement condition monitoring, i.e., pavement elastic deflection and/or displacement, that can be used to estimate the remaining useful lifetime of the pavement.
- Enables a preventative maintenance option to detect roadway deterioration at an early stage. Potentially, this will significantly decrease the cost associated with corrective maintenance actions and extend the lifetime of the pavement.
- The solution needs to enable continuous long-term monitoring of the pavement structure. Current options only assess the health of the roadways, at most biannually.

- The solution would offer pavement condition assessments at a lower cost compared to current APCS and FWD tests.
- Classification of vehicles should enable authorities to regulate the traffic in high density areas.
- Unroadworthy vehicles, such as heavy motor vehicles (HMs) with poorly maintained suspensions, can be identified and fined.

1.6 Research Scope

The scope of the project entails the development of an in-road sensor to monitor the pavement behaviour under dynamic loading and real-world environmental conditions. This requires the development of an in-road sensing device, the selection of an adequate wireless communication protocol and the required topology to efficiently communicate readings to a central server, and a means to store and display information for easy access. Primarily, the in-road sensing device should measure the vibrations (accelerations) of the pavement structure under loading and infer the elastic deflection and/or displacement thereof. The accuracy of the elastic deflection and/or displacement calculations should be compared to the traditional measurement methods to determine if the in-road sensor offers a feasible replacement/addition. Furthermore, inferential sensing techniques to assess the performance of the pavement structure should be investigated. All this should be done while ensuring that the cost and power consumption of the nodes are minimised, and the coverage is maximised. The study does not include the design of the core communication network and the user interface.

1.7 Deliverables

The following deliverables should be achieved at completion of the project:

- A system that measures the pavement elastic deflection and/or displacement under loading.
- A system that infers pavement performance indicators from pavement condition monitoring data.
- A high-level design of a WSN that allows access to sensor data from a remote location.
- Software associated with the data processing and power management.
- Valid test data in a real-world environment.

1.8 Research Methodology and Design

1.8.1 Methodology

To achieve the deliverables of this study, a thoroughly designed research strategy was developed. The approach starts off by identifying the shortcomings of current studies on this topic, which allow for improvements in future designs. The research focus on the system level design of a pavement condition monitoring network. A **Quantitative** research methodology is followed. The steps to develop such a system can be defined as follows:

- A prototype in-road sensor node to be designed by following a system engineering approach. The node needs to house multiple sensors to detect the condition of the pavement. Data sets generated by the sensors are pre-processed in-situ to reduce the load on the communication

subsystem. Wireless communication needs to connect the node to a gateway which forwards data to the server.

- Once the prototype is implemented, practical experiments to reveal the performance of the design need to be done. A dataset of elastic deflection and/or displacements, acceleration, temperature, moisture content, and humidity are continuously collected by means of the wireless communication interface and a suitable database.
- Further processing and data analysis are done in a suitable software package and various back-calculation methods to be explored to reveal certain pavement performance indicators.

1.8.2 Design

The following forms part of the study:

1.8.2.1 Literature Review

Review recent work on the topic and gain an understanding into the methods used as well as the respective advantages and pitfalls of each method. Discover the implications of real-world deployment and investigate external influences that should be considered in the design of an in-road sensor network.

1.8.2.2 Preliminary system design

Develop the system concept by following a system engineering approach. This to reveal the requirements of the system, the functions that need to be performed to meet the requirements, the resources to be used to fulfil the functions, and the overall architecture of the system. Furthermore, the component selection and trade-off studies to be done.

1.8.2.3 Experimental learning and initial testing

Once the components have been selected and acquired, a prototype to be developed and tested in a laboratory environment to gain a deeper understanding of the limitations of the system and to confirm that the device specifications have been met.

1.8.2.4 Detailed design

If the preliminary design proves to be satisfactory, a more detailed design be necessary. Therein, the design of the node on a printed circuit board (PCB), the software for data -acquisition, -preparation and -analysis, and a 3D model of the casing of the node needs to be done.

1.8.2.5 Implementation and Testing

Implementation in a practical setting expose the sensory node to real-world conditions in which thorough testing can take place. Various experiments to be conducted to test the device's accuracy against reference instruments. The overall performance of the system to be assessed to determine its suitability as a replacement to traditional pavement condition monitoring techniques.

1.8.2.6 Results analysis

Analysis of the results is needed to reveal the effectiveness of an in-road sensory network to monitor the state of the pavement and the possibility of implementing such a system to add value to current ITS technologies. The shortcomings need to be identified and possible improvement of the system to be proposed

1.8.3 Requirements

The following are some of the high-level requirements of the proposed solution:

- The system must determine the deflection of the pavement structure at its different layers, at least in the Asphalt Concrete (AC) surface layer and the Unbound Granular Base (UGB), for the first 200 mm from the surface.
- The sensor unit must be as small as possible to achieve minimum disturbance in the pavement structure.
- The sensor unit needs to measure the elastic deflection and/or displacement of the pavement as a vehicle passes over the road section at high-way speeds.
- The system needs to determine the pavement performance indicators from the gathered sensory node data.
- The sensory node must be implemented as part of a network of sensors that connect to a central node for easy information processing, storage, and visualization.
- The node must be imbedded in the pavement surface in such a way as to not infer additional stresses on the layers of the pavement structure.
- The node must withstand the environmental condition imposed on it in its operating environment.
- The sensor unit must be powered by an energy harvesting technique to eliminate the need for power cables and to provide a “green” solution.
- The sensor unit must communicate to the gateway by means of a wireless protocol to eliminate the need for communication cables, and to minimise the costs and the potential for vandalism.
- The sensor node needs to be easy to install and replace.
- The sensor node must have a casing that should be able to withstand the impact force from Heavy Motor Vehicles (HMV).

1.8.4 Timeline

To ensure that the study is completed in the intended time, a project timeline was used:

- Literature review – 4 months
- Preliminary Design – 1 months
- Experimental learning and initial testing – 2 months
- Detailed Design – 2 months
- Implementations and Testing - 3 months
- Results analysis – 4 months

1.9 Project Tasks and Resources

To successfully complete the project, the necessary tasks and required resources for each task need to be determined. Table 1 shows the project tasks to be completed to achieve the main deliverables and the associated resources required for each task.

Table 1-1: Project tasks and resources

Tasks	Resources
Construct in-road sensor	• Electronic Components • Device casing • Lab equipment (solder etc.)
Program in-road sensor	• Lab equipment • Personal Computer (PC) • Software libraries for specific sensors
Calibrate in-road sensor	• Reference instrumentation (Linear Variable Differential Transformer (LVDT), thermometer etc.)
Test in-road sensor functionality with different sensor configurations	• Lab equipment (oscilloscope etc.) • Reference instrumentation
Extract pavement behaviour characteristics from in-road sensor measurements	• Sensor measurement data • Vehicle • In-road sensor • Test-site • Test environment in operating conditions
Select features to be extracted from measurements	• Software libraries for digital signal processing (DSP) • Computer with adequate specifications • Pavement behaviour data
Infer pavement performance from feature data	• Mathematical model for deflection calculations • Mathematical model for pavement performance indicators
Construct WSN	• Multiple In-road sensors • IoT (Internet of Things) gateway • Server/Cloud access • Database
Test WAN communication, data storage, and remote access	• Testing equipment (computer etc.) • In-road sensor • IoT gateways • Server/Cloud access
Test WSN in practical environment	• Test site (N4 Pretoria) • Multiple In-road sensor units • IoT gateway • Fleet of vehicles to participate in the study • Server/Cloud access

1.10 Ethical Considerations

There are no ethical considerations or conflict of interest to consider for this study

2 Literature Review

This chapter delves deeper into the theoretical work and previous studies related to the envisaged system. The aim is to provide a better understanding of the problem background and possible solutions. Various pavement health monitoring techniques are discussed, with a focus on the vibratory aspects of pavement behaviour as a result of a moving load. Furthermore, key aspects associated with the operational environment are discussed, such as environmental effects, power management, network architecture, and the failure modes of the proposed system.

2.1 What are Intelligent Transportation Systems

Pavement health monitoring using *smart* solutions fall into a category known as Intelligent Transportation Systems (ITS). According to the Road Network Operations & Intelligent Transport Systems, ITS can be defined as the systems that apply Information and Communication Technologies (ICT) to accomplish specific goals. That is:

- Improving the mobility of people and goods,
- Increasing road safety, manage incidents, and reduce traffic congestion,
- Meet the transport policy goals set by authorities.

Considering the above, pavement health monitoring focuses on ensuring the safety and mobility of road users. The specifics thereof are considered in the following sections.

2.2 Pavement health monitoring

Road infrastructures are complex engineered systems and adds important economic and industrial value to a country. These roadways are developed in accordance with standardized design methodologies. Nevertheless, the road pavement infrastructure remains consistently subjected to environmental factors and varying traffic loads, leading to gradual, structural degradation in the long run. Unroadworthy vehicles, suffering from excessive vibration levels, also abuse this vital asset. These vehicles not only place the lives of road users in danger, but also limit the lifetime of the road infrastructure. This creates a need to monitor the health of the pavement infrastructure. An important aspect of health monitoring is the early detection of pavement degradation by continually monitoring the pavement performance, allowing road agencies to address the problem with a significantly lower maintenance cost.

2.2.1 Current systems for pavement health monitoring

Traditional systems used in the assessment of pavement health usually involve timely procedures, limited in coverage, and too expensive to conduct on a frequent basis. Automated Pavement Condition Surveys (APCS) is a popular technique used to identify possible pavement degradation and inform rehabilitation processes. While these surveys offer crucial data on the pavement performance of a specific section, their high cost restricts the frequency of assessments to once or twice a year. Furthermore, these surveys depend on visual feedback, rendering the assessment unaware of potential internal pavement damage. This limitation in early identification of internal distress or failure over the pavement's lifespan results in a significant escalation in maintenance costs. The non-destructive Falling Weight Deflectometer (FWD)

tests measures the physical properties of pavement. It provides a suitable alternative to traditional intrusive processes because tests are faster and does not require the removal of pavement material [18]. Figure 2-1 below shows a schematic of FWD load and downward elastic deflection measurements. The FWD test uses a series of equally spaced geophones to measure the deflection bowl produced by the applied load. A geophone is a passive device that uses a magnet suspended in a coil. When the base of the geophone is subject to vibrations, a current is induced in the coil which is proportional to the velocity of the movement. Unlike a 3D accelerometer, a geophone is only capable to measure in one axis.

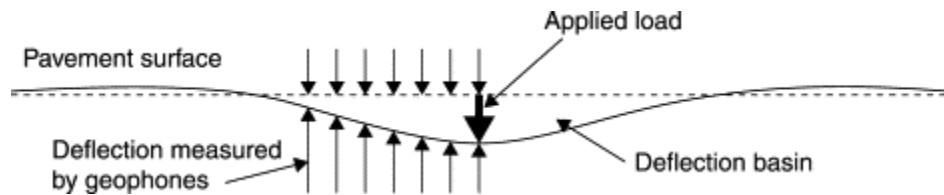


Figure 2-1: The FWD Test [32]

The pavement elastic deflection and/or displacement data obtained from the FWD test, together with other known variables such as layer thickness and the applied weight, can be used to calculate the Young's elastic modulus which is an indicator of the stiffness of the pavement structure [19]. Road agencies can then use this back-calculated layer stiffness as a pavement performance indicator. Regular FWD testing and subsequent layer stiffness calculations facilitate the monitoring of internal damage and the propagation of microcracks. A decline in surface layer stiffness throughout the lifespan of the pavement signals a decrease in performance, indicating the build-up of damage within that layer. Typically, the accumulation of damage results from microcracks at the aggregate-binder interface of the structure. The Falling Weight Deflectometer (FWD) proves effective in gauging the extent of these microcracks, enabling engineers to implement preventative maintenance before larger cracks emerge [19]. Despite the valuable insights provided by FWD testing in assessing pavement performance, its practical application is restricted by its relatively high cost and the necessity for road closures during the testing process, hindering its frequent utilization.

Consequently, there is a great need for low-cost, high coverage, and continuous monitoring of pavement performance indicators. This fuels the search for a wireless embedded sensor device that can measure the pavement elastic deflection and/or displacement as vehicles pass over the road surface.

2.2.2 Pavement Behaviour Under Loading

Having an adequate understanding of the behaviour of a pavement under loading conditions is important and gives insight into the deterioration thereof. The structural design of the pavement provides insight into the distribution of stresses observed in the different layers. Figure 2-2 below shows the multi-layer design of a flexible pavement loaded by a dual-wheel load. A tyre-pavement contact stress is applied to

tyre pavement interface on a small section of the surface layer. The contact stress dissipates, and its area of coverage increases as the depth increases. With an increase in depth and area, the concentration of the stress decreases, indicated by the colour matrix (red to yellow). Since the upper layers experience a higher shear stress, the shear strength of these layers is an important design consideration.

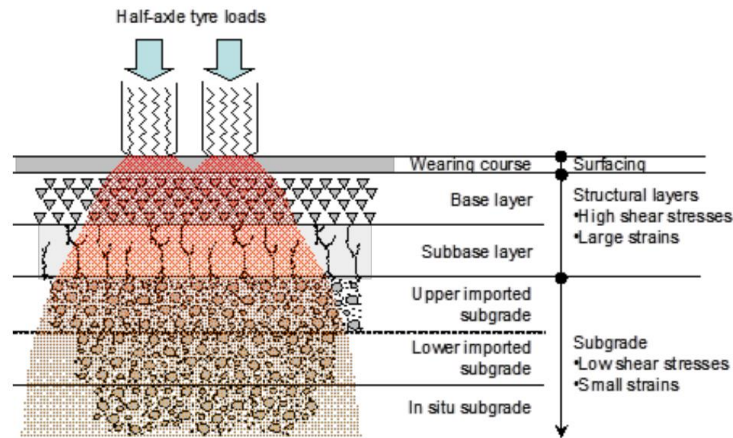


Figure 2-2: The stress distribution in the pavement structure as tyre loads pass over it [21]

The immediate effect of a passing load on the pavement is small, considering only the individual effects. However, the cumulative effect of many similar loads is what distresses the pavement structure. By first modelling the short-term behaviour, the long-term effects can be better understood.

When a moving load passes over a section in the pavement, the pavement structure deflects, and rebounds once the load moves away (i.e., elastic behaviour). Heavy vehicles tend to form a circular deflection area of around 1 to 2 meters from the contact point [21]. This deflection forms an indentation in the upper layers of the road, known as a deflection bowl. Factors that affect the parameters of the bowl are the properties of the road surface (strength and stiffness), the *pavement balance*, temperature, and the force applied by the load. Flexible pavements that are considered structurally 'sound' typically have a maximum deflection around 500 microns under an 80 kN axle load. Figure 2-3 shows an example of a deflection bowl as a wheel moves over the surface.

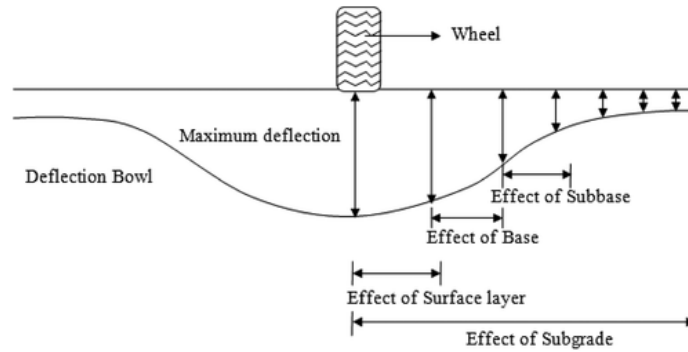


Figure 2-3: The deflection bowl created when a load is applied the pavement structure [20]

When a Heavy Vehicle (HV) passes over a section in the road, the response of the pavement structure is similar to that shown in Figure 2-4 below. As illustrated, a 5-axle semi-trailer truck passes over the sensing area with each axle causing a deflection in the pavement. The magnitude of vertical deflection is determined by the load on each axle.

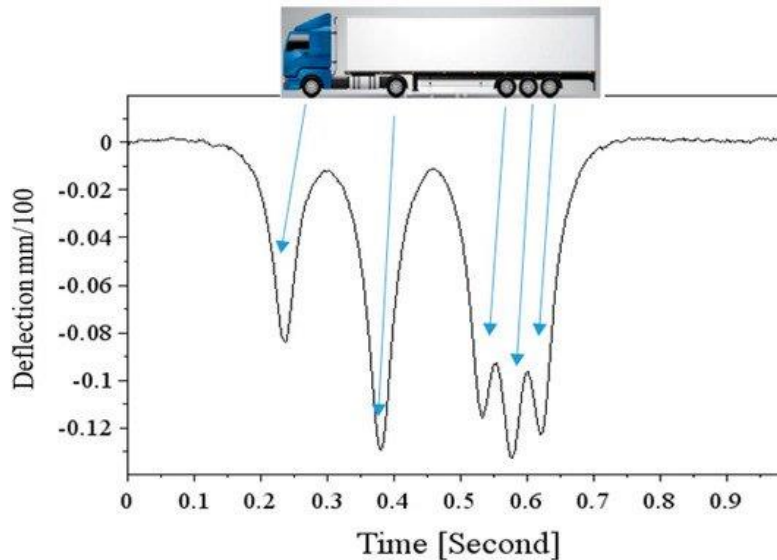


Figure 2-4: The road surface deflection of each truck axle [24]

The age of the pavement structure plays a significant role in its behaviour under loading. The deflection bowl for various age groups is shown in Figure 2-5. Three different age categories are summarised as follows [21]:

- **Context 1** – The pavement layers are stiff with a strong cemented subbase layer, leading to relatively low deflections with a wide bowl.
- **Context 2** – The pavement is relatively old but still structurally sound and made with quality materials. Deflections at this stage are higher than that of a new pavement since the stiffness is relatively lower compared to new roads.
- **Context 3** – The pavement structure is old, and the materials are of poor quality. The sub-base and sub-grade layers are moist. In this scenario, the deflections are relatively high, with a narrow bowl.

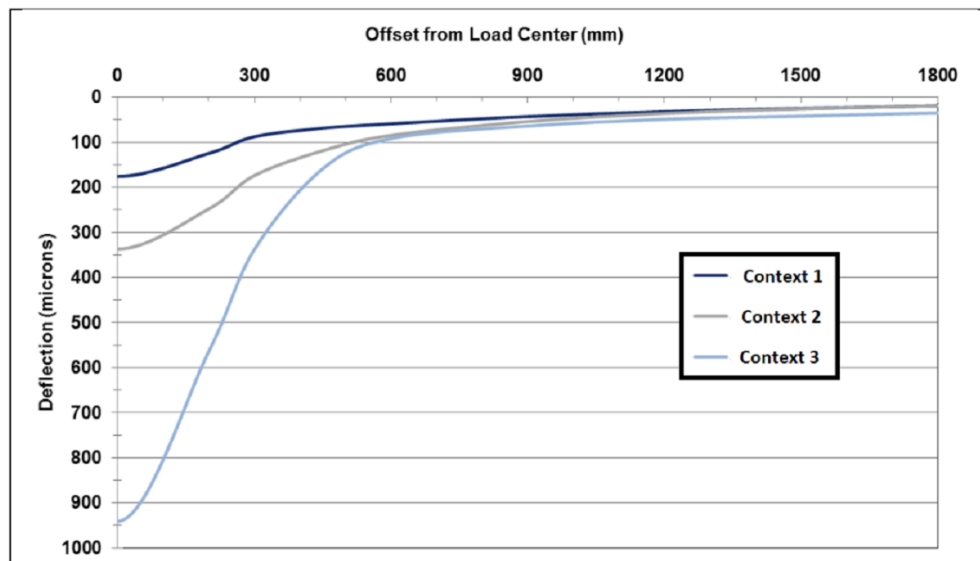


Figure 2-5: Deflection bowls created for different road ages [21]

So far, the behaviour of the pavement has only been analysed for static loading conditions. However, as a vehicle passes over the pavement structure, strain and stress is experienced in the vertical as well as the horizontal plane. This complex dynamic loading phenomenon can be categorized into three effects:

1. The stresses and strains in the pavement structure as the load moves over the surface.
2. The time dependent behaviour of the pavement materials.
3. Impact loading from Heavy Vehicles (HVs)

2.2.3 Stresses and Strains caused by a moving load

Figure 2-6 below shows the stresses and strains experienced by the pavement structure before, under, and after the load. The pavement experiences a compressive stress before and after the load has passed, while a tensile stress acts on the pavement under the load. There is also a vertical, horizontal and shear stress that acts on the bottom of the bound layers. The two principal stresses (σ_1 and σ_3) rotate throughout the movement of the load.

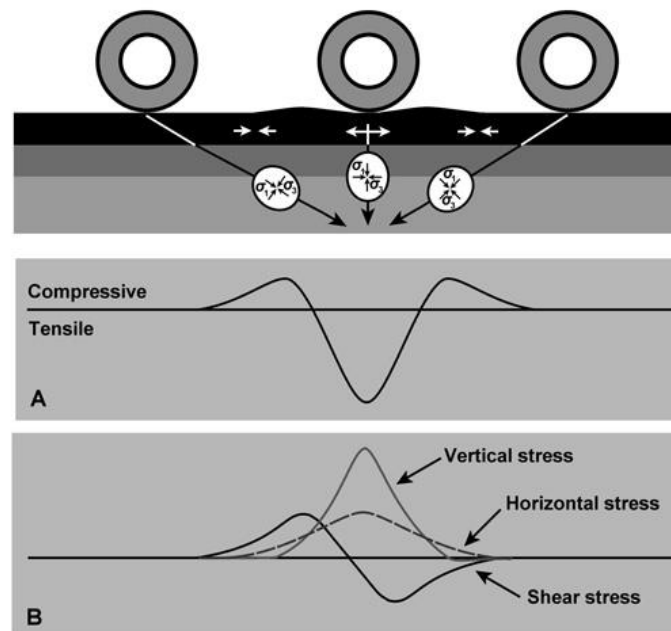


Figure 2-6: The stresses experienced by the pavement structure as a load passes over it [33]

1. Time dependant behaviour of the materials

Some of the materials that are used in the construction of the road are susceptible to plastic deformation (i.e. displacement) and do not have a completely elastic response under dynamic loading. The recovery time of these materials as the load passes may be slow, and as a heavy truck with multiple axis moves over the area, it may experience increased strain.

2. Impact loading from heavy vehicles

The profile of the road surface also has a significant effect on the magnitude of the forces experienced by the pavement structure. As a heavy vehicle passes over a bump, the suspension of the vehicle causes impact loads that are higher than that normally experienced by the pavement structure. This may cause phenomenon such as pumping that deteriorates the pavement structure faster [33]. Figure 2-7 shows the dynamic loading effect when a heavy vehicle with 3 axes passes over a bump in the road.

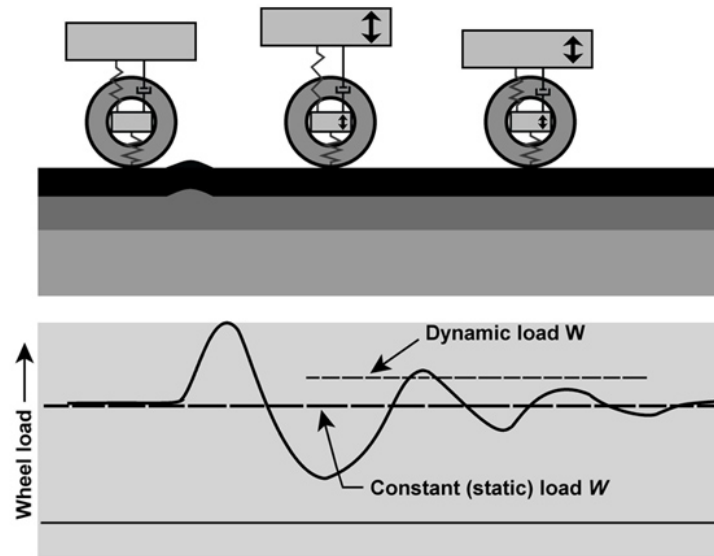


Figure 2-7: The dynamic loading effect [33]

The thermal images in Figure 2-8 below also illustrates the effect of dynamic loads on a relatively rough pavement profile

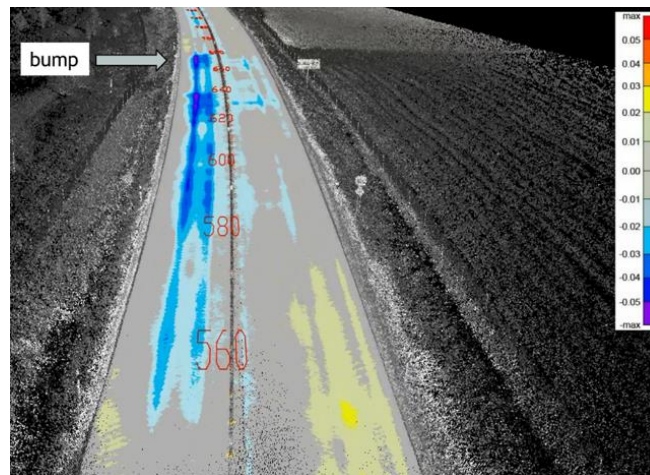


Figure 2-8: The effect of a bump in the road [33]

3. Deformation Phases

According to the South African Pavement Engineering Manual, the structural service level reflects the state of pavement structure and is a function of the structural deterioration thereof. The condition of the pavement is usually affected by cracking, fatigue damage, and permanent deformation (called rutting, or displacement)) in flexible pavements. A common source of these problems is the ingress of moisture in a pavement [21]. The service life of a pavement is a measure of the period between the initial structurally sound functional condition to the unacceptable functional condition (predefined level of functional deterioration). The service life of a pavement can be categorized in three phases:

- **Structural Distress** - The initial phase starts once the road is opened to traffic. Throughout this phase the pavement undergoes incremental permanent deformation, with distress levels that are initially insignificant.
- **Terminal Structural condition** – The level of distress on the pavement structure reaches an unacceptable level. This forms terminal conditions such as rutting of up to 20mm in flexible pavements. Corrective actions can be taken to rectify the issues, such as structural overlays and patching and extend the lifetime of the pavement. The pavement can then continue to provide years of excellent service.
- **Structural failure** – Once layers have lost their strength, they are unable to provide sufficient support. For example, rapid shear failure causes rutting in the layers and can only be corrected with structural strengthening.

2.2.4 Pavement States

The pavement structure can be categorized in four states described by their stiffness. Table 2-1 below shows the pavement behaviour state and its corresponding maximum stiffness.

Table 2-1: Pavement deflection for various pavement states [41]

Pavement State	Maximum Vertical Deflection (mm)
Very Stiff	< 0.3
Stiff	0.3 – 0.5
Flexible	0.5 – 0.75
Very Flexible	> 0.75

2.3 Pavement acceleration measurements for structural health monitoring

As discussed above, a low-cost, high-coverage, and energy efficient technique is required to measure the elastic deflection and/or displacement of the pavement structure. The traditional methods for assessing the condition of the pavement relies on expensive equipment and time-consuming techniques. Another possible method would be to use the pavement accelerations and derive the elastic deflection and/or displacement from these measurements. A typical acceleration signal as a passenger vehicle passes over a pavement section is shown in Figure 2-9 below. It shows both the time- and frequency domain properties [34]. Clear peaks can be seen at different frequencies, which can be extracted by applying a band-pass filter.

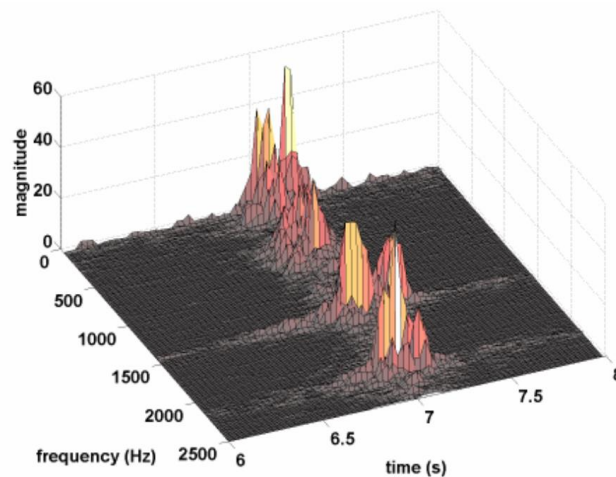


Figure 2-9: A typical vibration signal as a vehicle passes over the road surface [22]

Once the signal is filtered, a time-domain signal similar to the one displayed in Figure 2-10 can be obtained. It clearly shows the two axles of the passenger car as it passes over the sensor.

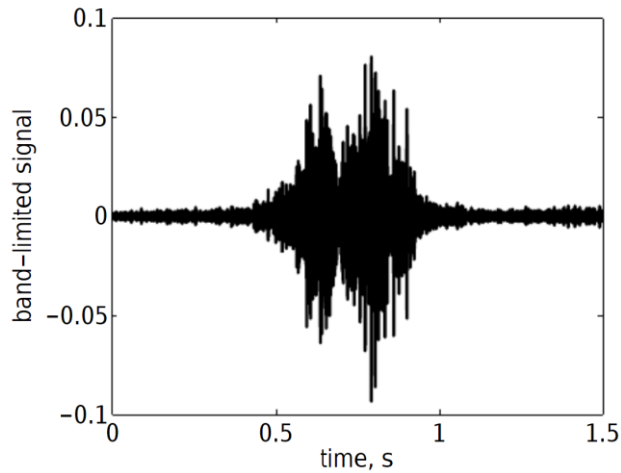


Figure 2-10: The filtered time-domain vibration signal [22]

This vibration signal from the accelerometer can be used to extract features which may be related to the pavement's elastic deflection and/or displacement, vehicle speed, axle count, and vehicle presence. Wolfgang *et al.* [22] uses this vibration signal to detect passing vehicles by calculating the envelope of the energy signal and feeding it as input to the detection algorithm. Figure 2-11 displays the envelope of the energy signal.

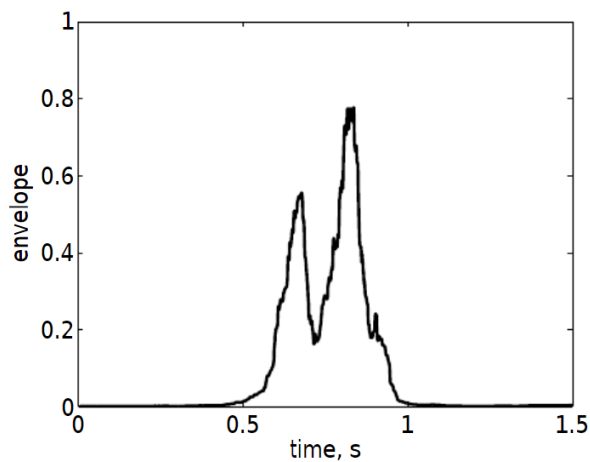


Figure 2-11: The envelope of the energy signal [22]

With more than one accelerometer contained in a single node, and an ADC sampling rate above 1 kHz, a significant amount of data is generated. It is not feasible to transmit the raw data to the gateway since the energy consumption for communication would be relatively high. An alternative would be to first extract the necessary features from the acceleration data and transmit it to the gateway. A pre-processing

algorithm is executed by the MCU of the sensing node to extract features from the raw data. Ye *et al.* [34] proposes a pre-processing algorithm consisting of baseline correction, filtering, and thresholding to extract the peaks of the vibration signal. The proposed algorithm works as follows: First, the raw acceleration data is collected. The raw data is then filtered to eliminate frequencies beyond the designated area of interest, such as those in the sound spectrum [19]. This process aids in identifying the local maximum within a single vibrational peak. Subsequently, all peaks are extracted using a find-peaks algorithm. A threshold then determines the peaks that are relevant and groups it with the timestamp to form the feature. Figure 2-12 below shows the pre-processing phase.

Although the peak value of the vibration signal provides an effective method to estimate the speed and axle count, it is greatly influenced by the speed, load position, and weight of the vehicle. For example, when a vehicle is travelling at a low speed and the load is far from the measuring point, the amplitude of the vibrational signal becomes small and susceptible to background noise. This makes the peak extraction difficult and leads to large errors. An important recommendation by Ye *et al.* [34] is to use multi-node deployment to accommodate for the variability in the load position, and an accelerometer with higher accuracy and resolution. The authors also highlight the importance of an efficiently designed power supply and a communication protocol that would minimize packet loss. This is especially important in an environment such as a roadway.

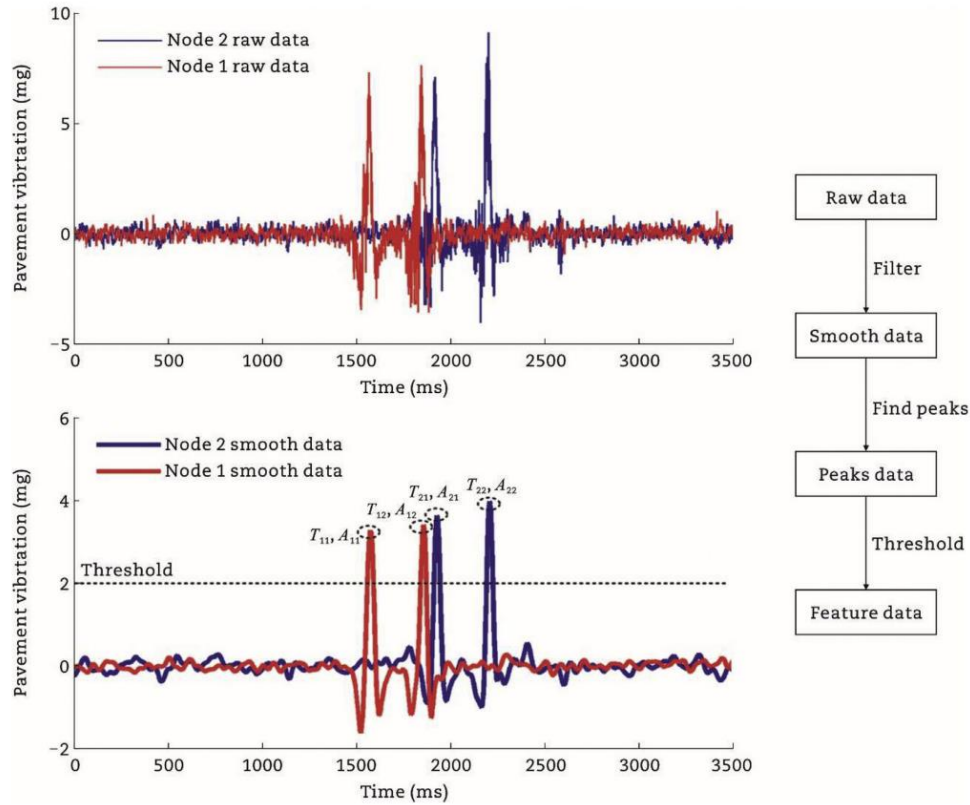


Figure 2-12: Extracting features from a vibration signal [34]

2.3.1 Specifications for monitoring vibrational signals in practical scenarios

Bajwa et al. [19] specifies the qualities of a suitable accelerometer for pavement deflection measurement. The chosen accelerometer should conform to the following specifications:

- Resolution $\rightarrow 500 \mu\text{g}$
- Bandwidth $\rightarrow 50 \text{ Hz}$
- Range $\rightarrow \pm 200 \text{ mg}$

Where μg is microgravity = 10^{-6} gravitational force, and mg is milligravity = 10^{-3} gravitational force.

Bajwa et al. [19] emphasises the need to properly isolate the accelerometer to effectively eliminate highway noise from the measurements. The author also reported that for low-speed applications, little displacement is observed in the measurements.

The sensitivity of the sensors is therefore also vital since the pavement displacement and acceleration levels as a vehicle moves over an area is very low [24]. Concerning the accelerometer's sensitivity, Bahrani et al. [24] outline typical pavement structure deflection levels ranging from 0.1 to 1 mm. Therefore, it is

crucial for the sensor to exhibit ample sensitivity for precise measurements within this range. The author opted for an accelerometer with a sensitivity below +/- 4g. Additionally, the author also stresses the importance of choosing sensors with a resonance frequency that is higher than the frequency at which pavement deflections typically occur (usually in the range of 2 and 20 Hz [19, 24]) to prevent inaccuracies in the results.

Shiferaw in [26] categorizes the frequency ranges of typical traffic induced vibrations. The first is the low-frequency content at frequencies below 2 Hz. These vibrations are induced by the impact force of the suspended mass of the vehicle. Above 2 Hz, the impact force of the unsuspended mass of the vehicle creates oscillations at frequencies between 10 Hz and 15 Hz. Vibrations in this frequency band are the most prominent and is the focus of this study. Furthermore, the impact force between the tyre and the road surface also produces vibrations in the frequency range between 600 Hz and 1500 Hz. However, according to Hajek et al. [27] the contribution of these high-frequency impact forces on the ground-borne vibrations is negligible.

2.3.2 Converting accelerations to displacement

Various techniques exist to calculate the displacement from acceleration measurements. Bajwa *et al.* [19] compares three different algorithms according to their estimation errors and practical worth.

2.3.2.1 Method 1 used in [19]

The first algorithm uses simple double integration from the known relationship between acceleration and vertical displacement as seen in Equation (1).

$$y(t) = y(0) + v(0)t + \int_0^t \int_0^\varepsilon a(\tau) d\tau d\varepsilon \quad (1)$$

However, a drift in the elastic deflection and/or displacement estimates is observed. This drift is a result of the amplification of measurement errors or small offsets in the signal at low frequencies. The drift contradicts the expected elastic behaviour of a flexible pavement structure, where the vertical elastic deflection is anticipated to be either zero or near-zero. Drift-compensation techniques can correct this error but adds additional complexity to this technique [19]. Figure 2-13 below shows the drift that is observed in the results.

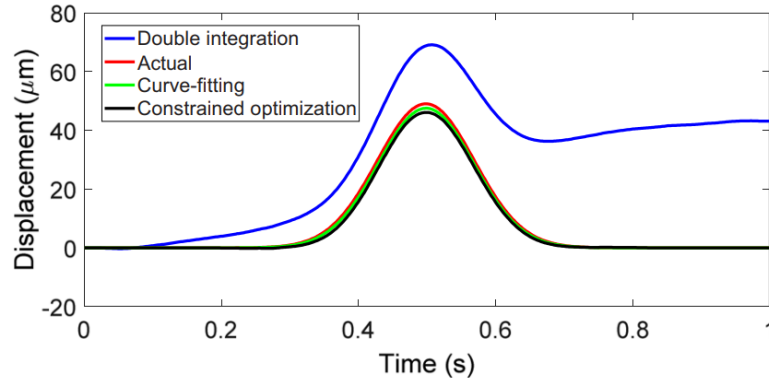


Figure 2-13: Elastic deflection and/or displacement after simple double integration [19]

2.3.2.2 Method 2 used in [19]

In the second technique employed by Bajwa et al. [19], a constrained least square estimation method is utilized. The algorithm leverages the correlation between acceleration and vertical displacement to compute the latter through a constrained least-squares estimation. This relationship between acceleration and vertical displacement can be expressed as follows:

$$a(t_n) = \frac{v(t_n) - v(t_{n-1})}{T} = \frac{y(t_n) - 2y(t_{n-1}) + y(t_{n-2}))}{T^2} \quad (2)$$

Equation 2 is then formulated in matrix form and solved for y by ensuring the mean-squared error between a and a_m is minimized, where a_m represents the measured acceleration. In addition, the initial and final state of the pavement is taken into account, with these states being set to zero under the assumption that the pavement is at rest both before and after the application of a load [19].

While this method surpasses the accuracy of a simple double integration operation, careful consideration is required when choosing the time window values. If a significant portion of the values within the time window represent the pavement at rest, the results may be inaccurate. The authors of [19] recommend techniques such as thresholding of the energy signal or zero-crossing to precisely estimate the time window. Figure 2-14 illustrates a comparison of displacement estimations for various time-window lengths. As k increases, more constraints are imposed on the system, but beyond $k = 3$, there is no substantial impact on the results.

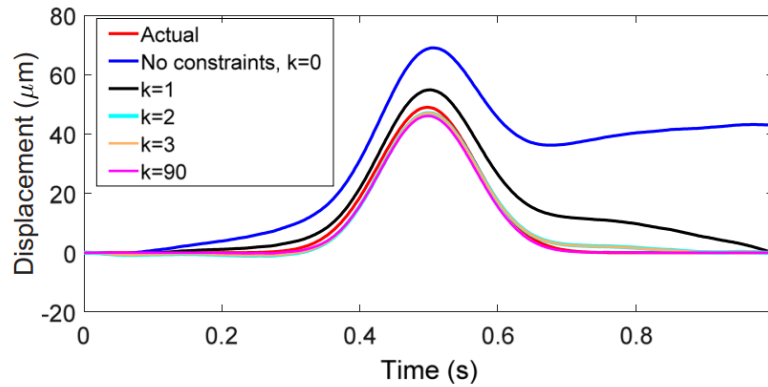


Figure 2-14: Performance of the least squares method [19]

2.3.2.3 Method 3 used in [19]

The third method uses a model-based approach in which the response of the pavement is approximated by using a family of functions. The signal is therefore first de-noised prior to double integration, eliminating the drift from displacement measurements. The choice of the model is important and if inaccurate, the error in estimations can be high [19]. The study used the elastic deflection and/or displacement measurements to back calculate the elastic stiffness of the pavement. The accuracy of this estimation could not be determined and was left for further testing. Another study uses an intuitive way to eliminate the trend effect when integrating the acceleration signal. Qihe [23] investigated the idea of frequency-domain integration and compared that to the traditional time-domain integration. As discussed above, time-domain integration (once the DC component of the raw accelerometer readings is removed) adds a trend term to the elastic deflection and/or displacement estimation. This can be corrected by using a de-trending method. This is done by fitting a polynomial function to the trend baseline and subtracting it from the input signal. In practice however, background noise has a significant influence on the result and the integral trend term is usually non-linear. The Least Squares method can be employed to remove the trend term; however, this necessitates fitting high-order polynomials as a baseline, which may still leave the trend term present post de-trending [23]. To effectively eliminate the influence of the trend term, integration in the frequency domain can be applied. The acceleration signal undergoes a Fourier Transform (FT), transitioning it into the frequency domain. Subsequently, integration occurs in this domain, and an inverse Fourier Transform is then used to obtain the time-domain signal. A downside of using this method is that frequency domain analysis usually requires a significant amount of processing power, which is a restriction in the studied case in [22]. Since the aim of this research is to design a low-cost, low-energy sensing node, this method may not fit the criteria of the proposed system.

A study in [29] also supports the use of frequency domain conversions of the acceleration signal and proposes a simple technique to accurately determine the elastic deflection and/or displacement from this signal. This technique involves the conversion of the signal to the frequency domain by means of the Fourier Transform whereafter zero-padding eliminates the effect of signal leakage. Spectral leakage causes the actual Fourier coefficients of a signal to lie between other frequencies. Therefore, low frequency

components appear significant compared to dominant components and distorts the signal. Zero padding eliminates the low-frequency noise components, allowing accurate conversion back to the time-domain [29]. In comparison, a band-pass filter can also be used to eliminate non-significant components, however, it is more difficult to adjust the filter's band. The author also tested direct time-domain integration of a signal to obtain elastic deflection and/or displacements. The results revealed that this method is effective, only if the signal contains frequencies much lower than the Nyquist frequency, which in practise is not the case. The only method to achieve accurate results is with frequency-domain analysis [29]. A drawback of this method is that it creates a discrepancy at the start point of the converted signal due to lost phase information.

The use of frequency domain methods can also be seen in the work of [30]. The author compares three methods for acceleration to displacement conversion.

2.3.2.4 Method 1 used in [30]

The first uses a Penzien filter, DFT (Discrete Fourier Transform), and a transfer function. This method is shown in Figure 2-15 below. This method proved to be the least accurate since it did not incorporate any correction techniques such as zero-padding or baseline-correction.

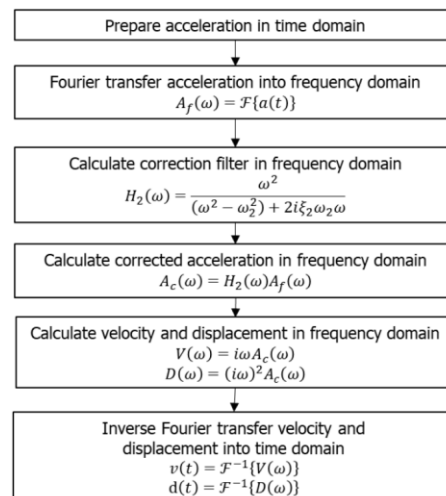


Figure 2-15: Flowchart for acceleration to displacement using a Penzien filter [30]

2.3.2.5 Method 2 used in [30]

The second method used by the author uses a time-domain analysis. Firstly, the acceleration data is zero-padded (meaning initial and final values are assumed to be zero). A baseline correction is implemented using a first-order equation. Subsequently, the corrected acceleration values undergo integration to derive elastic deflection and/or displacement. Following this, the elastic deflection and/or displacement undergoes cosine correction, as illustrated in Figure 2-16. This method proved to be the most accurate.

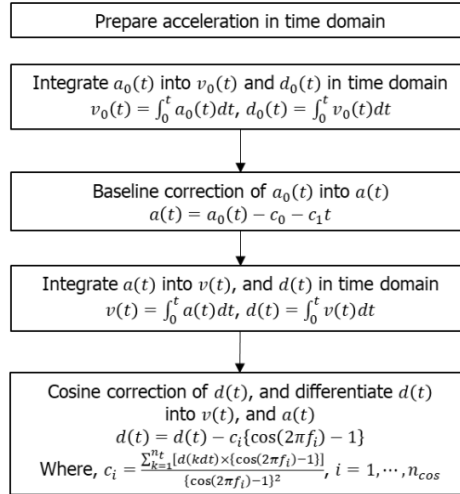


Figure 2-16: Flowchart for acceleration to displacement using baseline correction and cosine correction [30]

2.3.2.6 Method 3 used in [30]

For the last method the author also propose a least-squares fitting, similar to [19], to remove the linear drift in the signal. Furthermore, they also included a Butterworth filter to remove the low-frequency error caused by the time- to frequency-domain conversion of the signal as mentioned in [29]. The last step involves removing the linear trend caused by a non-zero initial velocity. This process is shown in Figure 2-17 below. This method also delivered relatively accurate results.

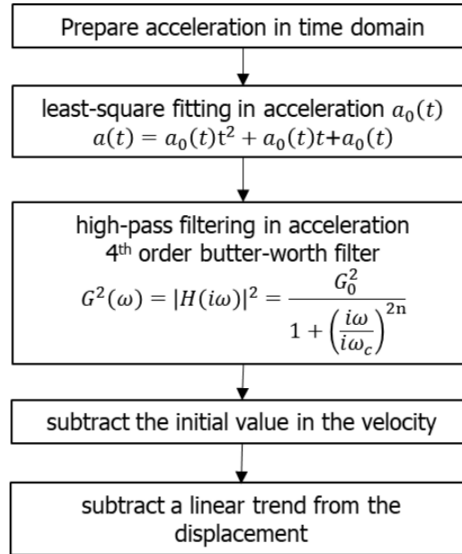


Figure 2-17: Flowchart for acceleration to displacement using least-squares and filtering methods [30]

2.4 Environmental Factors to consider for In-Road Sensing

This section describes the functional environment of the in-road sensor unit. It discusses the different environmental factors that may influence the operation of the unit. By analysing the current in-road sensor's specifications, various aspects can be derived to support the decision-making process.

2.4.1 Noise

EMI and background noise can significantly affect a sensor's measurement accuracy. Two categories of electromagnetic interference (EMI) have the potential to disrupt and diminish the efficacy of electrical circuits or signals. The first type, known as ambient EMI, happens when one electromagnetic signal obstructs another in free space. On the other hand, hardware EMI induces an unexpected electrical current within a circuit when the device is exposed to electromagnetic radiation.

Radio and other communication systems operate at a frequency of 500 kHz to 3 GHz, requiring the EMI to be at the same frequencies to cause possible interference. There are numerous sources of interference. According to [3], sources of RF signals include cell towers, broadcast towers, airport communication equipment, high-frequency communication systems used by public services, and local wireless communication systems. Additional interference stems from DC and low-frequency magnetic fields, such as ambient magnetic fields, high-voltage transmission lines, utility distribution lines, substations, switching stations, electrical power plants, and geomagnetic disturbances caused by passing. The major contributor to magnetic fields observed from a roadway would be electrical power lines/distribution points. Table 2-2 below shows the electric and magnetic field strengths at various distance from typical powerline configurations.

Table 2-2: Field strength at various distances from the source [3]

Voltage of Source	Field Strength at Specified Distances from Source				
	Directly under Lines	50 feet	100 feet	200 feet	300 feet
230-kV Transmission Line Electric Field Strength (kV/m)	2.0	1.5	0.3	0.05	0.01
230-kV Transmission Line Mean Magnetic Field (mG)	57.5	19.5	7.1	1.8	0.8
115-kV Power Line Electric Field Strength (kV/m)	1.0	0.5	0.07	0.01	0.003
115-kV Power Line Mean Magnetic Field (mG)	29.7	6.5	1.7	0.4	0.2

Since the in-road sensor is to be placed in an exposed/harsh environment, adequate electromagnetic compatibility (EMC) measures should be considered.

2.4.2 Tyre-to-Road Load

The physical requirements of normal road studs enable them to withstand the pressure from passing vehicles. Important considerations are the flexural strength, compressive strength, lens impact strength, and temperature cycling [4].

Accepted requirements for the various physical considerations are listed in Table 2-3 below.

Table 2-3: Physical requirements for in-road sensor packaging

	Physical Requirement
Flexural Strength	909 kg
Compressive Strength	2727 kg
Lens Impact Strength	< two 6.4 mm cracks
Temperature Cycling	no cracking / delamination
Stud height	15 mm to 22 mm

Any in-road object needs to be compliant with the structural requirements set out by road authorities to ensure that the impact on tire life/health is minimal. The South African National Standards (SANS) for roadstuds (SANS 1442:2008) limits the height of any roadstud to be 15 mm to 22 mm [4].

2.4.3 Effect of neighbouring in-road sensors

It is important to investigate the effect of neighbouring in-road sensors and their impact on the reliability, sensitivity and accuracy of data collected by another in-road sensor. The sensor spacing is an important consideration when determining the inter-sensor effects.

The South African Road Traffic Safety Management Association (SARTSMA) determines the longitudinal road stud spacing. An extract from the SARTSM - Vol 2 (2012) shown below gives the recommended spacing between road studs for various settings.

Table 2-4: Spacing requirements for in-road sensor

TABLE 2.2	RECOMMENDED LONGITUDINAL ROADSTUD SPACING			TABLE 2.2
	Normal (m) Centre - Centre	Intermediate (m) Centre - Centre	Abnormal (m) Centre - Centre	
Rural	24	12	6	
Urban	18	9	3	
Temporary	12	6	3 down to 1	

These requirements therefore need to be considered when choosing the communication technology. Sensors that communicate with one another need to have a minimum communication range of 24 m.

2.4.4 Natural Environment

Other structural requirements such as resistance to penetration of water, resistance to heat, resistance to motor fuel, resistance to lubricating oil, and resistance to corrosion also apply to any in-road sensor [5].

Table 2-5 below shows the structural test requirements of the in-road sensor [5].

Table 2-5: Structural requirements for the in-road sensor

	Structural Requirement
Resistance to penetration of water	10 min in 50°C water & 10 min in 25°C water
Resistance to heat	12h in 65°C oven
Resistance to motor fuel	5 min surface covered by n-heptane & toluene
Resistance to lubricating oil	5 min surface covered by detergent lubr. Oil
Resistance to corrosion	2 x 24h SANS 7253 (1996) salt fog test

2.4.5 Temperature effect at different pavement layers

The temperature profile over distance of the various layers of the pavement under heating from a bulb is shown in Figure 2-18. As seen, the curve shows a drastic decrease in temperature as heat is dispersed from the asphalt to the sand layers. The in-road sensor is to be placed in the asphalt and gravel layers of the pavement and should be able to operate in a temperature range between minus 10 to 100 °C. The components that cannot tolerate high temperatures should therefore be placed in the gravel layer.

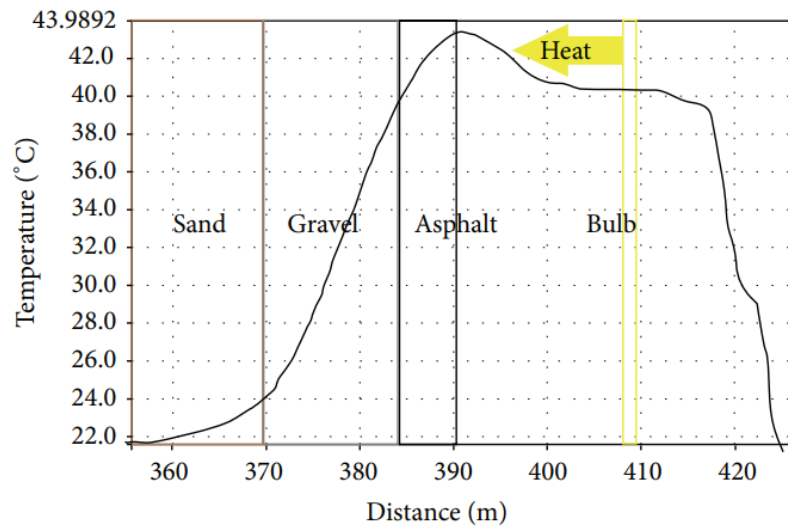


Figure 2-18: The heat distribution in the different layers of the pavement structure [25]

2.5 Power Management in Low-Energy Applications

Figure 2-19 below shows the various techniques that can be used to implement a power management solution. The two main categories are, Energy Provision such as energy harvesting techniques, and Energy Consumption techniques which aim to regulate the consumption of node to reduce the energy demand.

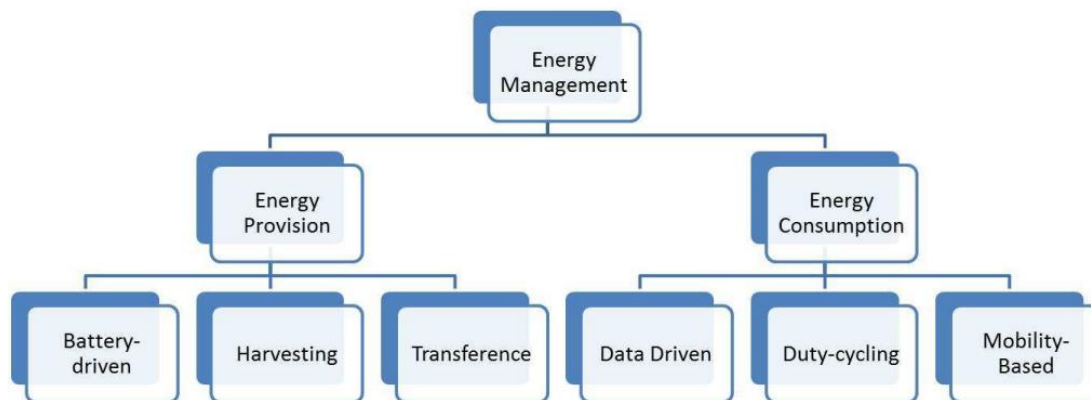


Figure 2-19: The categories of power management [35]

Energy provision utilises external components to supply power to the system, such as rechargeable batteries or a solar panel. In effect, this does not save any energy but only adds a source for it. Energy consumption on the other hand uses software techniques to either reduce the data that needs to be processed and transmitted or cycles the node between sleep and active states to ensure that energy is saved when the node is not actively handling any data. The next section gives an example of such an approach.

2.5.1 Calculating Regulator Efficiency

The efficiency of the regulator used in the power supply is vital since it greatly affects how much energy the device uses. A simple calculation can be used to assess a low-dropout (LDO) regulator's efficiency. If the battery outputs an input voltage (V_{in}) to the regulator of 4.2V, with a desired output voltage (V_{out}) of 3.3V and a current (I) of 500 mA flowing through it, the power dissipation can be calculated as in equations 3 and 4.

$$P_{dis} = (V_{in} - V_{out}) * I \quad (3)$$

$$P_{dis} = (4.2 \text{ V} - 3.3 \text{ V}) * 0.5 \text{ A} = 0.450 \text{ W}$$

The efficiency is then calculated as:

$$E_{ff} = (V_{out} / V_{in}) * 100 \quad (4)$$

$$E_{ff} = (3.3 \text{ V} / 4.2 \text{ V}) * 100 = 79 \%$$

2.5.2 Traffic flow during the day

An important aspect in power management is the sampling intervals of the sensors. A higher duty-cycle drains the battery rapidly, while a lower duty-cycle should conserve more energy. Therefore, considering the traffic volumes throughout a day, the sampling intervals may be adjusted according to the level of traffic at that time. Figure 2-20 and 2-21 below shows a typical example of congestion levels in Johannesburg throughout the day. As can be seen in the figure, congestion levels reach a peak between 6am and 9am and again between 3pm and 6pm, referred to as the “morning rush” and “evening rush”, respectively. Increasing the sampling intervals during these times should enable higher resolution data which effectively increases the accuracy of estimations.

What information is needed to implement such an approach:

- Real-time traffic flow data
- Location data
- Time information (yy:mm:dd:hh:mm:ss)

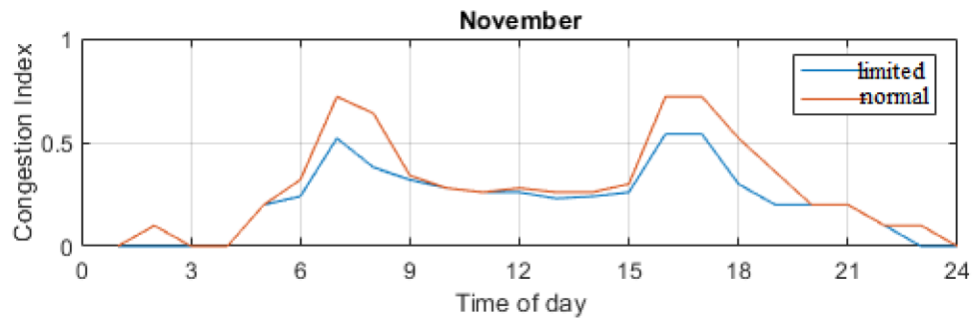


Figure 2-20: Traffic volumes during the day [31]

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
12:00 AM	1%	0%	0%	0%	0%	0%	1%
	0%	0%	0%	0%	0%	0%	0%
02:00 AM	0%	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%	0%
04:00 AM	0%	0%	0%	0%	0%	0%	0%
	0%	5%	4%	4%	3%	3%	0%
06:00 AM	1%	47%	45%	44%	43%	39%	1%
	2%	73%	69%	68%	67%	61%	5%
08:00 AM	4%	55%	50%	48%	49%	44%	8%
	7%	27%	27%	26%	28%	25%	12%
10:00 AM	8%	18%	19%	20%	21%	21%	15%
	10%	18%	19%	21%	22%	23%	17%
12:00 PM	11%	18%	20%	22%	23%	27%	19%
	9%	19%	21%	23%	24%	30%	18%
02:00 PM	8%	20%	22%	23%	26%	33%	15%
	7%	32%	35%	35%	39%	48%	12%
04:00 PM	7%	61%	63%	62%	65%	65%	10%
	8%	67%	67%	67%	67%	53%	10%
06:00 PM	8%	36%	34%	36%	36%	29%	11%
	7%	12%	12%	14%	15%	16%	10%
08:00 PM	4%	5%	5%	6%	7%	9%	7%
	2%	3%	2%	3%	4%	6%	5%
10:00 PM	0%	1%	0%	1%	2%	5%	4%
	0%	0%	0%	0%	0%	3%	3%

Figure 2-21: Congestion levels as a percentage during specific times of the day [31]

2.5.3 Duty-Cycling

Duty-cycling is an effective technique to reduce the overall energy consumption of a node by periodically switching between active and sleep modes. Some of the methods used to implement duty-cycling are [35]:

- Fixed Duty-cycle – The time that the node is active or asleep is fixed between a set interval. As an example, the node is actively handling data for 1 minute and asleep for the next 30 minutes. This method is effective but cannot adapt to a change in operating environments, for example traffic volumes as discussed above.
- Adaptive Duty-cycle – An adaptive duty-cycle provisions for changes in operational cycle of the node. It uses smart algorithms to adjust the duty-cycle based on a set of needs. For example, if the solar energy provision is limited by weather conditions, the duty-cycle can be lowered to accommodate for such days. This is explained further in the section below.
- Scheduling – A set schedule is followed that determines when a node should be active and when to be asleep. The schedule can be based on network traffic patterns etc.
- Wake-up techniques – The node uses a low-power technique to listen for incoming packets which wakes the node to perform a certain task. For the remainder of the time, the node is in the sleep mode.

Adaptive Duty-Cycling

Adaptive duty-cycling allows for an intelligent operation and control of the node's power consumption i.e., smart energy management. There are several techniques used for adaptive duty-cycling such as:

- Thresholding – A defined threshold value is used to adjust the duty cycle of the node. If for example, traffic volumes are higher than a certain threshold, the duty cycle can be increased to allow for data with higher accuracy.
- Fuzzy Logic – Fuzzy logic can handle imprecise input data to determine a certain output value. This technique is simple to implement and can take a range of input variables such as battery level, harvested energy, predicted energy consumption, to determine the duty cycle of the node.
- Prediction-based – Historical data is used to make a prediction on certain variables which can be used to adjust the duty cycle. However, this technique can be difficult to implement on an MCU with limited computational resources.

To implement an intelligent energy management algorithm, the energy models of the system need to be identified.

2.5.4 Energy models

In this section energy consumption and energy harvesting models are presented. For estimating energy consumption, the parameters proposed by [36] is to be used.

A node in a WSN typically has four main sub-systems, namely the processing sub-system, communication sub-system, sensor sub-system, and the power-supply sub-system. Modelling the energy consumption in each sub-system is needed to provide an accurate estimation of the overall energy consumption of the node. A model for energy consumption in each subsystem during different states is presented.

2.5.4.1 Processing Consumption Model (PCM)

The microprocessor is responsible for controlling the operations of the node, which include data capturing, processing, and transmitting. During operations, the controller needs to function in one of three states: active (running), idle, and sleep as seen in Figure 2-22 below.

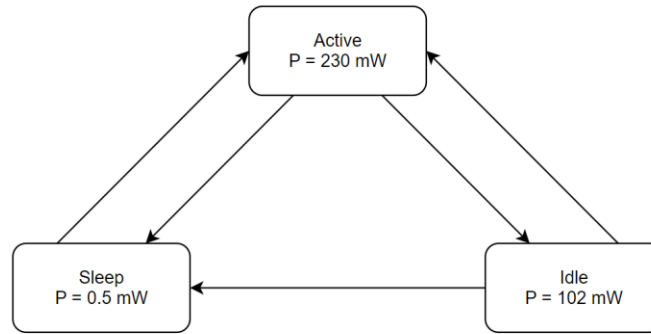


Figure 2-22: The processing consumption flow

The energy consumption of the controller can then be modelled as:

$$E_{uC} = E_{uC-state} + E_{state-change} \quad (5)$$

Where E_{uC} is the energy consumption of the controller, $E_{uC-state}$ is the energy consumption in each state of the controller, and $E_{state-change}$ is the energy consumption at state changes. This formula can be decomposed to include the power usage and time in each state.

$$E_{uC} = \sum_{i=1}^n P_{uC-state(i)} t_{uC-state(i)} + \sum_{j=1}^z n_{state-change(j)} \omega_{state-change(j)} \quad (6)$$

Where i is the state of the microcontroller which ranges from $i = 1, 2, \dots, n$, ($n=3$) and j is the transition type which ranges from 1 to z transitions. $P_{uC-state(i)}$ is power at state i of the controller and is found through measurements. $t_{uC-state(i)}$ is the time interval that the controller spends in state i and is dependent on the system requirements. $n_{state-change(j)}$ is the speed at which the state changes and $\omega_{state-change(j)}$ is the energy consumed when the state changes. According [36], the energy required for state transitions is very small and even negligible. Therefore, the state transition energy consumption will be omitted in equations 7 through 9 to simplify the model.

2.5.4.2 Transceiver Consumption Model (TCM)

The LoRa transceiver module is responsible for transmitting processed sensor data and receiving operating commands from the node head/gateway. The transceiver functions in one of five states namely, transmit, receive, off, sleep, and idle. Like the microcontroller energy consumption model, the transceiver's energy consumption is determined by the sum of energy consumption in each state and during state transitions. The equation below illustrates this relationship.

$$E_{tr} = E_{tr-state} + E_{state-change} \quad (7)$$

Where E_{tr} is the energy consumption of the transceiver, $E_{tr-state}$ is the energy consumption in each state, and $E_{state-change}$ is the energy consumption upon state transition. Once again, the negligible consumption on state transitions to be ignored to simplify calculations. The energy consumption in each state can be expressed as:

$$\begin{aligned} E_{tr-state} &= E_{tx} + E_{rx} + E_{slp} + E_{idle} \\ &= \sum_{i=1}^{n_{tx}} \frac{P_{tx} l_i}{R} + \sum_{i=1}^{n_{rx}} \frac{P_{rx} l_i}{R} + P_{slp} t_{slp} + P_{idle} t_{idle} \\ &= \sum_{i=1}^{n_{tx}} \frac{10^{(P_{tx}-L_{dB})} l_i}{1000R} + \sum_{i=1}^{n_{rx}} \frac{10^{(P_{rx}-L_{dB})} l_i}{1000R} \\ &\quad + V_t (I_{slp} t_{slp} + I_{idle} t_{idle}) \end{aligned} \quad (8)$$

Where $E_{tx}, E_{rx}, E_{slp}, E_{idle}$ are the energy consumption in each state. n_{tx} is the total number of packets of length l_i to be transmitted or received, R is the data rate of the transceiver, L_{dB} is the energy lost due to path loss, and P_x is the power of the transceiver (in dBm) in each state x . Furthermore, V_t and I_x is the operating voltage of the transceiver and the current of the transceiver in state x for time duration t_x , respectively.

2.5.4.3 Sensing Consumption Model (SCM)

The sensing consumption model provides a function that models the energy consumption of each sensor in the node. The node's sensing function is event-driven, meaning that a certain event will trigger the node to enter the sensing mode. In this paper, two event categories are utilized. The first is Periodic events, for example, the temperature of the pavement is sampled at hourly intervals. The second is Sporadic events in which an external trigger causes an event to occur, for example, a vehicle causes excessive pavement vibrations, triggering the accelerometer to start sampling. A sensor can operate in one of two states, namely, on and off. The energy consumption in each state is assumed to be constant and is given by the following formula.

$$\begin{aligned} E_{sen} &= \sum_{i=1}^s E_{on(s)} \\ &= \sum_{i=1}^s V_{sen(s)} I_{sen(s)} t_{sen(s)} \end{aligned} \quad (9)$$

Where V_{sen} and I_{sen} are the operating voltage and current of the sensor, and t_{sen} is the time that the sensor is active. s is the number of sensors connected to the in-road sensor device.

2.5.4.4 Combined Energy Model

Practically, the overall energy consumption of the node in the WSN cannot be assessed by considering the components individually. There is an interdependency in the energy consumption models of the components. In other words, the controller's energy consumption is intricately linked to both the sensing module and the transceiver module's energy consumption, and vice versa. Thus, it is crucial to consider the interdependencies among the different components of the system. Refer to Figure 2-23 below for a visual representation of the diverse relationships among these components. Table 2-6 categorizes the events and the target components that trigger the event.

- In the Processing Energy Model, the idle state is entered upon wake-up. The controller enters the “active” state under three events: an internally triggered periodic sampling event, for example hourly temperature readings, external interrupt event caused by the sensing module, and a packet transmission event triggered by the internal timers of the controller. The “sleep” state is activated based on an internal periodic interrupt event.
- The Transceiver Consumption Model transitions from states based on the events triggered by the control unit and data reception sources.
- The Sensing Consumption Model has two states: The “on” state can either be activated by a sampling request from the PCM or by an external event triggered by the environment, for example, excessive vibration levels. The sensors enter the “off” state when triggered by the PCM.

Table 2-6: Process flow and trigger events

Component	State	Trigger Event	Event Source
PCM	Idle	Wake-up Timer	Internal
	Active	Periodic Sampling, External Interrupt, Periodic Transmission, Data Reception	Internal, SCM, Internal, TCM
	Sleep	Periodic Interrupt	Internal
TCM	Idle	Default	Internal
	Off	External Event	PCM
	Transmit	Periodic Transmission	PCM
	Receive	External Packet Arrival	External
	Sleep	External Event	PCM
SCM	On	Sampling request, External Event	PCM, Environment
	Off	External Event	PCM

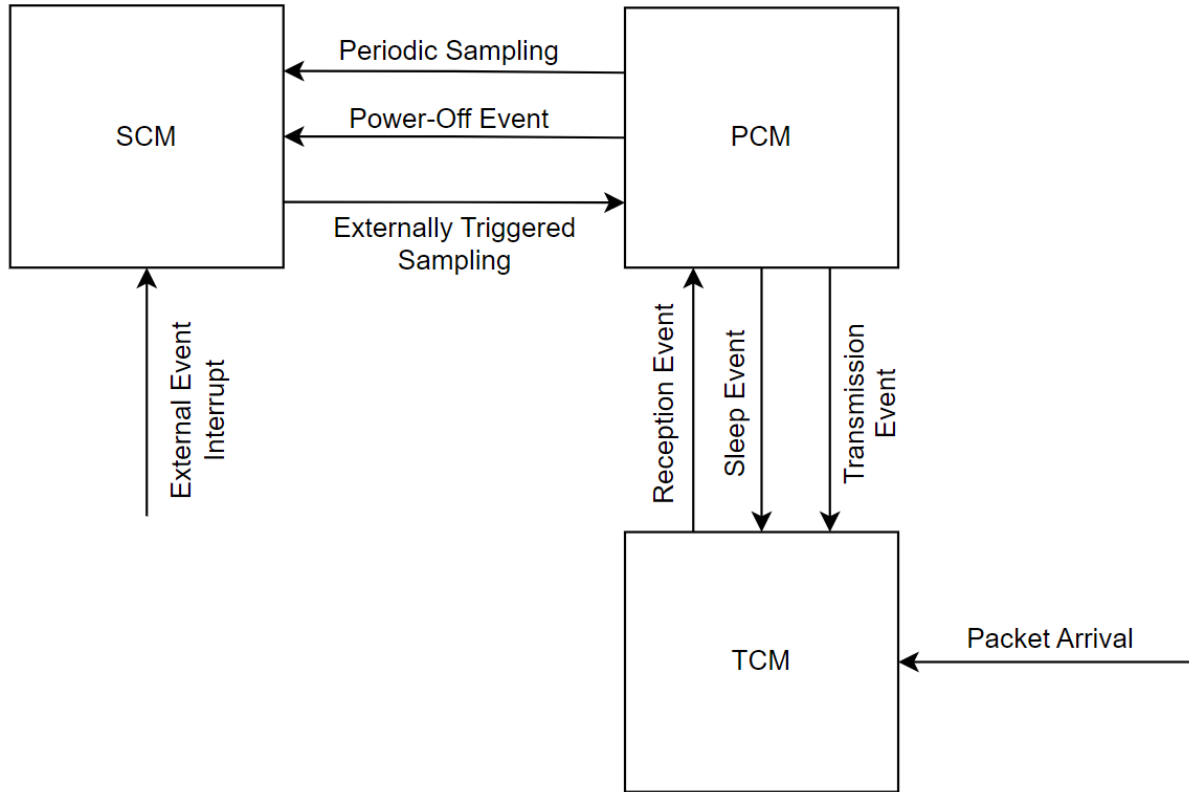


Figure 2-23: The events that trigger the processes of the system

2.6 A Network Architecture for Large-Scale Sensor Deployment

The network architecture models the link between the individual sensor – placed in the road – to the end-user who processes the information. This is also known as a Sensor Network. Figure 2-24 below shows a Wireless Sensor Network (WSN) [6]. The Sensor Network consists of sensors, computational units, and communication media to serve in recording, detecting, and responding to an event. These networks can be used for surveillance, data collection, and remote monitoring. Typical requirements when designing a networked sensor include a small form factor, low power, and robustness [17]. Its individual components are discussed in the next few sections. To start off with, it is important to define a sensor.

A sensor serves as a device that collects information about a physical environment or process, transforming it into an electrical signal for subsequent processing and analysis. Constituting the physical layer of the network, sensors interact with the physical environment. However, the question arises: How do these sensors convey their readings to the higher levels of operations?

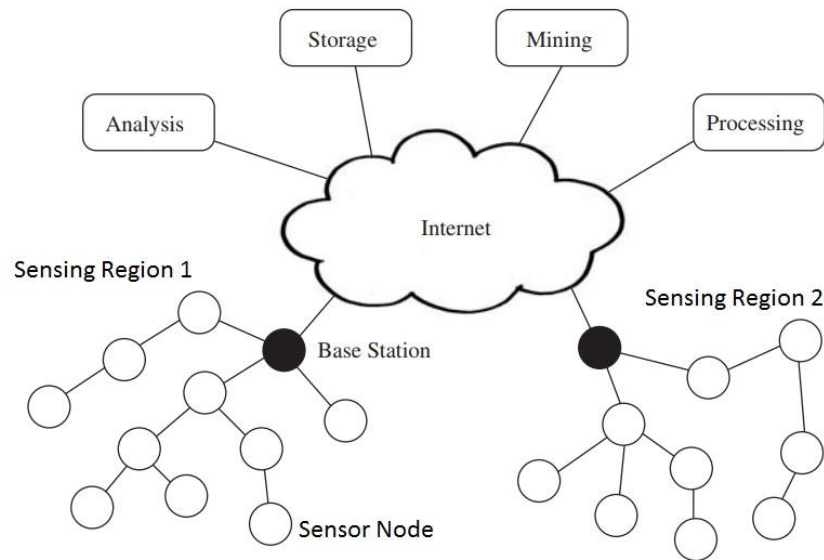


Figure 2-24: WSN architecture [6]

2.6.1 Wireless Sensor Network

When a Sensor Network employs a wireless protocol for its communication link, it is termed a Wireless Sensor Network (WSN). These networks capitalize on the latest advancements in Micro Electronic Mechanical Systems (MEMS) sensors and wireless communication protocols. This enables the cost-effective deployment of low-power sensors over a vast area, interconnected through wireless links and the internet, enhancing accessibility and control [6, 11].

A wireless sensor network (WSN) has several advantages over the traditional methods of data acquisition. Traditional methods rely on trained technicians to manually measure and collect data with expensive measurement devices. This also limits the reliability of data since only specific locations are monitored at a time. With a wireless sensor network, the component cost is significantly reduced by using inexpensive sensors. With these sensors, it is possible to distribute the network over a wide area, which increases the coverage of the system. Furthermore, a WSN allows real-time and continuous monitoring to allow predictive maintenance possibilities. How do these networks achieve this?

2.6.2 Elements of a WSN

There are two main aspects of a wireless sensor network. These are:

- Sensor subsystem
- Network architecture

2.6.2.1 Sensor Node Subsystem

The sensor subsystem node consists of various components, such as the power supply, sensor, microcontroller, and communication unit. Figure 2-25 below shows a block diagram of a sensor node. The process starts with a sensor that collects analog data from its environment. The data is then passed to the analog-to-digital converter (ADC) which converts it to a digital signal. The microcontroller processes and manipulates the data to reveal the information hidden in it. The node then stores and/or communicates the data to the base station.

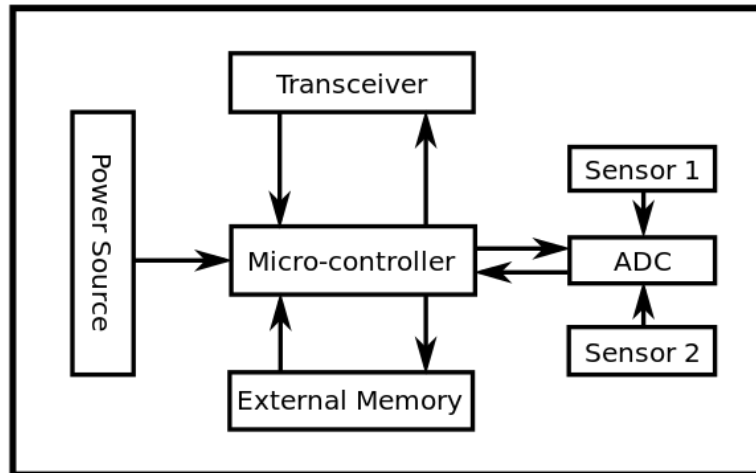


Figure 2-25: The physical architecture of a node device [6]

2.6.2.2 Network Architecture

Choosing the relevant sensor to be used in a WSN is an important task. An equally important aspect is the design of the network which connects the nodes and allows them to co-operatively collect data. The wireless network enables the sensors to communicate with one another as well as with the base station. The base station is responsible for sending commands to the sensor and receiving data in return. It also serves as a gateway to other networks connected through the internet, enabling it to send information to the end-user.

A project done in [12] aimed to create a Wireless Active Guardrail System using a WSN. The network topology consisted of a hierarchical architecture. In this structure, clusters of nodes are formed which communicate with a higher-layer cluster head node, which in turn relay data to the gateway node. This method reduces the time-delay between data sent compared to a flat architecture. In a flat network architecture, the base station sends a command to all nodes and only the node with a matching query responds using a multi-hop path through its peer nodes [6]. These architectures can be established by using different topologies, as discussed in the next section.

2.6.3 Different network topologies

In the sensing subsystem, sensor nodes acquire information relative to traffic and the state of the road. For different applications of WSN-based ITS, various network topologies are available which determine the lifetime, cost, and functionality of the system. In this section the distribution of information focuses on the link between nodes in a block and is restricted to local areas. A survey done in [13] compared the various network topologies for a near-road ITS:

2.6.3.1 Mesh Network Topology

In a mesh network, there exists no central point of connection. The nodes in this topology connect directly and non-hierarchically to neighbouring nodes. The node serves to route data to a final/destination node. These networks are self-forming and fault-tolerant and can perform many-to-one and one-to-many communication. Consequently, they are suited for grid-based applications such as parking lot sensing [14]. Figure 2-26 displays this topology.

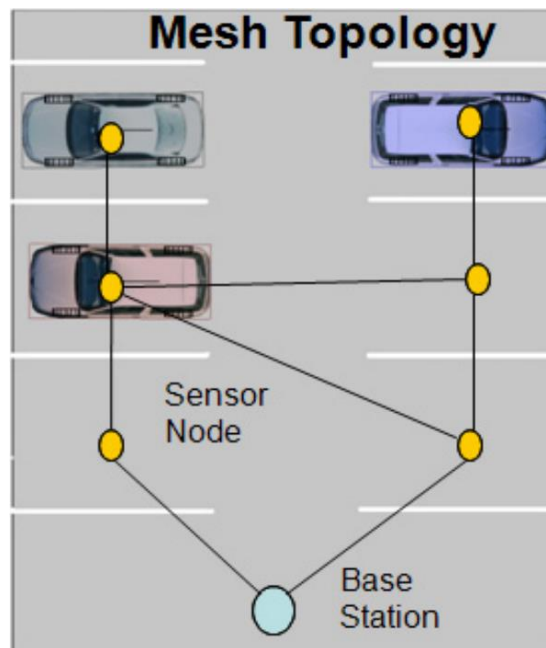


Figure 2-26: Mesh network topology [14]

2.6.3.2 Linear/ String Topology

In this configuration, static nodes are aligned parallel to the road, markedly simplifying the system's complexity as each node is restricted to forwarding data in only two directions. This facilitates point-to-point communication between nodes, following a one-dimensional routing policy. There are various alternatives to this topology – uniform string or the cluster string – which have their respective advantages. The uniform string nodes use the same hardware and perform equal tasks. With the cluster

string, a cluster head node is implemented to perform more resource demanding tasks, allowing a reduction in cost [14]. This alternative allows communication between different clusters and activation of a sleeping node upon vehicle detection as discussed in the next section. Figure 2-27 displays this topology.

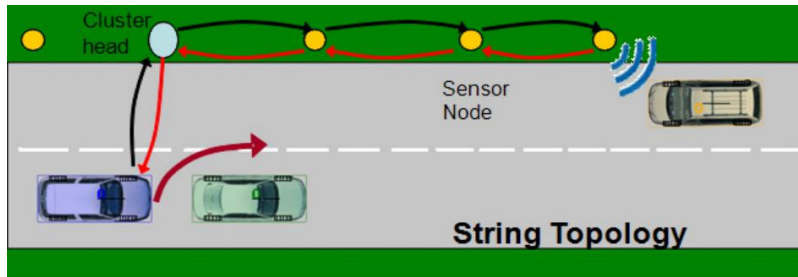


Figure 2-27: Linear/String network topology [14]

2.6.3.3 Star Topology

The star topology uses a central sink node together with sensor nodes and avoids complex routing in order to preserve energy. A consideration in this topology is to implement bi-directional or unidirectional communication. Unidirectional communication offers additional power-savings since nodes do not have to listen for incoming messages [14]. One disadvantage of this topology is the limited communication range of the sink node, which limits the placement of sensor nodes. Figure 2-28 displays this topology.

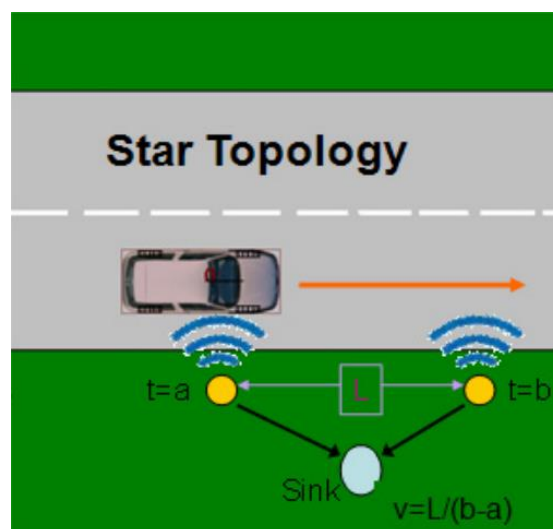


Figure 2-28: Star network topology [14]

2.6.3.4 Barrier Topology

The barrier topology is a common architecture found in in-road sensing. Several nodes are placed across the road, one per lane, in a straight line. It is similar to the star topology but is useful in sensing characteristics of individual vehicles in a lane. It can be combined with the cluster topology to use cluster heads as communication managers. Figure 2-29 displays this topology.

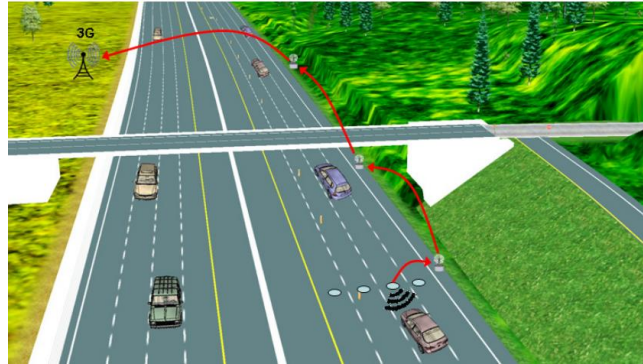


Figure 2-29: Barrier network topology [14]

2.6.4 Choosing a wireless network protocol

Choosing the best suited wireless network protocol is mainly determined by the environment in which the system needs to operate. By first defining the actual environment, the selection process needs to identify the best candidate and reduce the risk for expensive re-development.

As previously mentioned, the sensor node consists of three components, the power supply subsystem, sensing subsystem, and the communication subsystem. According to literature, the communication subsystem or more specifically the data transmission consumes significantly more power compared to the processing and sensing systems. Therefore, in order to design a low-power wireless sensor node, focus should be directed towards a power efficient communication subsystem.

Various enabling techniques exist to conserve energy during data transmission, as discussed by Anastasi's in [8]. This includes duty cycling, data-driven approaches, and mobility.

- **Duty cycling** – The main function of duty cycling is to eliminate network redundancy and increase the network longevity, and to periodically place a node in sleep mode to reduce the energy dissipation [9]. This technique minimizes the number of active nodes. An often-employed connectivity-driven protocol for Wireless Sensor Networks (WSN) is the Adaptive Self-Configuring Sensor Network Topologies (ASCENT). In this protocol, each node assesses the network capacity using locally gathered information on connectivity and packet loss. Subsequently, it makes a decision to either join the network or remain in a sleep state [9].

- **Data-driven** – The data-driven approach models the system to predict data instead of using sensed data. This approach is useful when the sensor subsystem consumes a significant amount of energy. It focuses to reduce the number of data acquisitions by excluding unneeded samples [9].
- **Mobility** – A dense sensor network is required to ensure successful communication between two nodes. This can be improved by using mobile sensor nodes, which are fixed to vehicles or animals. Mobilizers can be used but increases the cost significantly. An example of mobility is seen in the M SParc LoRaWAN Sheep tracking [10].

2.6.5 Technologies used in WSN

The three main wireless protocols used in a WSN are Wi-Fi, Bluetooth, ZigBee, and LoRaWAN [11, 28, 42, 43]. Wi-Fi provides excellent speed and data exchange but is a power-hungry protocol. On the other hand, Bluetooth or BLE, has a high data rate, low power dissipation but a much shorter range. In contrast, ZigBee provides a low-power protocol with a long range of communication. However, it suffers from a low data rate. Table 2-7 below compares the four sensor technologies.

Table 2-7: Communication technologies of a WSN

	Bluetooth Energy (BLE)	Low	Zigbee	Wi-Fi	LoRaWAN
Data Rate	1 – 3 Mbps		20 – 250 kbps	54 Mbps	37.5 – 62.5 kbps
Frequency band	2.4 GHz		868/915 MHz, 2.4 GHz	2.4 GHz, 5 GHz	400 – 915 MHz
Cost	Low		High	Low	Low
Range	10 m		100 m	100 m	10 km
Risk of data collision	High		Medium	-	-
Maximum number of nodes	8		> 65 000	2 007	1 000
Power efficiency	Acceptable to Good		Excellent	Bad	Excellent

Considering the power-hungry nature of Wi-Fi and Bluetooth technologies, another protocol that is used for low-power applications is needed.

Another available technology that is widely used in the field of wireless sensor networks is LoRa [42, 43]. LoRa is a newer communication protocol that uses RF technology to enable long range, low-power communication. This is especially useful when designing a WSN which requires nodes that have limited battery capacity. With a long communication range, less network infrastructure is required to construct the WSN, decreasing the cost and time associated with its setup.

This technology is used in a study done by Botero-Valencia et al. [15] which focusses on the design of a sensor node to measure various environmental variables such as $PM_{2.5}$, gas, electromagnetic radiation, and inertial sensors. Another challenge faced in the implementation of WSNs is the abundance of data generated in the nodes of the network. The huge amount of data needs to be transmitted, processed, and stored which places a heftier demand on the resources required for these tasks. [15] tackles this challenge by employing techniques such as dynamic subsampling, combining data from various sensors through data fusion, and implementing data scaling as techniques for data reduction. The main advantages of data reduction according to [15] are:

- Saving Energy
- Reducing transmission time
- Reduce congestion
- Saving storage space

The data reduction method used in this study started by reading the sensor measurements. The output of the PM sensor specifically, has a high noise component and is identified as Gaussian noise. Therefore, a 1-D Kalman filter can be used to smooth the signal. This signal is then down sampled by using a threshold that only allows data with a significant change from the previous sample to be recorded. Thirdly, the data fusion technique provides correlated measurements from various sensors of the same measured variable and data scaling reduces the data to an expected range and remove irrelevant data [15].

Another Radio Frequency (RF) device that is widely used for IoT applications is the NRF24L01 module [44]. Like the LoRa protocol, it also features long-distance, low-power, and high sensitivity Frequency Shift Keying (FSK) wireless communication. It works on the 2.4 GHz band. Table 2-8 below compares this technology with the LoRa (470 MHz) and ZigBee devices.

Table 2-8: Comparing the RF devices

	LoRa (SX127x)	Zigbee (XBee)	NRF24L01
Data Rate	37.5 kbps	20 – 250 kbps	250 kbps - 2 Mbps
Frequency band	470 MHz	868/915 MHz, 2.4 GHz	2.4 GHz
Cost	Low	High	Low

Range	10 km	100 m	300 m
Receiver Sensitivity	-148 dBm	-85 dBm	-115 dBm
Power	30 dBm	20 dBm	-20 – 10 dBm
TX current	20 mA @ + 13 dBm	45 mA	12 mA
RX current	9.9 mA	31 mA	13 mA

Comparing the three technologies several things can be noted. The data-rate of the LoRa protocol is significantly lower than that of the other two technologies. However, the range is significantly increased with a higher receiver sensitivity. Comparing the cost of the technologies, the ZigBee technology is seen to be more expensive. As for the power consumption, the NRF24 and LoRa devices provide similar specifications, with ZigBee being the most power hungry.

Sources that review short-range radios such as ZigBee and NRF24 [42, 44] technologies states that they are most effective when used for industrial applications and indoor use since it requires proximity between enabled devices and a line of sight (LOS) connection. It is therefore not suitable for an in-road sensor. Projects such as IoT streetlight control uses LoraWAN technologies which suggests that LoRa is the preferred choice for deploying WSNs in relatively large areas.

2.7 Failure modes of the system

An important aspect in the design of a robust in-road sensing system is correctly identifying the failure modes thereof. According to [38], there are three categories of possible failure in a WSN:

- Software failures/ bugs
- Hardware failures
- Communication failures

Consequently, mitigation techniques can be implemented to ensure the reliable operation of the system. The possible failure modes of the system are listed below [37, 38]. These failure modes are specific to the system in question and may vary from system to system.

2.7.1 Failure Modes

1. **Battery:**

- **Failure/End-of-Life:** Once the battery reaches the end of its designed life, the battery might fail, leaving the system without power.
- **Deep discharge:** If the depth of discharge is high, permanent damage to the battery may occur.

2. **Solar Panel:**

- **Obstructed sunlight:** The polycarbonate plate may be covered by an object or stain and prevent sunlight from reaching the solar panel.

3. **Wireless communication:**
 - **Interference:** Interference from various sources can obstruct communication, which may lead to data loss.
 - **Obstruction:** Metallic objects that cover the sensor may impede communication to the client for a certain period.
4. **Environmental Factors:**
 - **Harsh Weather:** Extreme weather conditions may damage the device and/or affect its performance.
 - **Vandalism:** Tampering with or intentionally damaging the device may affect the functionality thereof.
5. **Mechanical Failure:**
 - **Structural Damage:** Vibrations and loading conditions from heavy traffic may affect the structural integrity of the device housing over time, ultimately leading to a damaged device.
6. **Sensors:**
 - **Sensor drift and calibration:** A gradual drift in sensor readings without frequent calibration may lead to inaccurate data.
7. **Software:**
 - **Software bugs:** Bugs and glitches in the software may result in system malfunctions, failures, and inaccurate processing.
8. **Storage:**
 - **Insufficient memory:** Faults in the communication subsystem, can lead to an overflow in data on the storage subsystem if left unmanaged.

2.7.2 Managing the failure modes

Table 2-9 below shows the mitigation techniques that can be followed to ensure that the fault is effectively dealt with, and the risk of total system failure is minimized.

Table 2-9: Mitigating the system failures

Failure Mode	Mitigation Technique
1. Battery Failure	- Planned battery replacement - Power management algorithms
2. Solar Panel Fault	- Routine maintenance and cleaning
3. Communication Interference	- Save data to the attached storage - Network Partitioning
4. Environmental conditions	- Frequent device maintenance and checkup
5. Mechanical Failure	- Routine maintenance/ adequate maintenance plan
6. Sensor Drift	- Scheduled re-calibration of sensors
7. Software Bugs	- Regular software updates/patches
8. Storage limits	- Regular software updates to efficiently manage memory allocation.

2.8 Design Questions

This section discusses various questions that need to be answered before the design of the system can commence since the results affect the overall design of the system.

How does power consumption compare between pre-processing data at the node level or transmitting short messages to the upper-level nodes?

According to Hill *et al.* [17], the energy spent to transmit and receive data is significantly more compared to processing and storing the data. This observation is also supported by findings in [7]. This is important since WSN tend to consist of nodes that have limited battery capacity, storage, and processing power. A method to calculate the power consumption in each case is presented in the following section: accounting for the specific hardware chosen for the application.

As an example, which is to be verified by practical experiments, the energy consumption under different processing stages is calculated. Table 2-10 shows the energy consumption of the ESP32, and Table 2-11, the energy consumption for the transmission of data. From the table it is evident that local processing and the transmission of fewer bytes result in the least amount of power usage (170 mJ). Comparing this to the energy usage when transmitting raw data to the sink (573 mJ), there is seen to be a significant increase in energy consumption.

Table 2-10: Energy consumption of the processor in different stages of processing

Processing Stage	No. of bytes	T_ESP (ms)	E_ESP (mJ)
Raw	241078	1.5	0.297
Pre-Process	30134	88	17.424
Labelling	458	463	91.674
Features	114	857	169.686

Table 2-11: Energy consumption of the communication device in different stages of processing

Processing Stage	No. of bytes (#)	T_LoRa (ms)	E_LoRa (mJ)
Raw	241078	3857.2	572.801
Pre-Process	30134	482.1	95.464
Labelling	458	7.3	1.450
Features	114	1.8	0.361

For transmitting short messages to an upper-level node, the system power consumption can be calculated as:

The maximum allowable duty cycle of the EU 868 ISM band is 1% using CSS then,

$$\text{Average Drain current} = 0.01(\text{active current}) + 0.99(\text{sleep current}) \quad (10)$$

$$\text{Average Drain current} = 0.01(I_{tx} + I_{rx} + I_{meas}) + 0.99(I_s)$$

Where I_{tx} is the current used when transmitting data, I_{rx} is the current used when receiving data, I_{meas} is the current when data is being acquired, and I_s is the current consumed when the device enters a sleep state.

Considering the specifications of the ESP32 MCU and the SX1276 Lora module, the average drain current can be calculated as follows:

$$\text{Average Drain current} = 0.01(105 + 12 + 60) + 0.99(17) \quad (11)$$

$$\text{Average Drain current} \approx 18.60 \text{ mA}$$

Say for example we choose a battery with a capacity of 2000 mAh, then the lifetime is around 108 hours which is just over 4 days.

Now if data is first pre-processed at the sensor node, less frequent communication has to take place, but the device would be active for a longer period. The duty cycle would therefore be significantly less for communication, but higher for data processing. Then the average drain current can be calculated as:

$$\text{Average Drain current} = 0.001(105 + 12) + 0.015(60) + 0.984(17)$$

$$\text{Average Drain current} \approx 17.74 \text{ mA}$$

Which would give 113 hours of battery life for the same capacity. Therefore, by first pre-processing the readings at the node level, the design should be more efficient in terms of power usage.

The energy consumption of individual components is shown in Figure 2-30 below. It shows the usage per night, when only battery power is available to power the sensory node. The table also shows the total energy required per day, as seen in the red block. Furthermore, the input from the solar panel is also calculated. The nightly drain from the battery is also calculated.

Component Energy Usage							
	Accelerometer (SEN-17871)	Humidity & Temperature	LoRa (SX1268)	RTC	SD	MC Sensor	ESP32 (@80MHz)
Run Current (mA)	0.239	1.500	105.000	0.200	100.000	0.450	30.500
Run Time (min)	1440.000	3.200	14.768	1440.000	4.003	0.000	1000.000
Standby Current (mA)	0.001	0.045	0.600	0.001	0.200	0.001	9.800
Standby Time (min)	0.000	1436.800	1425.232	0.000	1435.997	1440.000	440.000
Effective (avg) Current	0.239	0.048	1.671	0.200	0.477	0.001	24.175
Power (@ supply volt), 25C	0.789	0.159	5.513	0.660	1.576	0.003	79.778
Nightly Consumption	0.014	0.003	0.099	0.012	0.028	0.000	1.436
Daily Consumption	0.019	0.004	0.132	0.016	0.038	0.000	1.915
Total consumption/night							1.593
Total consumption/day							2.123
* Response times for sensors are obtained from the respective datasheets							
* LoRa Module on-time is determined by TOA for 100 Byte packet							
* 3 816 cycles per day according to 1% duty cycle limit (maximum)							

Figure 2-30: An example power consumption calculation of individual components in the in-road device.

The time on air for the LoRa device is calculated as shown in Figure 2-31 below. The Time on Air (ToA) is limited by regulations regarding the shared spectrum. At the default LoRa device settings, and with a 100-byte payload, the allowable transfers per day is limited to be around 5 046.

LoRa TOA Calculator		
Payload Size	100.0	Bytes
Preamble	8.0	Bytes
SF	7.0	(limits range to 2km)
BW	125.0	kHz
CR	1.0	
TOA	174.3	ms
Duty Cycle/Periodicity	17.0	1 msg every 17 sec
Allowable trans/day	5082.4	sec per day / DC
Allowable bytes/day	508235.3	Bytes
Buffered Data per node	508235.3	Bytes
Req trans/day	5082.4	
TOA/day	14.8	min

Figure 2-31: Time-on-air calculation example for a communication subsystem

Another important consideration is the solar production profile over the course of the day. This is to determine whether the node can be sustained for a longer period before the battery runs out. Figure 2-32 below shows the typical production profile for South Africa over the course of a day in summer as well as winter months. As can be expected a significant decrease in solar energy turnover is prevalent in winter months, with a 30% drop in production. This profile is associated with the 55 mm x 70 mm solar panel with a maximum output of 550 mW.

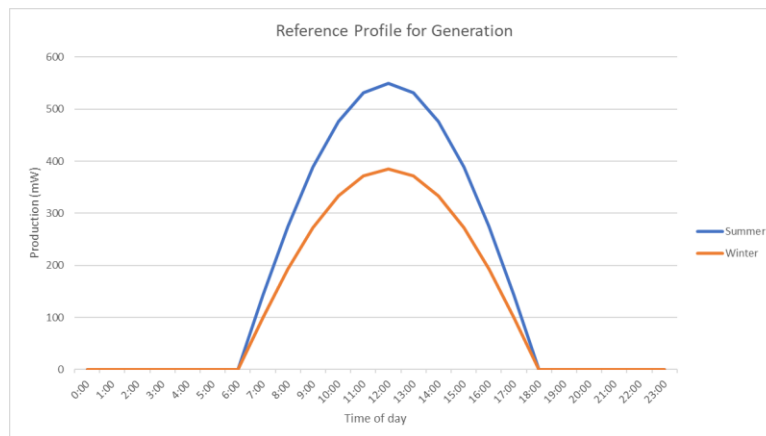


Figure 2-32: An example of a solar production profile in South Africa (-26.6745, 27.1035)

What should the spacing of the nodes be, considering the cost and vehicle population in different areas of the country?

The population density varies significantly between different regions. Urban regions have a higher population density compared to rural areas. This affects the distribution of nodes since air and noise pollution tend to be significantly higher in densely populated areas. More nodes are required in these regions which also have a dense road network and experience higher volumes of traffic. South Africa has a network of around 746 978 km of road. Furthermore, the assumption is made that the different road types used by SANRAL, reflect the traffic density in these areas. For example, dual-carriageways and 4-lane roads are used when high traffic volumes are present. 2-lane single roads are suited for less dense traffic. Table 2-12 below shows the SANRAL road network in kilometres for the different road types in 2018.

Table 2-12: SANRAL's road network [40]

Description	Non-Toll	Agency Toll	BOT	Total
Dual Carriageway	817	557	519	1 893
4-Lane Undivided	30	302	231	562
2-Lane Single	18 414	823	521	19 758
Total	19 262	1 681	1 271	22 214
% of SANRAL network	87%	7%	6%	

Table 2-13 below shows the spacing of nodes and the number of nodes required to saturate the SANRAL road network. The manufacturing cost of a single unit is estimated at R5 000.

Table 2-13: Sensor placement and cost (2022)

Description	Total Network (km)	Spacing (km)	# of nodes required (1 per lane)	Cost (R5000 per unit Installation inc.) (ZAR)
Dual Carriageway	1893	0.5	22716	R 113,580,000.00
4-Lane Undivided	562	1	2248	R 11,240,000.00
2-Lane Single	19758	2	19758	R 98,790,000.00
Total	22214	-	44722	R 223,610,000.00

The cost of the sensors per kilometre can be weighed against the cost to construct a road as seen in Table 2-14 below. The cost percentage that the sensors form in the total cost of a road is but a fraction of the price. It would therefore be a feasible option to deploy such a large scale WSN to continually report on the condition of the road.

Table 2-14: Comparison with new road construction per km (2022)

Description	Cost/km (ZAR)	Sensor cost/km (ZAR)	Percentage of total cost (%)
Dual Carriageway	R110,000,000.00	R60,000.00	0.054%
4-Lane Undivided	R 65,000,000.00	R20,000.00	0.030%
2-Lane Single	R 35,000,000.00	R 5,000.00	0.014%

* The cost/km is affected by terrain, number of interchanges, number of trucks, climate etc.

3 Preliminary Design and Technology Selection

During the engineering design process, it is important to carefully consider the characteristics of the system and the context in which the system exists. A good product is always the result of a well-structured design phase in which the context, requirements, functionality, architecture, and resources are carefully selected. This chapter discusses the context in which the system needs to exist to inform on the external influences that need to be considered. Thereafter, the functional flow of the system is given, outlining the functions to be performed to meet the requirements of the system. Finally, items should be selected that fulfil the functions of the system, creating the architecture thereof.

3.1 System Context

The context diagram of the in-road system is shown in Figure 3-1 below. The in-road sensor is to be installed in the first few layers of the pavement structure of a national roadway. Consequently, it will be exposed to several external devices, such as vehicles, the outdoor environment, vandals etc. which provide either important information to the system or oppose it. Each of these devices may affect the operation of the system and as a result needs to be considered in the design of the in-road sensor.

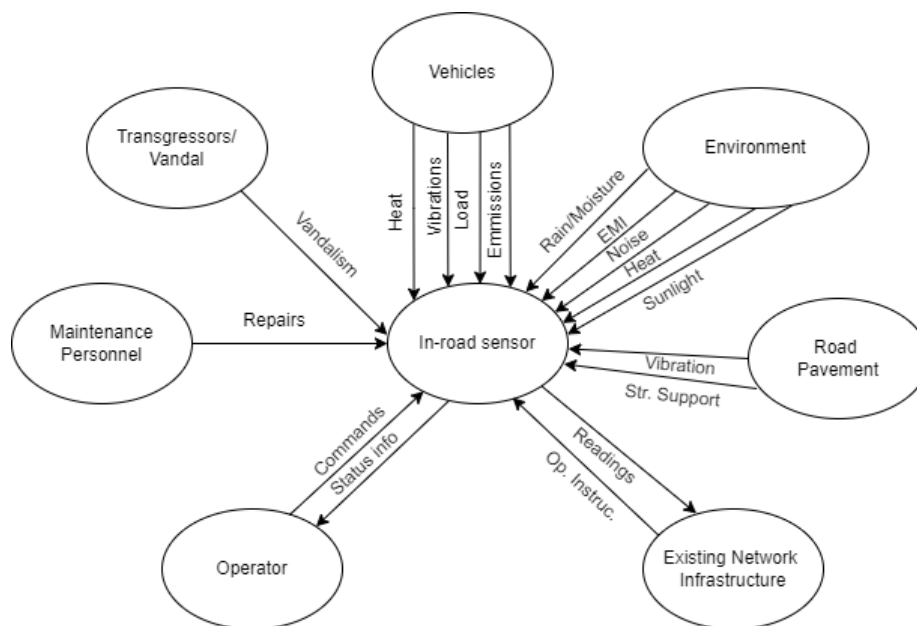


Figure 3-1: The System Context

3.2 System Functional Flow

Figure 3-2 below shows the lifecycle of the project. It starts off with the installation of the system, followed by the standard operation thereof. Once the system reaches a stage where it requires maintenance actions, a maintenance plan is followed to ensure minimal downtime. At the end of the project's lifecycle, it is decommissioned. This is the Level 0 lifecycle diagram.

Level 0

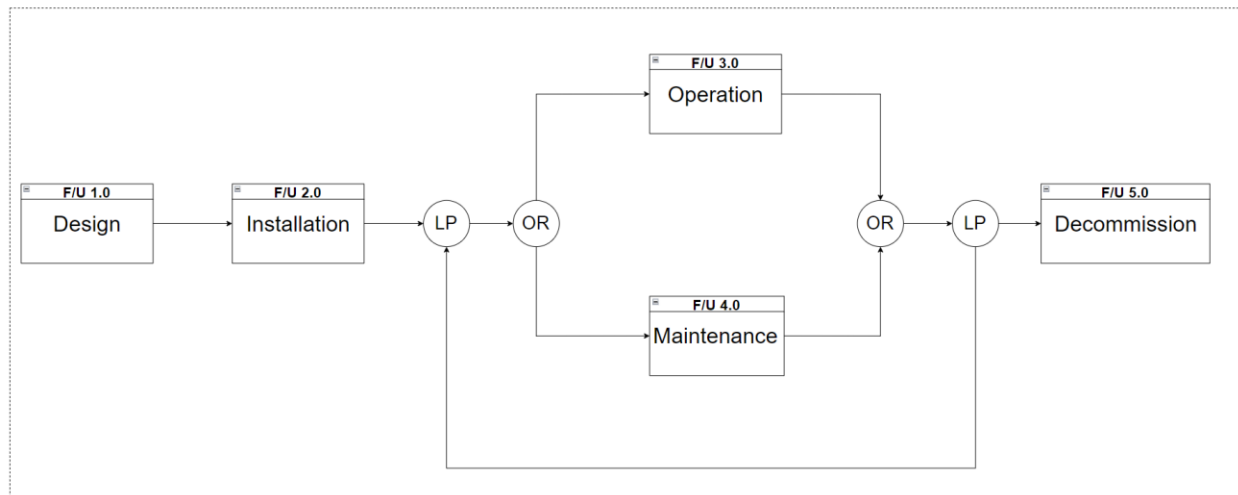


Figure 3-2: System Lifecycle (Level 0)

Isolating the operational phase of the product, Figure 3-3 represents the second level of the device's functionality. Firstly, a start-up procedure initiates the device by ensuring that all sensors are connected and readable, the communication link with the gateway is started, and all device configurations are applied. This is followed by the intake of sensor readings from the stack of available sensors. Thereafter, the data is processed and transmitted to the gateway. The upper-level control is to further process the data and display the information to the system operator. The operator will then be able to view and adjust certain system parameters from a remote interface. The device cycles through these stages until it is interrupted by an error source or shuts down.

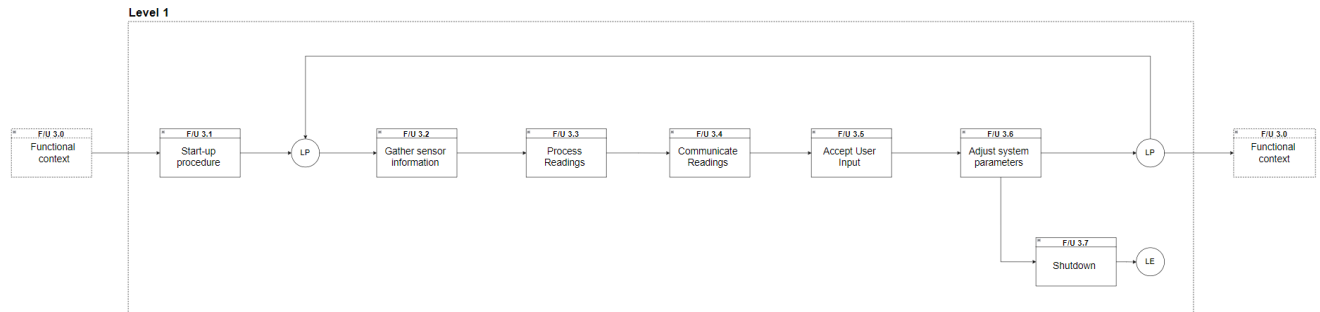


Figure 3-3: The functional context of the system (Level 1)

Further elaboration on some of the sub-phases are necessary to provide additional context to the system's operational cycle. Figure 3-4 below shows the context for functional unit 3.2 (F/U 3.2). The various sensing methods are shown in the first functional units. The pre-processing stage allows the data to be cropped significantly and reduces the demand on the storage and communication subsystems. In addition, the pre-processing stage is to provide the vehicle detection function that uses the vibrational data to accurately pinpoint the start- and end-events of a passing load.

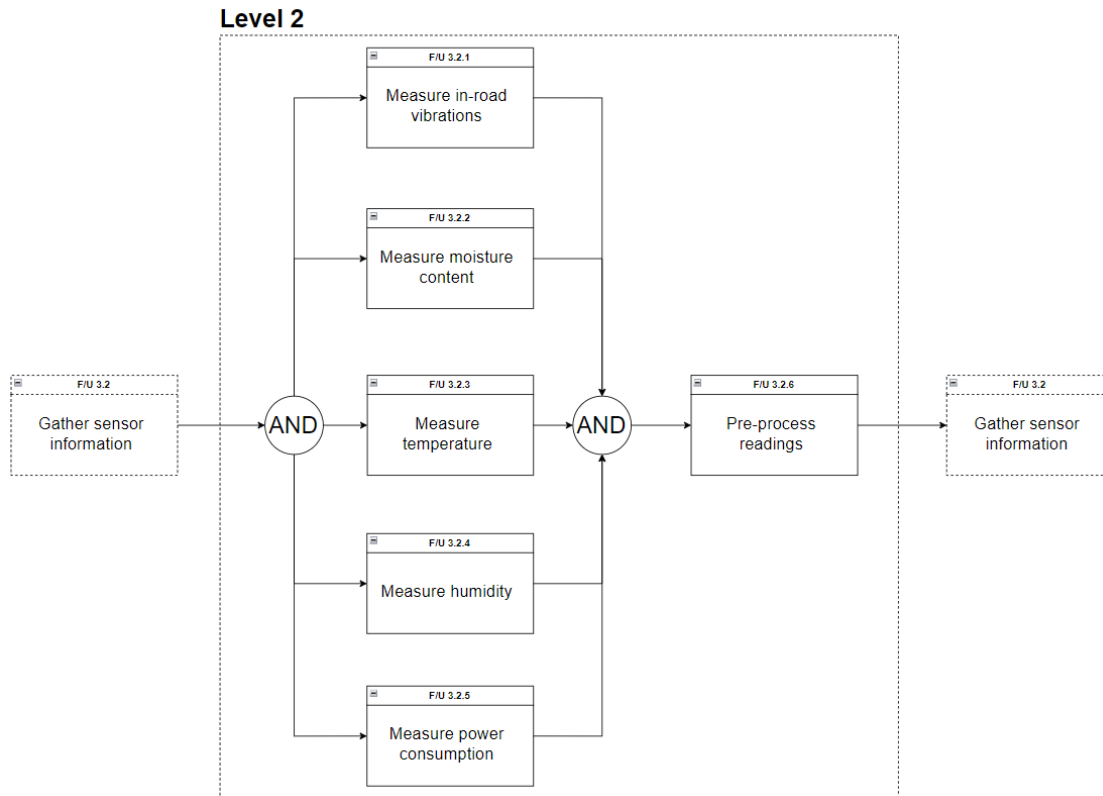


Figure 3-4: The sub-level functional flow (Level 2)

Another operational functional unit that can be expanded upon is the processing phase, as shown in Figure 3-5. In a practical setting, noise is always a part of the system and needs to be removed to increase the validity of the results. Furthermore, referring to the system context diagram in the figure above, several devices force additional parameters into the system, for example, the vibrational forces exerted by the engine of a vehicle. These additional components should be filtered from the raw data to improve the accuracy of the results.

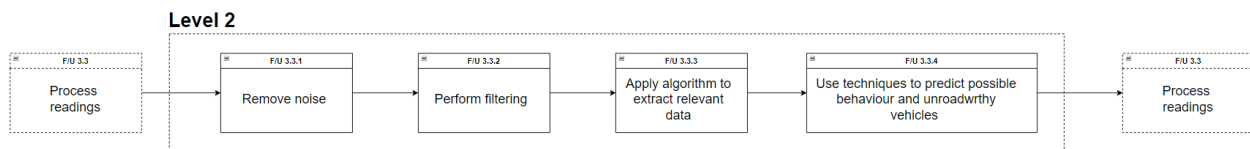


Figure 3-5: A sub-level functional flow (Level 2)

Now that the functional aspect of the system is known, resources can be selected to fulfil these functions. The next section covers the necessary components to meet the functional requirements of the system.

3.3 System Architecture

The system boundary provides the designer with a clear picture of what should be included in the specifications of the system. Figure 3-6 shows the boundary of the system together with the interfaces that connect it to the external components.

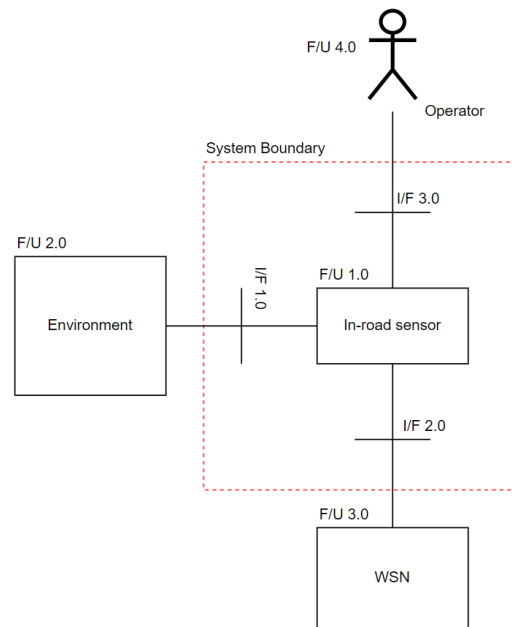


Figure 3-6: High level system architecture

The high-level system architecture is shown in Figure 3-7 below. The architecture contains all the components that should fulfil the functions identified in the previous section of this paper. The basic architecture of any electronic device consists of three main components: a microcontroller unit, a power-supply unit, and sensor sub-system. Additionally, a communication sub-system provides access to a device from a remote location. An important aspect to note is the interfaces that connect the various components. These should be chosen in accordance with the physical constraints of the system.

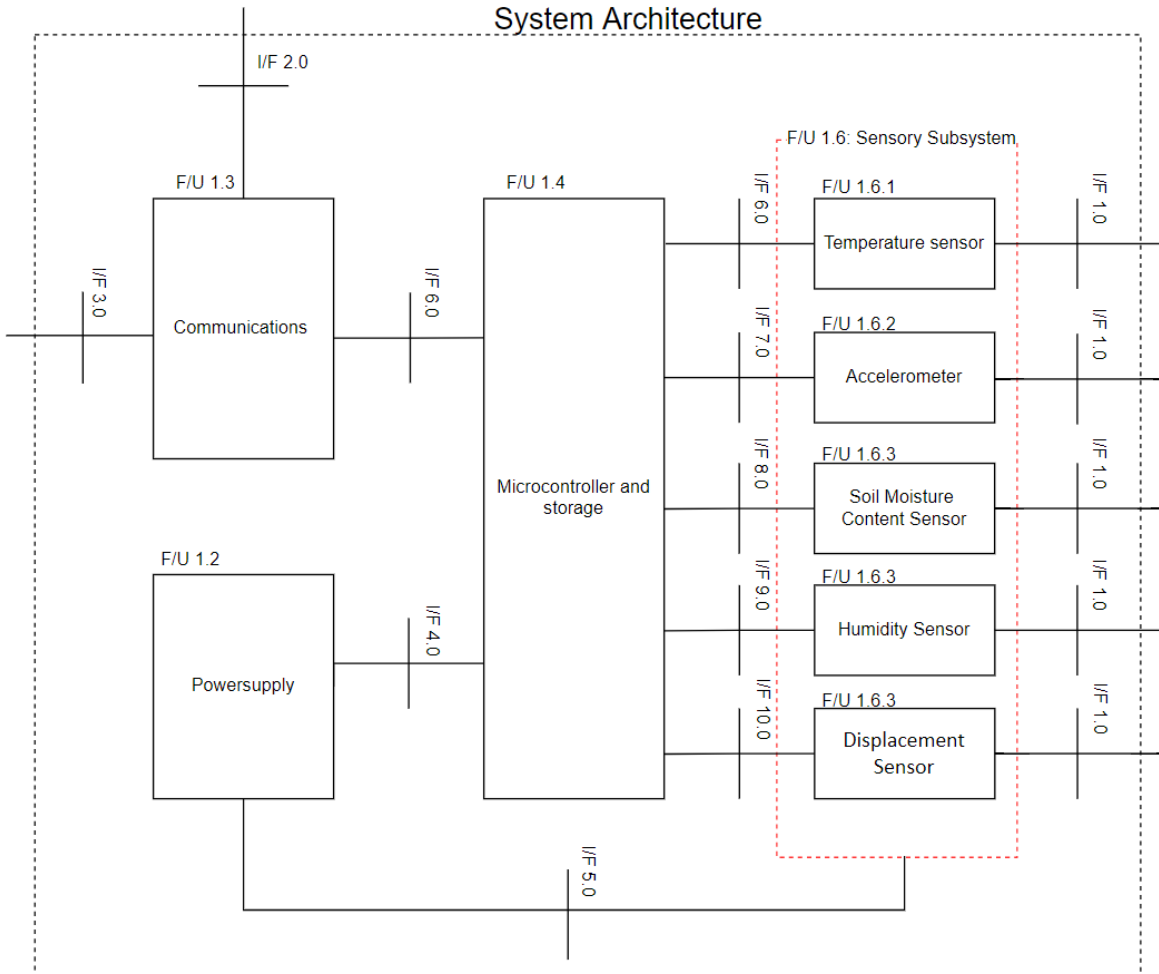


Figure 3-7: The full system architecture

3.4 Component Selection

The selection of components depends on several factors, such as insights gained from previous research, budgetary requirements, and availability of resources. Additionally, the environment is a significant factor that influences the components to be selected: with a harsh environment such as a roadway, attention should be given to the level of exposure of the electronic components to the elements. This means that environmental variables that can degrade the lifetime of the components, such as moisture, wind, heat, oxidation etc, need to be considered when designing the packaging of the in-road sensor to minimize exposure. i.e. hermetically sealed.

3.4.1 Sensor for Temperature and Humidity

Temperature and humidity sensors need to provide important information regarding the exposure of the road and the sensor to weather conditions. The next section compares various technologies in this regard.

3.4.1.1 Description

There are three main types of humidity sensors: Capacitive, Resistive, and Thermal. The capacitive type provides the ability to measure relative humidity over a wide range (0% to 100%) with minimal temperature effects. These sensors are also linear which means that the capacitance is directly proportional to the humidity in the environment. However, these sensors require a complex circuit and regular calibration [16]. In comparison, the resistive humidity sensor provides a low-cost option that does not require frequent calibration. The resistance of the conductive film decreases as the amount of absorbed moisture increases. Another advantage is that it can operate in remote sensing applications where there is a large gap between the sensing unit and the signalling circuit [16]. The third type of sensor is the thermal conductivity humidity sensor which uses two thermistors to estimate the absolute humidity. These sensors are suitable for harsh environments, are durable, and provide a higher resolution than other sensor types.

The SHT-31 weatherproof sensor from DFRobot is designed for measuring humidity and temperature, featuring a convenient I2C interface [45]. This factory-calibrated sensor offers a hassle-free "plug-and-play" experience, eliminating the need for additional components. While it excels in harsh environments, it is advisable to recalibrate it annually. The sensor, utilizing a capacitive design, accurately measures relative temperature and humidity. Additionally, it is equipped with a protective metal mesh encasing for weatherproofing.

3.4.1.2 Technical Information

Figure 3-8 shows the SHT-31.



Figure 3-8: SHT-31 [45]

The specifications of the device are as follows:

Table 3-1: SHT-31 Specifications

Specification	Value
Supply Voltage	3.3 V
Current Consumption	1.5mA
Standby Current	40 – 50 uA
Humidity range	0 – 100 % RH
Temperature Detection range	Minus 40 – 125 °C
Accuracy (Humidity)	± 2% RH
Accuracy (Temp)	± 0.5 °C

3.4.1.3 Selection Motivation

The first requirement of a sensor (to be used in an in-road unit) is its ability to operate in harsh environments. It therefore must be hermetically sealed.

Table 3-2 below compares various types of available weatherproof sensors according to several characteristics.

Table 3-2: Comparison of temperature and humidity sensors (2022)

	Parameters				
Sensors	Accuracy (%RH, °C)	Resolution (%RH, °C)	Cost (ZAR)	Repeatability (%RH, °C)	Response Time (s)
DHT22	±2, ±0.5	0.1, 0.1	R82.00	±1, ±0.2	0.001
SHT-31	±2, ±0.5	0.01, 0.015	R376,99	±0.15, ±0.1	2
AM2315C	±2, ±0.3	0.024, 0.01	R407,21	±0.1, ±0.1	8
HM1500LF	±3	0.4	R1 409,76	-	10

The DHT22 seems to provide the best option. However, its datasheet warns that it should not be used in dew conditions. Alternatively, the SHT-31 is suitable for harsh environments and has good accuracy, a

better resolution, better repeatability, and a reasonable response time but at a higher cost. Comparing the SHT-31 to the other pricier units, it appears to provide the best solution.

3.4.2 Sensor for Vibration Monitoring

The vibration sensor (accelerometer) is needed to provide information on the impact of vibrations caused by road traffic on the integrity of the road surface. This information can then be used to identify vehicles with abnormally high levels of vibration.

3.4.2.1 Description

There are various types of vibration sensors:

- Strain Gauge – The strain gauge offers an inexpensive option to measure vibrations based on a change in resistance. They can easily be applied to curved surfaces; however, they require additional expensive equipment to process the measurements.
- Accelerometer – The most popular solution for vibration sensing relies on measurements of the velocity change in a component. The piezoelectric type produces an electrical signal for vibrations over most frequencies. The piezoresistive type improves on the accuracy of piezoelectric sensors at high and low frequencies but is more costly.
- Eddy-Current – This sensor type uses changes in the magnetic field produced by vibrating objects to measure the level of vibration. They measure relative vibration and should be fixed in place. They are typically only used in laboratories.
- Laser Displacement – Like the eddy-current sensor, this is also a non-contact method and uses a laser beam with triangulation techniques to measure vibration. They work well with stationary objects but are not robust and tend to be quite expensive. They also do not measure vibrations in three dimensions.
- Acoustic pressure sensor – This sensor type measures the sound produced by high-frequency vibrations. These devices are inexpensive, but they provide limited information. They also can't detect changes in absolute vibration values but changes in vibration frequency.
- Geophones – These sensors use an analog signal to capture the velocity of movement. These sensors have long been used in the industry and is often seen as outdated. They provide very accurate results, however, require additional conditioning circuitry, measure only in one direction, are not readily available, and may be bulky compared to accelerometers. Their low resonance frequency (typically 3 – 4 Hz) may also interfere with pavement motion which typically appears in the lower range of the frequency spectrum.

The chosen KX132 from Kionix is a triple axis MEMS accelerometer with signal conditioned voltage outputs and provides extremely low noise and power consumption. It has a small footprint and a selectable bandwidth.

3.4.2.2 Technical Information

Figure 3-9 below shows the KX132 breakout board.

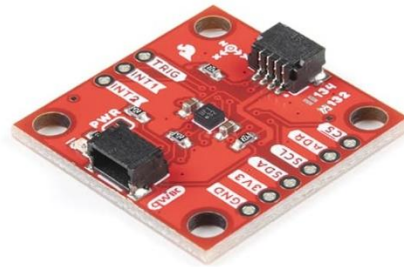


Figure 3-9: KX132 Accelerometer [46]

The specifications of the device are as follows:

Table 3-3: Specifications of the KX132

Specification	Value
Supply Voltage	3.3 V
Current Consumption	0.239mA
Impact resistance	10000 g
Range	$\pm 2 - \pm 16$ g
Operating Temperature	-40 – +105 °C
Sensitivity	16384 counts/g
Bandwidth	0.39Hz ~ 12.8kHz

3.4.2.3 Selection Motivation

The above review of sensor types can be used to narrow down the selection. The clear disadvantages of the strain gauge do not make it a feasible option. The clean environment that the eddy-current sensor requires, also removes it as a possible candidate. The high cost of laser displacement sensors removes it from the selection. The acoustic type only gives limited information on the level of vibration and is not considered in the selection. Furthermore, the geophone is highly accurate, but its resonance frequency may pose a problem later. The accelerometer is widely available and finds great applicability in the industry. What are the requirements of such a sensor?

Typical vibration levels experienced on road surfaces range from 0.5 – 2 m/s² [19]. Therefore, the chosen vibration sensor needs to have range from 0.05 g to 0.2 g. For such low-amplitude signals, the sensitivity of the accelerometer needs to be high. One of the most important requirements is the bandwidth or

frequency response of the sensor. The bandwidth needs to include the frequency of vibrations. For road vibrations, the important frequency content lies between 2 Hz and 30 Hz [26]. The speed of the passing vehicle is used to determine the required sampling rate. A sampling rate of more than 3kHz would be adequate to capture vibrations from a passing vehicle. The linearity is also important since the output must accurately reflect the actual vibration value with minimal error. Since the in-road sensor is powered by a battery, the current consumption must be limited. Measuring accelerations with small amplitudes becomes difficult when the noise floor is also high. Table 3-4 below shows a list of available sensors:

Table 3-4: Comparison of available accelerometers

Sensors	Parameters					
	Range (g)	Resolution (LSB/g)	Current Consumption (uA)	Cost (ZAR)	Noise performance (mg)	Bandwidth (Hz)
SEN-17871	± 2	16384	239	R184.44	0.7	0.5 – 4200 (X, Y) 0.5 – 2900 (Z)
MIKROE-4826	± 2	16384	70	R109.69	0.7 (X,Y) 1.3 (Z)	0.25 - 500
MMA7360LR2	± 1.5	860 mV/g	600	R95.30	350 μ g/VHz	400 (X,Y) 300 (Z)

The sensor specifications above give a good summary of the important features of an accelerometer. From the table above, the SEN-17871 (housing the KX132) shows to be the best option. It has an adequate range and a good noise performance. Its current consumption and cost are higher compared to the other options, however its Output Data Rate (ODR) compared to the MIKROE-4826 is better (25.6 kHz to 2 kHz respectively). The noise performance is also good, and the noise floor should not overcrowd measurement data.

3.4.3 Sensor for Communication

A LoRaWAN network offers great communication range, low-cost and most importantly, a low-power option for connecting several nodes in a large area [42, 43].

3.4.3.1 Description

The most common communication protocols and devices are discussed in Section 2.6.5 above and it was concluded that LoRaWAN would be best suited for the need considering its long range and low power consumption.

3.4.3.2 Technical Information

Figure 3-10 below shows the LoRa module used for the design.



Figure 3-10: The Ra-01H module housing the SX1276 LoRa chip [47]

The specifications of the device are as follows:

Table 3-5: Specifications of the SX1276

Specification	Value
Supply Voltage	3.3 V
Current Consumption	120 mA (TX) 11 mA (RX)
Data Rate	300 kbps
Power Output	19 dBm
Operating Temperature	minus 40 – +85 °C
Sensitivity	-140 dBm
Frequency	803 MHz ~ 930 MHz

3.4.3.3 Selection Motivation

The various option for the communication module is shown in Table 3-6 below.

Table 3-6: A comparison of available LoRa devices (2022)

	Parameters				
Sensors	TX Current (mA)	RX Current (mA)	Bitrate (kbps)	Cost (ZAR)	Sensitivity (dBm)
SX1276	120	10.8	37.5	R118.00	-148
SX1262	45	5.3	62.5	R178.00	-148
RFM95W	120	10.8	37.5	R98.00	-139

From the Table 3-6 above it is evident that the SX1276 and the RFM95W have similar specifications. However, the latter comes at a lower price point. The SX1276 is the first generation of LoRa ICs from Semtech, with the SX1262 being the 2nd generation. Comparing those two, the newer version has 50% less power in RX mode and 25% less power in TX mode. The next generation of ICs also has a higher TX power (22dBm vs 20 dBm). However, the improved features of the SX1262 comes at a higher price and the availability of documentation and software libraries are limited. Therefore, the SX1276 would be best suited for the system.

3.4.4 Sensor for Moisture Content Levels

Moisture content sensors provide important information regarding the exposure of the road to water which may significantly degrade the lifetime thereof. The next section compares various technologies in this regard.

3.4.4.1 Description

Moisture content sensing techniques can be grouped into three categories namely, Capacitive, Time Domain Reflectometry (TDR), and Frequency Domain Reflectometry (FDR). Both TDR and FDR are very accurate techniques, however the cost is high, and they are usually bulky compared to capacitive sensors. The downside of capacitive sensors is that their accuracy is rather low.

3.4.4.2 Technical Information

Figure 3-11 shows the moisture content sensor used in the final design.

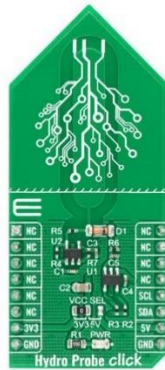


Figure 3-11: The MIKROE Hydro Probe click moisture content sensor [48]

The specifications of the device are as follows:

Table 3-7: Hydro Probe click Specifications

Specification	Value
Supply Voltage	3.3 V
Interface	I2C
Current Consumption	< 1 mA

3.4.4.3 Selection Motivation

Table 3-8 below gives an overview of the moisture content sensor options.

Table 3-8: A comparison of available Moisture Content sensors (2022)

Sensors	Parameters		
	Current (mA)	Interface	Cost
ATSAMD10	3.36	Digital	R142.73
MIKROE-4131	< 1	Digital	R171.27
SEN-0114	35	Analog	R51.38

As seen in Table 3-8, little technical information is available for these sensors, making it difficult to compare their accuracy. However, comparing the cost of the sensors, the analog SEN-0114 is the least

expensive and the MIKROE costing the most. Another important consideration is the interface between the sensor and the microcontroller. The SEN-0114 has a analog interface, requiring additional circuitry to convert the voltages to the correct range. This makes it less ideal compared to the I2C interface of the other sensors. Furthermore, comparing the current consumptions of the sensors, the MIKROE boasts with a sub-milliamp consumption. As a result, the MIKROE seems to be the better option even though the cost is higher than alternatives.

3.4.5 Microcontroller Unit

The microcontroller is responsible for the gathering, processing, and the communicating of sensor data. It serves as the central control of the imbedded device.

3.4.5.1 Description

The MCU accepts measurements from the sensor units identified above, process the readings, and forward them to the communication module. It therefore must provide the necessary interfaces to connect these external components. Additional peripherals are required for standard on-board modules such as the real-time clock, current sensor, microSD card, and battery voltage monitor. The peripheral requirements are as follows:

- 3 x I²C
- 1 x ADC
- 3 x SPI

3.4.5.2 Technical Information

Figure 3-12 shows the microcontroller unit used in the final design.



Figure 3-12: The ESP32-WROOM 32-E modules [49]

The specifications of the device are as follows:

Table 3-9: ESP32 Specifications

Specification	Value
Supply Voltage	3.0 – 3.6 V
Clock Frequency	240 MHz
Current Consumption	80 mA
SRAM	520 KB
Flash Memory	4 MB
Interfaces	Wi-Fi/ Bluetooth

3.4.5.3 Selection Motivation

Considering the requirements above, Table 3-10 below shows three different MCUs and their relevant characteristics.

Table 3-10: A comparison of available MCUs (2022)

MCU	Parameters				
	Clock Speed (MHz)	Flash Memory (MB)	Current Consumption (mA)	Availability	Support for MCU
ESP32-WROOM	240	4.00	80	High	Good
STM32L072CZ	32	0.19	3	Very low	Moderate
Raspberry Pi Pico	133	2.00	100	High	Moderate

Comparing the available MCUs, ST's chip requires the least amount of power followed by the ESP and the Pico. However, STM chips are high in demand and has a very low availability. The clock speed of the Pico is superior to the rest, with the ESP running slightly faster than the STM. With regard to flash memory, the ESP comes out on top. Another important factor is support in terms of software and documentation. With good support, creating code and connecting hardware is much faster. The ESP32 offers the best support. Considering the alternatives above, the ESP32 would provide the best option for an MCU. The current consumption can also be reduced by using available sleep modes.

4 Detail Design

This chapter discusses the detailed design of the system, based on the functional and physical components identified in Chapter 3. It includes a discussion of both the hardware and software components. This encompasses a detailed examination of the printed circuit board, the device installation technique, and the device casing. Furthermore, a detailed software flow is provided, along with the algorithms that form part of the system.

4.1 System Architecture

Now that the components of the system are known, an updated architecture can be presented as in Figure 4-1.

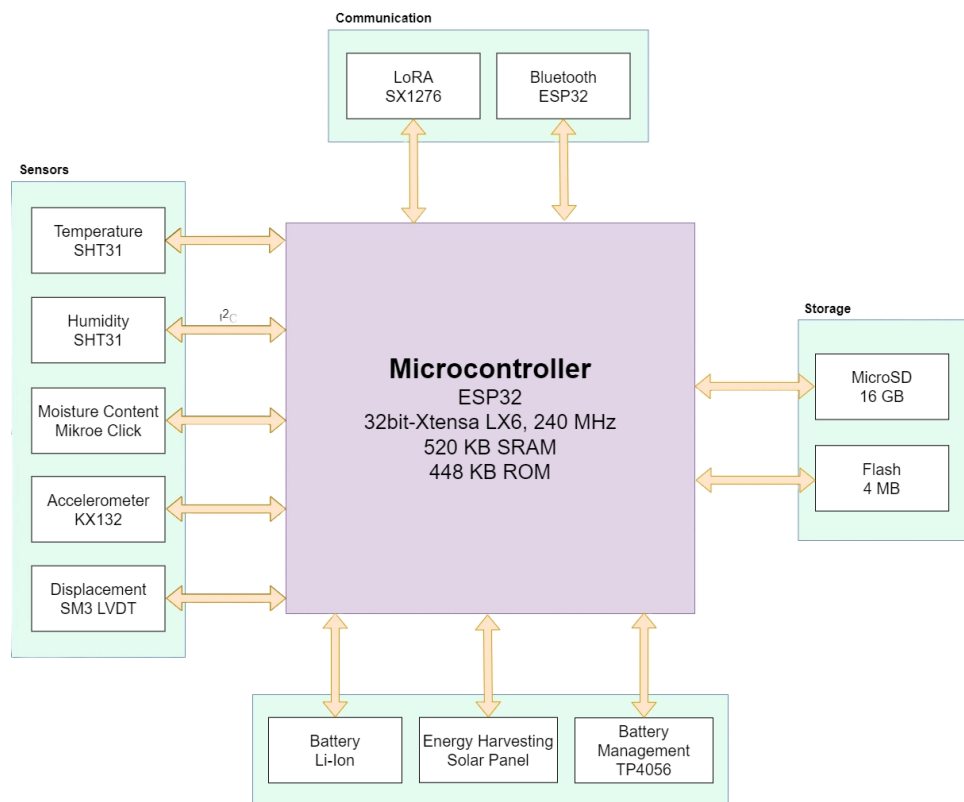


Figure 4-1: The updated architecture of the proposed device used for this thesis

4.2 Hardware

4.2.1 The Printed Circuit Board

The hardware design of the device requires the manufacturing of a Printed Circuit Board (PCB). The design of the PCB was done in the KiCad software program [50]. Figure 4-2 below shows the circular control card on the left, and the rectangular power card on the right. The control card houses the microcontroller, real-time clock, microSD card, LoRa communication module, and the necessary connectors to the sensors. The power card allows input for a lithium-ion battery and a 6 V solar panel. Furthermore, it houses a TP4056 charge controller which ensures that the battery is charged efficiently and safely. Another important component is the linear regulator which ensures that the voltage provided to the control card is always constant. Optionally, a current sensor can also be added to record the power consumption of the device.

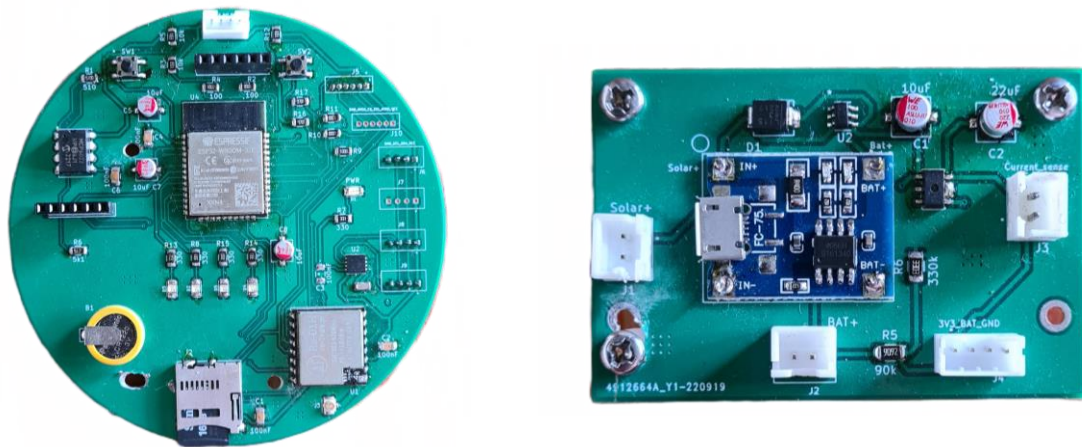


Figure 4-2: (a) The control PCB and (b) The power PCB (This Study)

4.2.2 The Casing

The casing design is vitally important to ensure that the delicate electronics are protected from the environment and the normal loading conditions on a road. The device is to be imbedded in the first few layers of the pavement as shown in Figure 4-3 below. Furthermore, the device is to be fitted in a 200 mm deep cavity with a diameter of 150 mm and flush with the surface of the asphalt layer. For the initial tests, one of each of the sensors is to be imbedded in the pavement. However, for the final design, three of each of the sensors need to be imbedded in various layers of the pavement spaced 50 mm from one another.

4.2.2.1 Revision 1

The initial casing design sees the LVDT core fixated to the bottom of the inner housing as shown in Figure 4-4 below. As proven later, this design provided inadequate results, therefore, a second revision of the casing was needed.

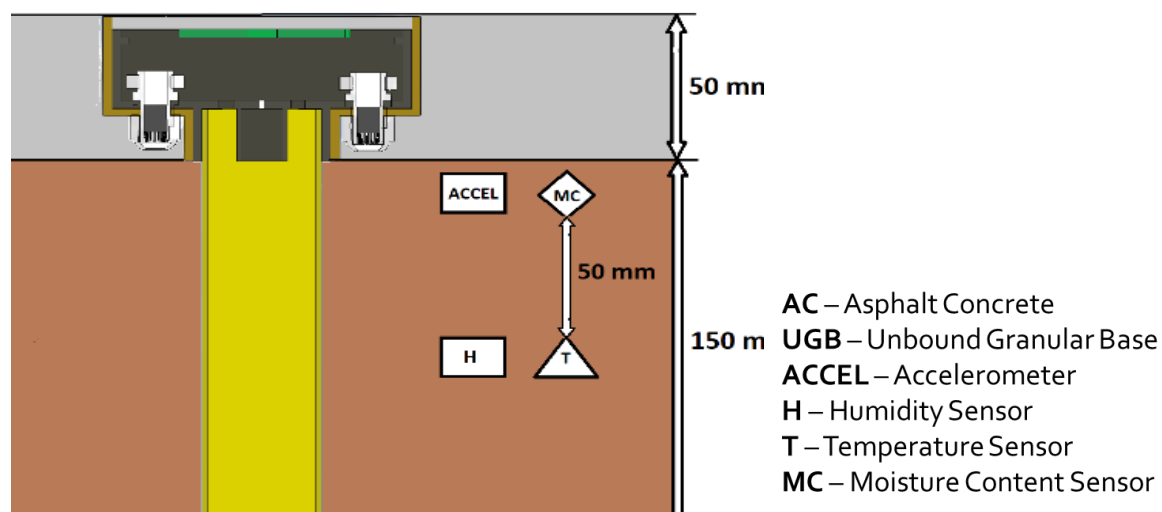


Figure 4-3: The installation of the in-road sensing device

The physical design of the casing, with all its components, is shown in Figure 4-4 below. To allow sunlight to reach the solar panel a transparent lid is needed. A 6 mm polycarbonate plate provides adequate strength, durability, and visibility to be used for this purpose. Furthermore, the LVDT core is connected at the centre of the casing, sliding in the LVDT body, which is anchored at the bottom of the cavity. The casing consists of a 3D-printed inner casing and an outer PVC casing, which adds additional structural support. The entire casing is hermetically sealed.

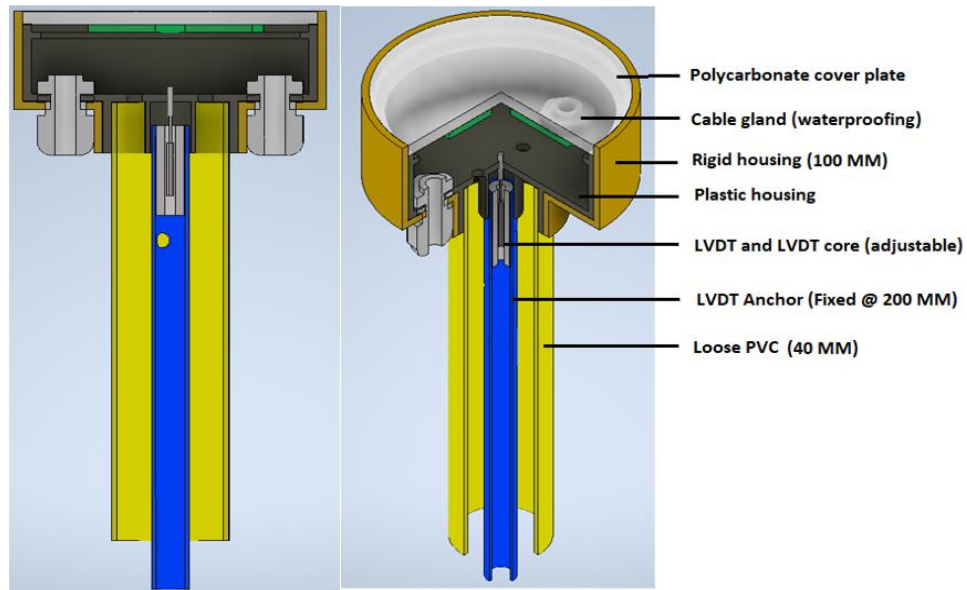


Figure 4-4: The components of the in-road casing

The implemented casing is shown in Figure 4-5. It has a removable foot piece which aids in the installation process.



Figure 4-5: The implemented in-road casing assembled (left), with a separate foot piece (right)

4.2.2.2 Revision 2 of the In-Road Casing

The second casing design centred around improving the fixation of the LVDT core to represent the movements of the pavement layer more accurately. This entailed the use of a bracket fixed to the side of the cavity with screws, essentially allowing the LVDT core to fixed to the pavement rather than the casing. This installation technique is shown in Figure 5-31.

4.2.2.3 Revision 3 of the In-Road Casing

In Revision 2 of the casing, the bracket yielded satisfactory results; however, upon fixation to the Asphalt Concrete (AC) layer, the screws tended to loosen after adjusting the LVDT core's position. Therefore, a third method was proposed, and is shown in Figure 4-6 below. A 150 mm cavity is initially drilled to a depth of 30 mm into the asphalt concrete, followed by a subsequent 120 mm cavity extending down to the final depth of 200 mm. This method creates a shoulder that serves as the resting point for the outer casing. Additionally, as depicted in the figure below, a u-shaped bracket is securely affixed to this shoulder, ensuring stability at both ends of the bracket. Notably, a slot incorporated into the bracket facilitates the adjustment of the LVDT core position in relation to the anchor. This layout should be able to report on the elastic deflection and/or plastic deformation of the top 200 mm of pavement structure, with the top of the pavement taken as the reference.

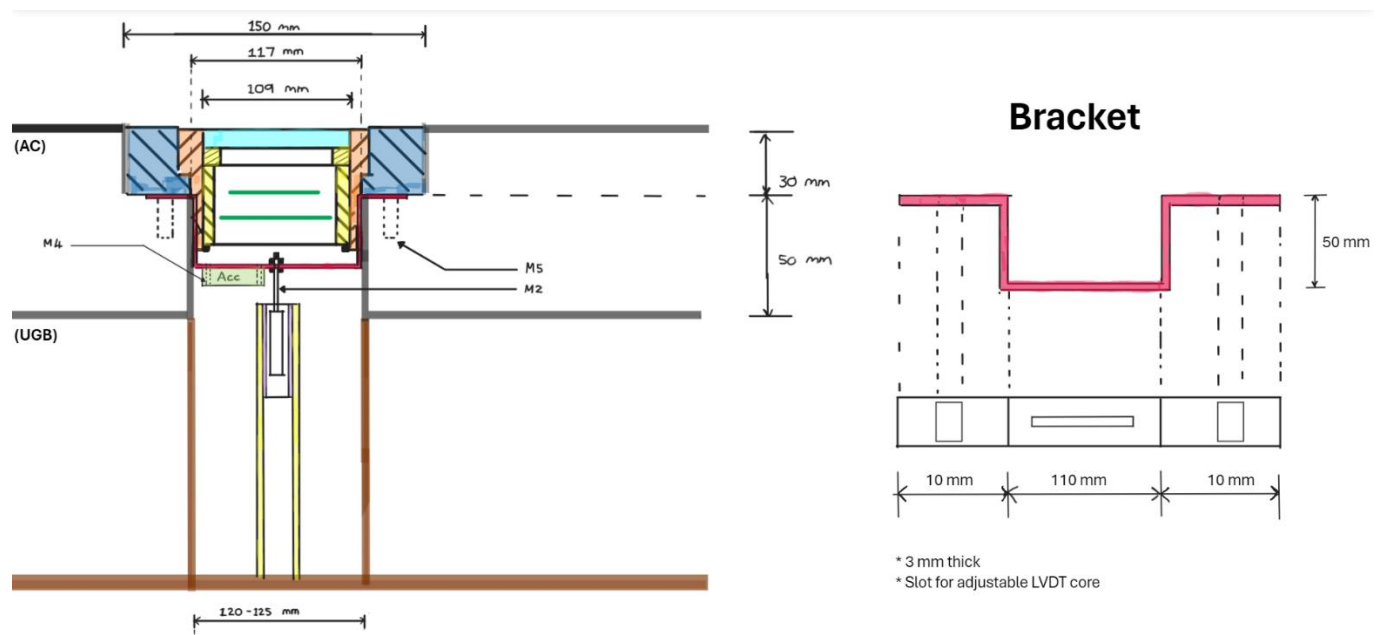


Figure 4-6: The final casing design implementing a u-shaped bracket (This Thesis)

4.3 Software

The software for the device consists of two components, the software running on the microcontroller and the algorithm for the external processing of the data, i.e., converting the acceleration signal to a displacement signal.

4.3.1 Device software

The microcontroller software is written in the C/C++ language, and handles data collection (using I²C and SPI interfaces), data processing, and data communication. Due to the limited data capacity of the LoRa link, for the initial phase of in-road testing, the data is captured on a .csv file on a PC via the Bluetooth interface, to allow all raw measured data to be communicated to the backend system, where it can be analysed in detail. A second algorithm (in Python) running on a PC extracts the accelerometer and LVDT data from the file for further processing. In the production design the embedded software is to be extended to extract the necessary features from the measured data on the microprocessor, thus drastically reducing the data volume to allow all external communication to be handled via the LoRa link. Figure 4-7 below shows the software flow diagram for the device when imbedded in a real-world traffic flow scenario. The system starts by checking connections to the peripherals of the device and establishes the LoRa link. Thereafter it calculates the duty cycle by means of Fuzzy Logic, and calculates the time that the device has been active in a given period (t_{active}), and compares that to the allowable time determined by the duty cycle (t_{dc}). If the allowable active time hasn't been reached the device starts its operational flow. Then when the device's counter reaches the time to interrupt (t_{int}) or the pavement acceleration is higher than the threshold, measurements are taken. These measurements are then processed, packed, timestamped, stored and finally transmitted to the gateway by means of the LoRa transceiver.

The power management algorithm should ensure uninterrupted operation during the system lifecycle. A simple power management technique as discussed in Section 2.5.3 uses duty cycling to save energy. This technique requires some of the subsystems to be deactivated or set in a sleep mode if not required. For example, the temperature, humidity, and moisture content need only be measured in hourly intervals, therefore these devices can be set to sleep outside of these intervals. Furthermore, the MCU can also be set to sleep mode when no accelerations are detected, or other measurements need to be taken (see Figure 4-7). Only when an acceleration above the set threshold is detected the pavement accelerations to be captured by the MCU. To maximize energy efficiency, a sophisticated smart power management algorithm has been developed. A fuzzy logic algorithm implemented on the MCU uses the current and future state of the device to calculate the duty cycle thereof. For instance, when the battery capacity is low, solar input is limited, and expected current consumption is high for that time of day, the algorithm adjusts the duty cycle to a lower setting. This strategic adjustment significantly reduces the device's overall energy consumption. Table 4-1 shows the Fuzzy Rulebase designed for the in-road sensor. It is a list of all the logic input conditions that result in a specific output condition. The input conditions are obtained from the device and can be described as follows.

- Solar input – The measure of input current from the solar panel obtained from the current sensor.
- Battery Capacity – The remaining capacity of the battery as a percentage.

- Expected Energy Consumption – Uses the time of day to predict the traffic flow at a specific time as mentioned in section 2.6.2.

The state of these inputs determines the duty cycle of the device in terms of the inactive and active times of the subsystems and is updated on hourly intervals. The fuzzy logic algorithm is implemented on the MCU by means of conditional statements known as Fuzzy Rules. The algorithm needs to inform on the sampling data threshold of the accelerometer.

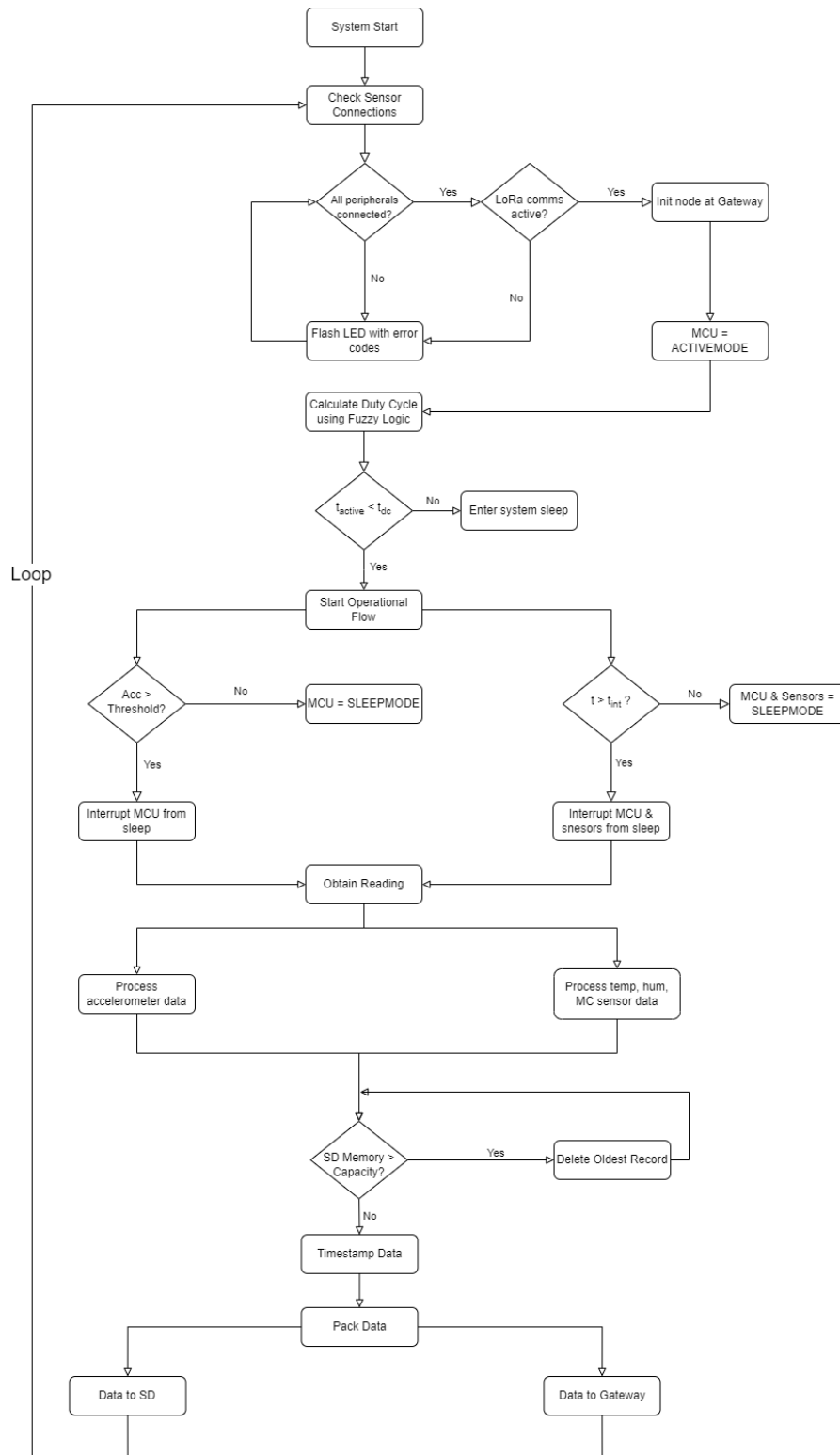


Figure 4-7: The software flow for the in-road device (This Thesis)

Table 4-1: The Fuzzy Rulebase

Fuzzy Rules			
Inputs			Output
Solar Input	Battery Capacity	Expected Energy Consumption	Duty Cycle
Low	Low	Low	Very Low
Low	Low	Medium	Very Low
Low	Low	High	Very Low
Low	Medium	Low	Low
Low	Medium	Medium	Low
Low	Medium	High	Low
Low	High	Low	Very High
Low	High	Medium	High
Low	High	High	High
Medium	Low	Low	Very Low
Medium	Low	Medium	Very Low
Medium	Low	High	Very Low
Medium	Medium	Low	High
Medium	Medium	Medium	Medium
Medium	Medium	High	Medium
Medium	High	Low	Very High
Medium	High	Medium	High
Medium	High	High	High
High	Low	Low	Very Low
High	Low	Medium	Very Low
High	Low	High	Very Low
High	Medium	Low	Very High
High	Medium	Medium	Very High
High	Medium	High	High
High	High	Low	Very High
High	High	Medium	Very High
High	High	High	Very High

In addition to power management, it's crucial to incorporate communications management. The Fuzzy Logic algorithm, determining the duty cycle, directly impacts the frequency of data transmission. A lower duty cycle results in less frequent data sampling and subsequently fewer data transmissions. As mentioned earlier, the final device version needs to internally process accelerometer measurements, reducing the necessity to transmit extensive data over the LoRa link.

The communication subsystem utilizes a LoRaWAN stack to relay data from the in-road device to a LoRa-enabled gateway. This gateway establishes connections to either local or remote servers for data storage and analysis purposes. The outlined software flow in Figure 4-7 demonstrates that the communications subsystem initializes the device on the gateway, and that data is sampled, processed, and packed before being communicated over the LoRa link. This sequence ensures efficient handling and transmission of the measurements.

4.3.2 Acceleration to Elastic deflection and/or Displacement Algorithm

Vertical downward pavement deflection measurements are critical in pavement condition assessment. Therefore, a means to obtain a pavement deflection value should be established. Coupled with this is the need for low-cost and low-power sensing, which is not possible using an LVDT. This provides the motivation to use accelerometers, which are much smaller and require less power. The measured accelerations are converted to displacement values by means of integration. However, this is not a trivial task. The double integration acts as a filter, amplifying the lower frequencies of the signal [32]. Consequently, even a slight baseline offset in the measured acceleration can be magnified, resulting in substantial drifts in the estimated displacement. Additionally, the integration action adds a low-frequency component to the data. Correction methods must therefore be implemented to obtain the desired result. This usually includes filtering, amplification, and detrending of data. The strategy used to convert acceleration to displacement is shown in Figure 4-8.

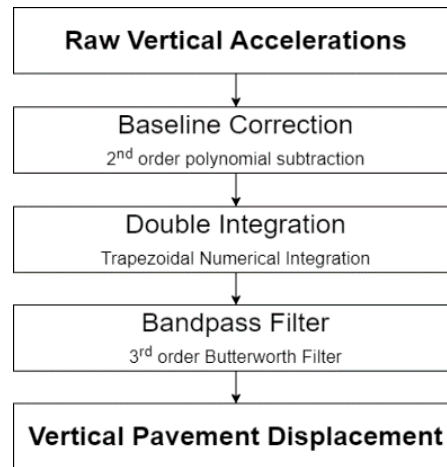


Figure 4-8: The acceleration to elastic deflection and/or displacement algorithm

Firstly, the baseline drift needs to be removed from the data. This is done by computing a second-order least-squares polynomial fit using the accelerometer data and then subtracting it from the original dataset. Thereafter, the velocity and the displacement are obtained by applying the trapezoidal numeric integration method to the acceleration and velocity data, respectively. Equations 12 and 13 show this integration step. Note that the formula assumes a zero initial acceleration.

$$v(n) = \sum 0.5(a(n) + a(n + 1))(\Delta t) \quad (12)$$

$$d(n) = \sum 0.5(v(n) + v(n + 1))(\Delta t) \quad (13)$$

where a is the acceleration, v is the velocity, d is the elastic deflection and/or displacement, and Δt is the time step in seconds, while n indicates the incremental time steps. Next, the low-frequency component added by the integration step needs to be removed together with high-frequency noise in the data. This is done by adding a band-pass Butterworth filter with a passband between 2 and 40 Hz. Figure 4-9 below shows the frequency response of the designed Butterworth filter with the following specifications:

- Filter type: band-pass
- Cut-off frequencies: 2 Hz to 20 Hz (low) and 40 Hz (high)
- Order: 3
- Passband Ripple: Minimal
- Stopband Attenuation: -40 dB at 150 Hz and at 0.8 Hz

The selection of these parameters can be explained as follows. The filter type was chosen as bandpass, to filter both low-frequency content from the integration calculation as well as noise in the original signal. The cut-off frequencies specified above is obtained from recommendations made by researchers on the same topic as mentioned in the literature study above. Thirdly, the filter is specified as third order which gives a balance between attenuation and phase distortion. If a higher order filter is chosen, the phase distortion increases, leading to changes in the deflection estimate. The Butterworth filter compared to other types of filters such as Chebyshev and Elliptical has a maximally flat frequency response in the passband and phase linearity. Preserving the phase relationship between different frequencies is important for vibration analysis. Furthermore, there is not significant high frequency noise in the data, meaning stopband attenuation is not a crucial consideration.

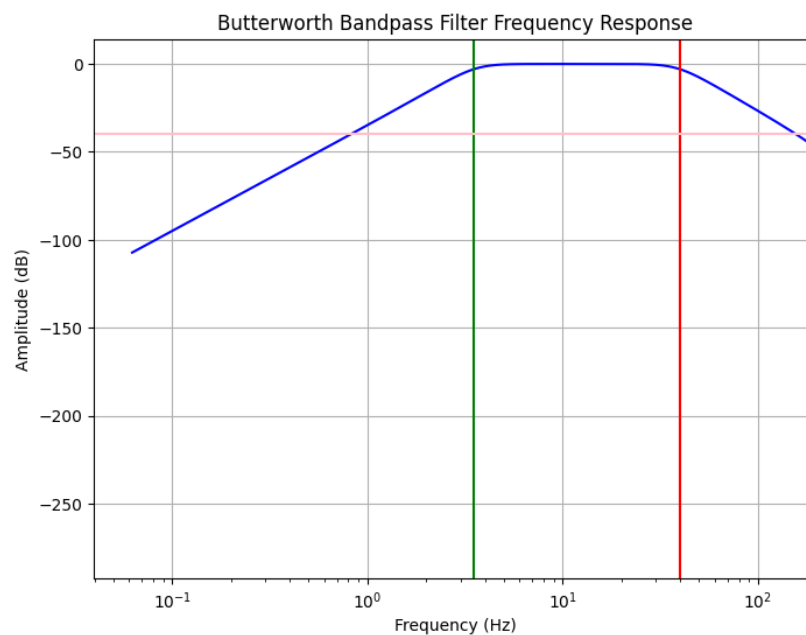


Figure 4-9: Butterworth filter frequency response

As the vehicle's speed increases, it becomes necessary to raise the lower cut-off frequency of the filter [24]. The cut-off frequency is manually adjusted since the vehicle's speed is predetermined before filtering. Table 4-2 below lists the current cut-off frequencies, determined through manual inspection of the displacement signal. Adjustments were made until no distortion was evident in the signal. However, in the device's production version, adaptive selection needs to be implemented. Yet, this method necessitates prior knowledge of the vehicle's speed. This information can be acquired by installing an additional accelerometer longitudinally within the asphalt concrete layer, positioned opposite the existing one. Analysing the time difference between the peaks of the first axle detected by both accelerometers allows for the calculation of the vehicle's speed. Signal synchronization then becomes an important consideration.

Table 4-2: The lower cut-off frequencies of the filter based on the speed of the vehicle

Speed (km/h)	Lower cut-off frequency (Hz)
30	3.50
40	4.25
50	7.00
60	11.00

5 Testing and Evaluation

This chapter focuses on evaluating the system components to determine the ability of the designed device to assess the condition of the pavement. Tests are applied to the communication subsystem, sensor subsystem, and power supply subsystem. The sensor subsystem includes the temperature sensor, humidity sensor, and moisture content sensor. Furthermore, a critical evaluation of the results obtained from various experiments is conducted to validate the techniques, algorithms, and hardware used for the device, relating these findings to further research on this topic. Each subsystem of the in-road device is tested both in the laboratory and while embedded in the physical pavement structure. The acceleration-to-displacement conversions and the associated tests are discussed in-depth, revealing the underlying constraints of the algorithms under test.

5.1 LoRa Communication System

The placement of the gateway is determined by several factors such as the coverage, accessibility, and security of the device, to name a few. The most important of these is the communication range of the device. In this experiment the LoRa devices are placed at certain checkpoints which have various characteristics. A node forwards sensor readings and profile data to a gateway by means of a wireless communication channel. The success of transmission is influenced by several factors, including the buildings in-between communicating devices and the height of the receiver. This test is used to evaluate the uplink and downlink communication performance of the LoRa module in term of its range. This is a determining factor in the placement of the units, as well as the IoT gateway.

5.1.1 Purpose

The purpose of this test is to determine the maximum communication range of the in-road sensor unit in its operational environment. In a typical metropolitan environment, dense property infrastructures populate the non-roadway areas. This poses as an obstacle to communicating devices as path loss is significant in these areas. The placement of sensors in these populated environments should be carefully considered.

5.1.2 Setup

The test should be carried out in an urban environment with a non-Line of Sight (NLOS) connection between the communicating devices. The placement of the receiving device is shown in Figure 5-1 in terms of distance to the in-road device. The following parameters should be used for the communication interface:

- Line of Sight and Non-Line of Sight connection (multiple buildings in-between communicating devices).
- Automatic spreading factor adjustment (for maximum range and minimum time-on-air). The spreading factor refers to the rate at which the frequency of a signal changes within the entire bandwidth of a channel and affects the time-on-air of the transmission.
- Output power of 14 dBm.

- Frequency channel: EU 868 MHz band.
- The transmitting device (in-road unit) should be installed in the pavement under real operating conditions.
- The receiving unit position should be changed between various points at each distance as seen in Figure 5-1.
- 100 transmission attempts should be carried out at each control point.
- The range between communicating devices should be varied between 100 and 400 meters for the various control points. The number of obstacles should be noted.

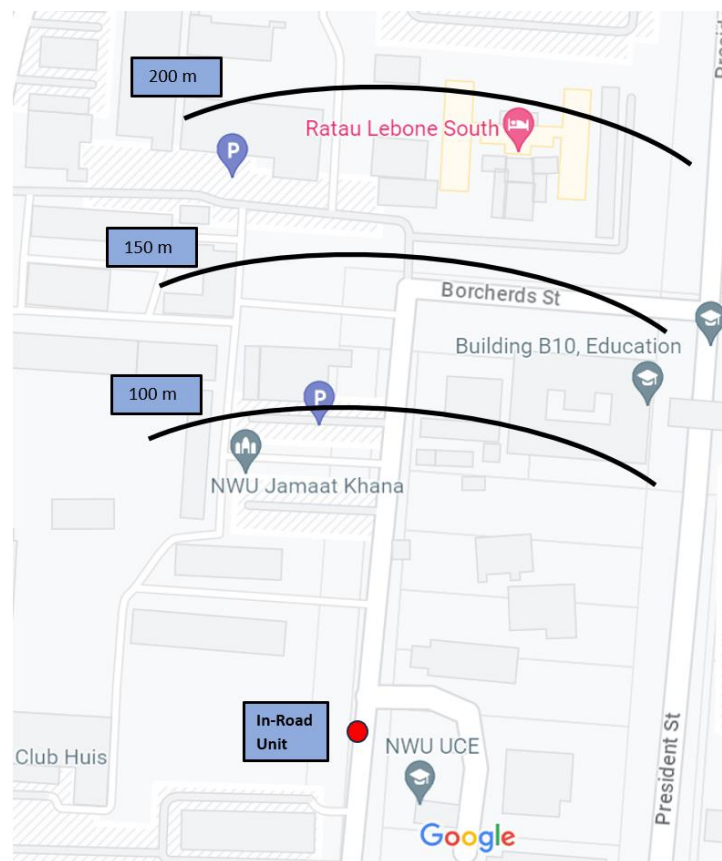


Figure 5-1: Checkpoints on NWU campus (This Thesis)

5.1.3 Method

- Mount the transmitting device securely on a section of the pavement.
- Mount the receiving device on a pole with recorded height.

- c) Ensure that the antenna is not covered.
- d) At the first control point, transmit 100 (hundred) 15-byte packets at the correct spreading factor (SF) and frequency band.
- e) Record the success rate, distance, and obstacles between the communicating devices.
- f) Move to the next control point and repeat steps a) to e) above.

5.1.4 Results

The communication capabilities of the in-road sensor are significantly influenced by the distance between communicating devices. Table 5-1 and Figure 5-2 shows the success rate of communication over distance. Furthermore, the range is significantly limited by imbedding the device in the pavement. When referring to the average success rate, it means that the effect of all other factors is considered/included in the evaluation. For example, at a 100 m distance, the average success rate at different heights, number of buildings, and cars over the device is taken.

5.1.4.1 LoRa Range Test

Table 5-1: LoRa distance test

Range (m)	Avg. Success Rate (%)
100	84
150	77
200	6

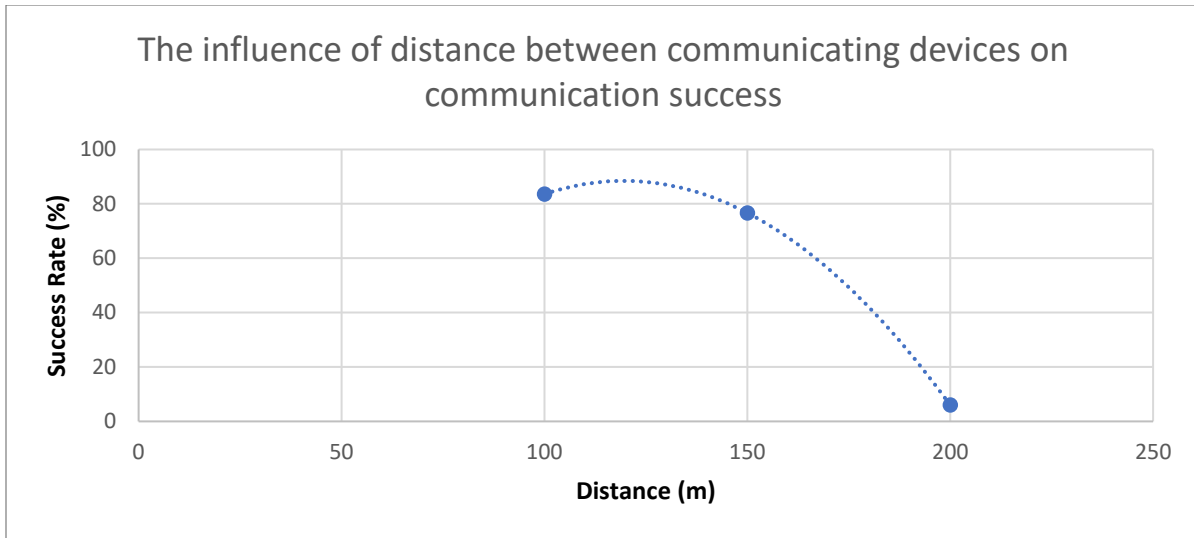


Figure 5-2: The LoRa communication success rate at various distances

5.1.4.2 LoRa Obstruction Tests

Another factor that influences communications is the presence of vehicles that cover the imbedded device. Table 5-2 and Figure 5-3 shows this.

Table 5-2: LoRa success rate for a car covering the sensor

Cars (#)	Avg. Success Rate (%)
0	87
1	71

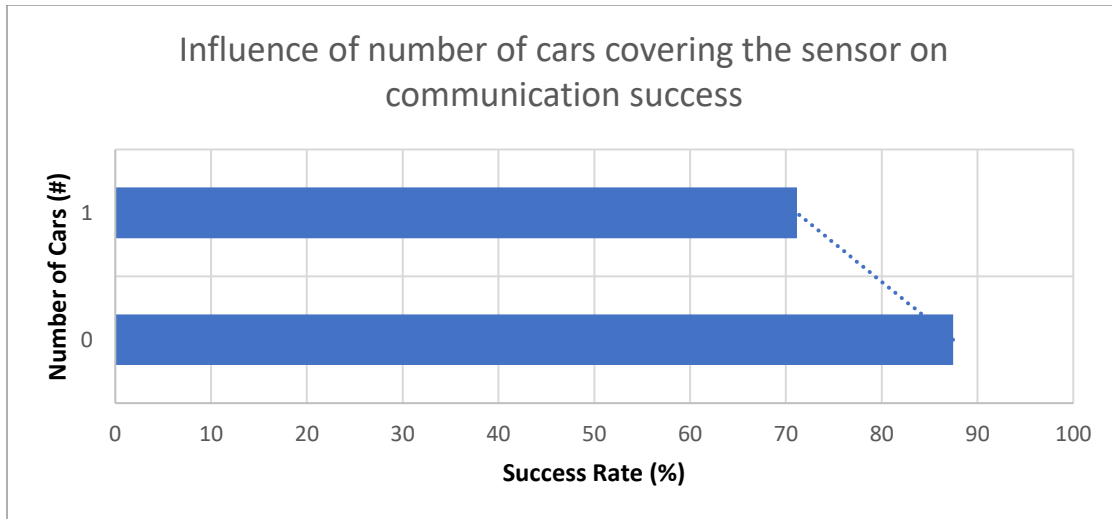


Figure 5-3: LoRa success rate for a car covering the sensor

Still considering the effect of objects that may block communication, the effect of buildings between communicating devices are also assessed as seen in Table 5-3 and Figure 5-4 below.

Table 5-3: LoRa success rate with interfering buildings

Buildings (#)	Avg. Success Rate (%)
0	99
1	86
2	61

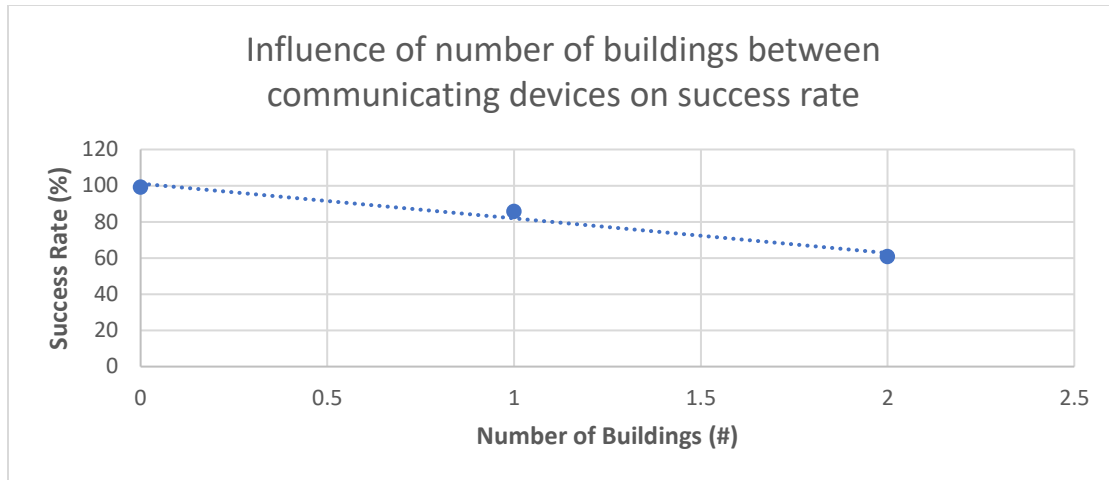


Figure 5-4: LoRa success rate with interfering buildings

5.1.4.3 LoRa Receiver Height Test

The placement of the gateway is also important, and specifically the height thereof. As seen in Table 5-4 and Figure 5-5 below, the height has a significant effect on the communication capabilities of the system.

Table 5-4: LoRa success rate at various receiver heights

Height (m)	Avg. Success Rate (%)
1	64
2	89
3	92

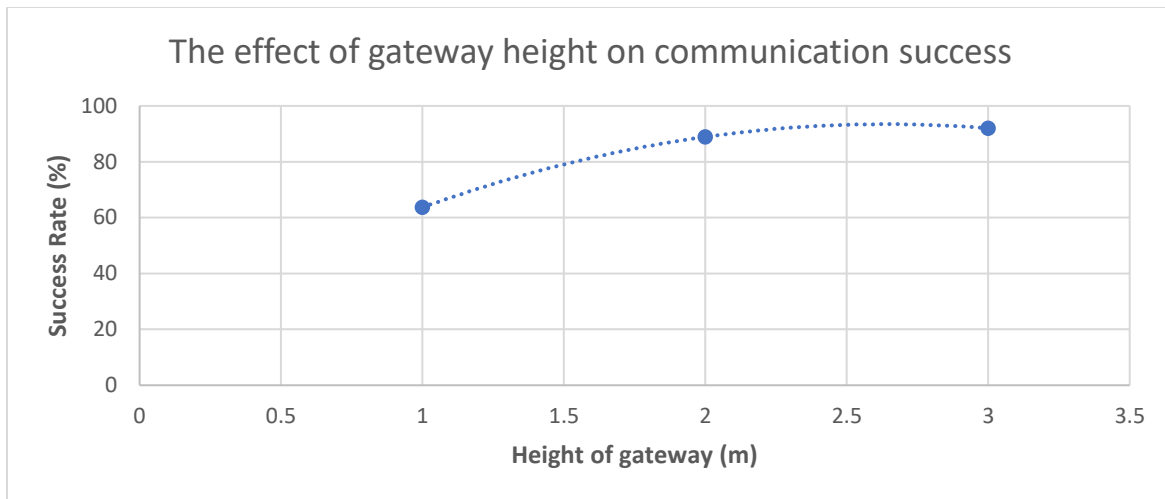


Figure 5-5: LoRa success rate for different receiver heights

The signal strength measured in “-dBm” can be used as a measure of the capabilities of the communicating devices. With an adequate signal strength, the success of communication is high as seen in Figure 5-6 below. In this test a line of sight between the communicating devices was established with the receiving device at a height of 1 meter with no objects covering the in-road device.

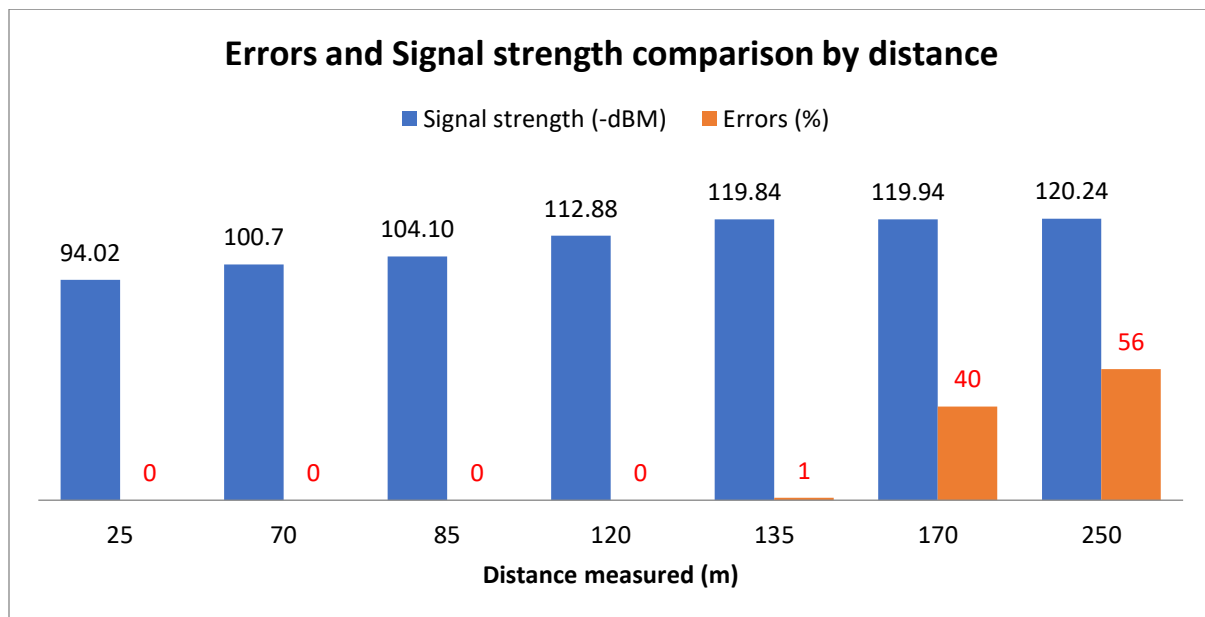


Figure 5-6: Error rate and signal strength over distance

5.1.4.4 Communication Duration Estimation

A crucial assessment of the communication subsystem relies on its capability to swiftly transmit messages, ensuring it aligns with the rate at which vehicles pass the in-road device. Consequently, the time it takes to transmit a package needs to be determined. There are several factors that determine the transmission rate of packets, including but not limited to the bandwidth, coding rate, spreading factor and the packet construction. For example, a spreading factor of 12, bandwidth of 125 kHz, coding rate of 1, and payload length of 51 bytes, result in a time on air of 2.5 seconds. However, for a spreading factor of 7, bandwidth of 250 kHz, coding rate of 1, and payload length of 51 bytes, result in a time on air of 50 milliseconds. The latter example is significantly faster however this configuration limits the range of communication. Considering the in-road device, a single elastic deflection and/or displacement estimate is 2 bytes in size, together with a 3-byte timestamp, gives a 5-byte payload. Transmitting this information to the gateway, with a spreading factor of 7, bandwidth of 125 kHz, and coding rate of 1, results in a time-on-air of 30 milliseconds. Now, take the axle spacing of a small hatchback vehicle to be 2 meters. Driving at 100 km/h, the second axle passes the in-road device in 20 milliseconds. This implies that the LoRa subsystem cannot transmit packets between consecutive axles. Nevertheless, implementing a buffering system that transmits data as the buffer fills can resolve this issue, enhancing the efficiency of data transmission.

Furthermore, the maximum transmission capacity of the LoRa subsystem needs to be analysed to ensure that the communication subsystem is able to keep up with the data generated by the device. Firstly, the data generated by the device for a single day is shown in Table 5-5. As seen in the table below, there are three primary sources of data, namely the deflection measurements, profile measurements, and the system status. The data required for deflection measurements include the 2-byte deflection measurement and a 3-byte timestamp. The temperature, humidity, and moisture content constitute 4 bytes in total plus the timestamp of 3 bytes. A one-byte status update together with a timestamp is also included. The number of measurements for deflection is estimated as 50 000, 2-axle vehicles per day, 24 hourly profile measurements for temperature, humidity, and moisture content, and 24 status updates during the day. The total bytes generated by the inroad device totals at just over 500 KB.

Table 5-5: Daily data amount generated by the in-road device

Source of data	Bytes Required	Number of measurements	Total Bytes generated
Pavement deflection measurement	5	100000	500000
Temperature, Humidity and Moisture Content measurement	7	24	168
System Status Byte	4	24	96
Total	16	100048	500264

To determine if the LoRa subsystem can manage this amount of data, the duty cycle limit should be investigated. The 868 MHz frequency band has a duty cycle limit of 1%. Using the online LoRa duty cycle calculator, the allowable data transmission size is approximately 508 KB per day.

5.1.5 Discussion

The success of wireless data transmission is significantly affected by the obstacles that block the line of sight (LOS) of communication between the transmitting node (Tx) and the gateway (Rx). When studying the effect of a vehicle covering the in-road device, an average decrease of 16% in the success rate can be

observed when a single vehicle covers the device. In a typical high-way traffic scenario, vehicles may cover the device for an extended period during periods of high congestion levels. Therefore, the distance of the gateway from the transmitting device should be limited. However, the effect of a vehicle covering the sensor is not as significant as buildings that may block the LoS of communication as seen in Table 5-2 and Table 5-3. A 38% reduction in success rate can be seen when two buildings separate the communicating devices. In metropolitan areas, with high-density urban development, this may pose a challenge. Furthermore, the effect of structural attenuation on the signal caused by the pavement layer material is evident. The typical range of LoRa communication stretches over a few kilometres, while the in-road device achieves a mere range of less than 200 m.

The effect of gateway height also plays a role in the success of communication as seen in Table 5-4. Raising the receiving antenna significantly increases the success rate of communication, congruent with the Hata Propagation Model which clearly describes the relationship between height and range: a higher receiving antenna can receive signals more effectively, reducing the overall path loss in the estimation. Thus, given the effect of the distance of communication and the height of the gateway, its placement should be carefully considered. Communication at a distance below 100 meters and an antenna height above 2 meters can significantly reduce the number of failed transmissions.

Considering the communication speed of the LoRa subsystem, the LoRa module would not be able to communicate readings fast enough to allow transmissions between each deflection measurement at highway speeds. However, if data is buffered and transmitted at regular intervals, the LoRa subsystem would be able to handle the load. Furthermore, considering the amount of data generated by the device, the LoRa subsystem would theoretically be able to transmit the data generated in a single day on a busy highway. However, this does not account for failed or re-transmissions.

5.1.6 Conclusion

The gateway should be placed in a line-of-sight (LoS) link with the node at a height of 2m or more. The distance between the gateway and node should be limited to 100 m. The LoRa subsystem would be suitable to communicate the data generated by the device.

5.2 Temperature Sensor Test

The temperature of the pavement structure affects the stiffness modulus and rutting resistance thereof. It is therefore important to accurately monitor the temperature at the different layers of the pavement structure.

5.2.1 Laboratory Test

The laboratory test needs to reveal the accuracy of the temperature sensor by comparing it to a known reference.

5.2.1.1 Purpose

The purpose of this test is to determine the accuracy of temperature readings from the chosen temperature probe.

5.2.1.2 Setup

The test can be carried out in the laboratory environment. The probe should be placed in three different temperature environments. Firstly, from a freezer with a temperature below minus 10 °C , use a cup of frozen water as the first environment to ensure minimum specifications are met. Secondly, place the probe uncovered in the room, to measure ambient temperature. Thirdly, place a probe in a hot air oven to measure a maximum temperature of plus 100 °C. For reference measurements, use a calibrated thermometer in each case.

5.2.1.3 Method

- a) Connect the temperature probe to the readout circuit.
- b) Ensure that the probe is securely fixed in its measurement environment.
- c) Place the probe, together with the reference temperature logger, in the test environment and leave it for 10 seconds before recording the temperature to ensure a stable temperature reading is reached.
- d) Record 20 samples in an Excel spreadsheet.
- e) Move to the next controlled environment and repeat steps c) to d).

5.2.1.4 Results

Table 5-6 below shows a sample of the measured temperature of the SHT31 and that of the reference thermometer. Figure 5-7 shows the linear relationship that exists between the reference instrument and the SHT31 sensor [45]. Note that the measurements provided only encompass a portion of the specified test range. This limitation arises from the unavailability of instrumentation capable of replicating environments with extreme temperatures. Moreover, subjecting the sensor to the available environments that can reach these extreme conditions might pose a risk of potential damage, further justifying the constrained scope of measurements.

Table 5-6: : A sample of temperature test results

Time	Thermometer (K)	SHT31 (K)	Inaccuracy (%)
12:17:00	327.65	328.43	0.24
12:18:00	326.65	327.71	0.32
12:19:00	326.15	327.05	0.27
12:20:00	325.15	326.35	0.37
12:21:00	324.15	325.72	0.48
12:22:00	323.40	325.12	0.53
12:23:00	322.65	324.51	0.58
12:24:00	321.90	323.88	0.62
12:25:00	321.15	323.28	0.66
12:26:00	320.65	322.70	0.64
12:27:00	319.90	322.11	0.69
12:28:00	319.15	321.53	0.75
12:29:00	318.65	320.98	0.73
12:30:00	318.15	320.42	0.71
12:31:00	317.65	319.87	0.70
12:32:00	316.65	319.33	0.85
12:33:00	316.15	318.82	0.85
12:34:00	315.65	318.32	0.84
12:35:00	315.15	317.81	0.84
12:36:00	314.65	317.31	0.84

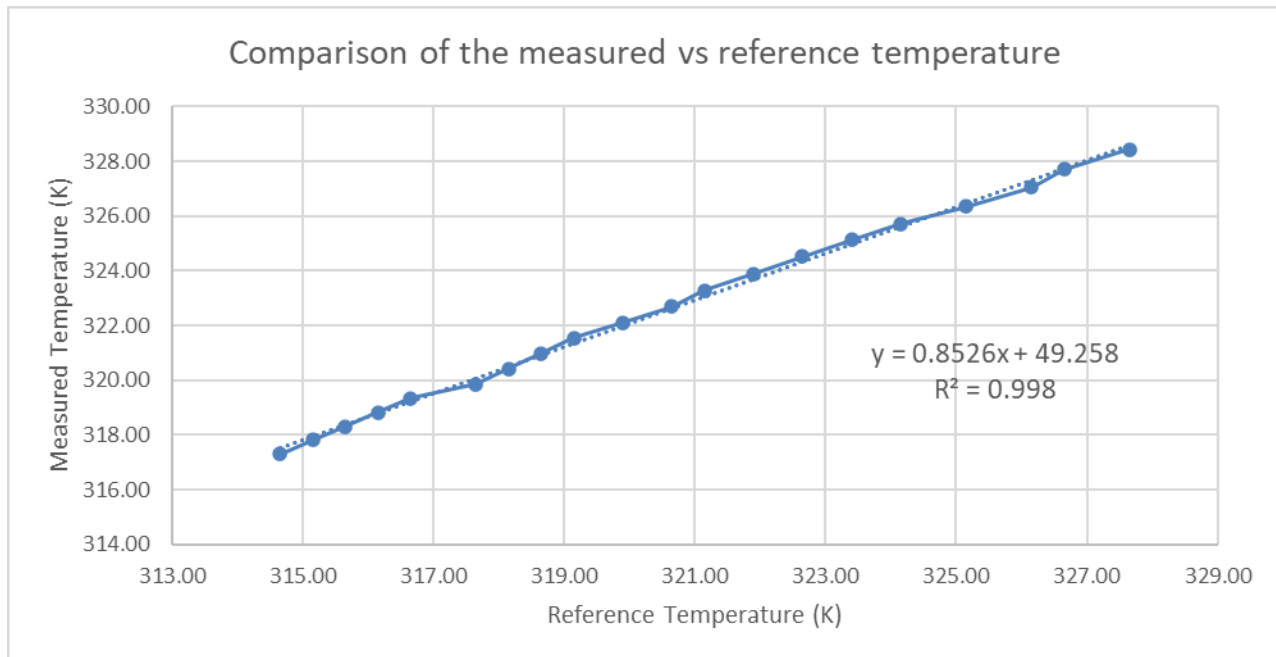


Figure 5-7: The linear relationship between the SHT31 reading and the reference temperature

5.2.1.5 Discussion

As seen from the table above, the maximum inaccuracy of the SHT31 is 0.85 %. Furthermore, Figure 5-7 shows a linear sensor response, and a high goodness of fit (R^2) close to 1. This suggests a good correlation with the reference values and a low level of inaccuracy. Considering the percentage of inaccuracy outlined in the table above, it is evident that the error increases over time, signalling a delay in the SHT31's responsiveness. This delay could potentially stem from the sensor's design. The enclosure is made with moisture-resistant and filtering materials and requires a brief period to accurately reflect the actual temperature. However, in practice, this lag may not pose a significant problem since temperature alterations typically occur gradually. Moreover, the sensor's permanent fixation to the pavement enables it to gradually adapt to the ambient temperatures, mitigating potential issues arising from the delay.

5.2.2 In-road tests

5.2.2.1 Purpose

The purpose of this test is to create a temperature profile of the pavement structure at a depth to confirm the functionality of the device in its intended operational environment.

5.2.2.2 Setup

The test should be conducted with the temperature sensor installed in the road. A 150 mm diameter and 200 mm deep cavity in the pavement was made in which the in-road sensor unit could be installed.

Readings from a single temperature probe installed at a depth of 100 mm to be captured at hourly intervals starting at 08:00 AM and ending at 05:00 PM.

5.2.2.3 Method

- Install the node securely in a section of the pavement at a dedicated lane on the UP Test-road.
- Record the temperature of the pavement and transmit the information to a local PC via the Bluetooth and/or LoRa connection.
- Store the data in a suitable format for further processing.
- Repeat steps b) and c) at hourly intervals.
- Create a profile of the daily fluctuations in the pavement temperature.

5.2.2.4 Results

Experts rely on a pavement temperature profile at different depths to evaluate the likelihood of damage and gather insights into aspects such as pavement design, material properties, and necessary preventative maintenance measures. Figure 5-8 displays the temperature profile obtained at a depth of 10 cm within the pavement.

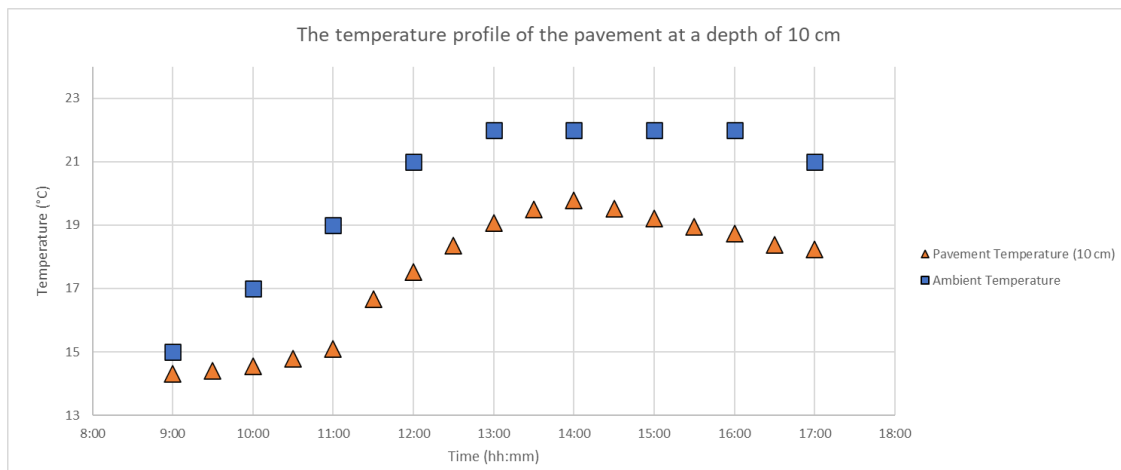


Figure 5-8: The temperature profile at 10 cm (-26.6943, 27.0900)

5.2.2.5 Discussion

The measurements indicate a maximum pavement temperature of 19.78 °C during midday and a minimum temperature of 14.3 °C in the early morning hours. It's important to note that the temperature readings during nighttime were not recorded. Additionally, the figure presents the ambient temperature,

highlighting an average temperature difference (ΔT) of 2.7 °C in comparison to the pavement temperature.

5.2.3 Conclusion

The SHT31 temperature sensor demonstrates a linear response, as depicted in Figure 5-7, with a high correlation to the reference measurements indicated by its goodness of fit (R^2) close to ideal. Additionally, the observed delay in the sensor's response necessitates acclimation to its operational environment. However, this delay is unlikely to cause significant errors, given that pavement temperatures typically change gradually. Consequently, it was expected that the SHT31 to provide an accurate pavement temperature profile like that illustrated in Figure 5-8.

5.3 Humidity Sensor Test

The humidity of the pavement structure affects the stiffness modulus and rutting resistance thereof, with a high humidity leading to increased pavement deflections. It is therefore important to accurately monitor the humidity at the different layers of the pavement structure.

5.3.1 Laboratory Test

5.3.1.1 Purpose

The purpose of this test is to determine the accuracy of humidity readings from the chosen humidity sensor.

5.3.1.2 Setup

The test can be carried out in the laboratory environment. A common method to test the accuracy of a humidity sensor is to use the Saturated Salt Test. The test uses Sodium Nitrate together with water to cause a standardized atmospheric humidity of 75% in a sealed container. The method therefore just requires some table salt, water, a container, and the humidity sensor under test.

5.3.1.3 Method

- a) Mix table salt and water to form a saturated solution without excess water.
- b) Place the solution in a bowl or open container and ensure that $\frac{3}{4}$ of the container is not filled with the solution. This contains air which has a standard relative humidity value. Place the sensor in this area.
- c) Place both the solution and sensor in a sealable bag.
- d) Remove all air in the bag by using a straw.
- e) Leave the setup for at least 4 days to ensure a stable reading.
- f) The sensor should give a reading of 75% +/- the sensor's error margin.
- g) Calibrate the sensor accordingly.

5.3.1.4 Results

Table 5-7 below shows the test results of the SHT31 humidity sensor together with the reference humidity and errors observed in the measurement.

Table 5-7: A summary of the humidity test-results

Time (s)	SHT31 Hum (%)	Reference Hum (%)	Absolute error	% Error
16:39:06	72.54	75	2.46	3.28
16:39:07	72.51	75	2.49	3.32
16:39:08	72.52	75	2.48	3.31
16:39:09	72.52	75	2.48	3.31
16:39:10	72.55	75	2.45	3.27
16:39:11	72.5	75	2.5	3.33
16:39:12	72.51	75	2.49	3.32
16:39:13	72.48	75	2.52	3.36
16:39:14	72.51	75	2.49	3.32
16:39:15	72.54	75	2.46	3.28
16:39:16	72.54	75	2.46	3.28
16:39:17	72.52	75	2.48	3.31
16:39:18	72.5	75	2.5	3.33
16:39:20	72.53	75	2.47	3.29
16:39:21	72.53	75	2.47	3.29
16:39:22	72.51	75	2.49	3.32
16:39:23	72.53	75	2.47	3.29
16:39:24	72.53	75	2.47	3.29

5.3.1.5 Discussion

The average percentage error of the SHT31 relative humidity sensor is 3.21% with a maximum deviation of 2.52% from the reference humidity. To address this, calibration involves adjusting the SHT31 reading by the average error or bias (2.41 %RH). This calibration yields an average percentage error of 0.06% when compared to reference humidity. However, it is essential to note that the testing method relied on a single standardized atmospheric humidity as a reference, limiting the assessment of the sensor's accuracy. In practice however, more than one standardized humidity is needed to provide a more comprehensive assessment of the accuracy of a humidity sensor across its full range. Unfortunately, the testing was limited by the availability of specific chemicals required to recreate diverse standardized humidities. Hence, the accuracy stated earlier pertains only to a single reference humidity and may not fully represent the sensor's performance across its entire measurement range.

5.3.2 In-road tests

5.3.2.1 Purpose

The purpose of this test is to create a humidity profile of the pavement structure at a depth to confirm the functionality of the device in its intended operational environment.

5.3.2.2 Setup

The test was conducted with the humidity sensor installed in the test-road. A 150 mm diameter and 200 mm deep cavity was made in the pavement in which the in-road sensor unit was installed. Readings from a single humidity sensor installed at a depth of 100 mm should be collected at hourly intervals starting at 08:00 AM and ending at 05:00 PM.

5.3.2.3 Method

- Install the node securely in a section of the pavement at a dedicated lane on the NWU Test-road.
- Record the humidity of the pavement and transmit the information to a local PC via the Bluetooth and/or LoRa connection.
- Store the data in a suitable format for further processing.
- Repeat steps b) and c) at hourly intervals.
- Create a profile of the daily fluctuations in the pavement humidity.

5.3.2.4 Results

The level of humidity plays a significant role in the moisture absorption within pavement layers. Increased humidity results in higher moisture absorption, consequently impacting properties like pavement stiffness and layer adhesion. Figure 5-9 shows the humidity profile of the pavement at a depth of 10 cm.

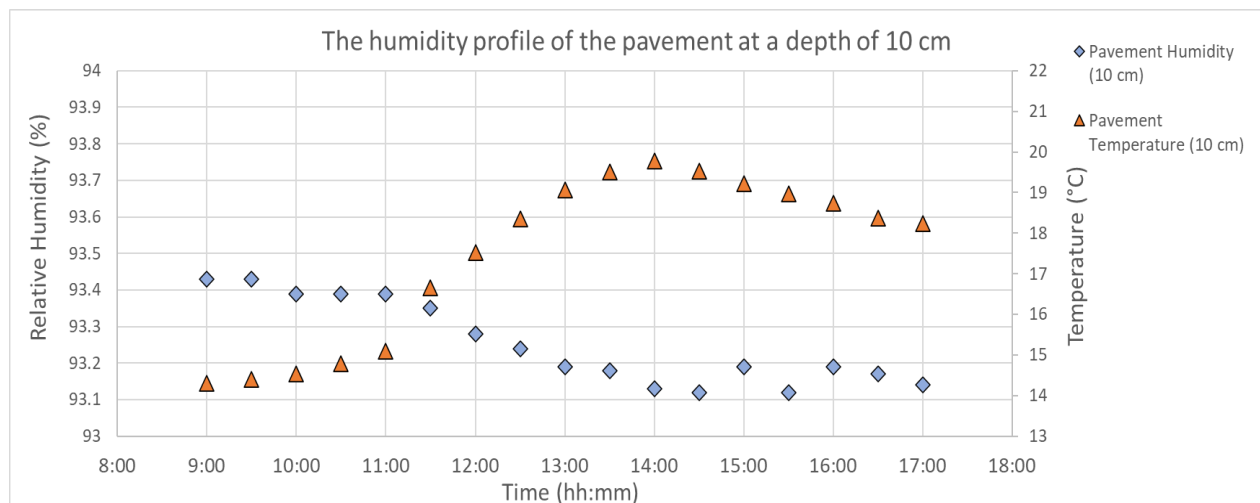


Figure 5-9: The humidity profile at 10 cm (-26.6943, 27.0900)

5.3.2.5 Discussion

By monitoring humidity levels, experts can gain valuable insights into potential locations of moisture-related distress, facilitating the implementation of preventative measures such as additional drainage

systems. Figure 5-9 depicts a relatively consistent humidity value throughout the day, with a maximum decrease of 0.31 in humidity levels recorded during warmer temperatures. The elevated humidity levels can be attributed to the rainy weather conditions that occurred prior to the measurements.

5.3.3 Conclusion

The SHT31 relative humidity sensor shows a consistent bias in measurements, which is improved through calibration, resulting in acceptable accuracy at a single standardized reference humidity. However, the evaluation of the sensor's performance is limited by the range of humidity levels that the device was tested at. Consequently, the performance of sensor across its full range of measurement remains unclear.

5.4 Moisture Content Sensor Test

A relatively high moisture content in the pavement decreases the suction which reduces the inherent stress of the pavement. This reduces its effective stiffness leading to early deformation in the layers. It is therefore important to accurately monitor the moisture content at the different layers of the pavement structure.

5.4.1 Laboratory Test

5.4.1.1 Purpose

The purpose of this test is to determine the accuracy of moisture content readings and to calibrate the sensor.

5.4.1.2 Setup

The test can be carried out in the laboratory environment. The test uses a precision scale to measure the mass of the soil extracted from the pavement layers. It is then dried in an oven and weighed again to determine the mass after moisture has been removed. The water content can then be calculated.

5.4.1.3 Method

- a) Take 5 soil samples of known volume at each layer of the pavement structure and seal each in a separate bag. Ensure that the moisture content of each sample is measured and recorded prior to removal.
- b) Weigh the samples on a precision balance to determine the Wet weight of the sample.
- c) Dry the sample in an oven set at a temperature of 105 °C for 24h.
- d) Weigh the samples again to determine the Dry weight.
- e) Convert the gravimetric water content to volumetric water content by multiplying it with the bulk density of the soil.
- f) Compare readings to measured volumetric water content.
- g) Repeat the test for the different pavement layers and samples.

5.4.1.4 Results

The first set of tests were done with a soil sample consisting mostly of loam and clay making the particles small. Table 5-8 below shows the sensor accuracy of the HydroProbe Click Moisture Content Sensor [48]. The first column shows the actual percentage moisture content (MC), the second shows the capacitance value measured by the sensor. The expected value is obtained from the equation of the linear trendline as seen in Figure 5-10 below.

Table 5-8: A summary of the moisture content test-results

Moisture Content (%)	Hydroprobe Click (#)	Expected value (#)	Residual (#)	Error (%)
0.0	3439	3426	13	0
2.3	3362	3330	32	1
4.5	3237	3234	3	0
7.3	2994	3118	-124	4
9.5	3189	3022	167	6
10.0	3111	3003	108	4
12.3	2995	2907	88	3
14.1	2859	2830	29	1
17.3	2446	2695	-249	9
20.0	2705	2580	125	5
24.5	2014	2387	-373	16
30.0	2200	2156	44	2
31.8	1979	2079	-100	5
40.0	1970	1733	237	14
70.0	1923	463	1460	315
100.0	1955	-807	2762	-342

The second set of soil samples consisted mostly of crushed rock and sand which has a much larger particle size compared to the first test. Figure 5-11 shows the results obtained. As seen in the figure, the sensor reaches its limit at 20% moisture content.

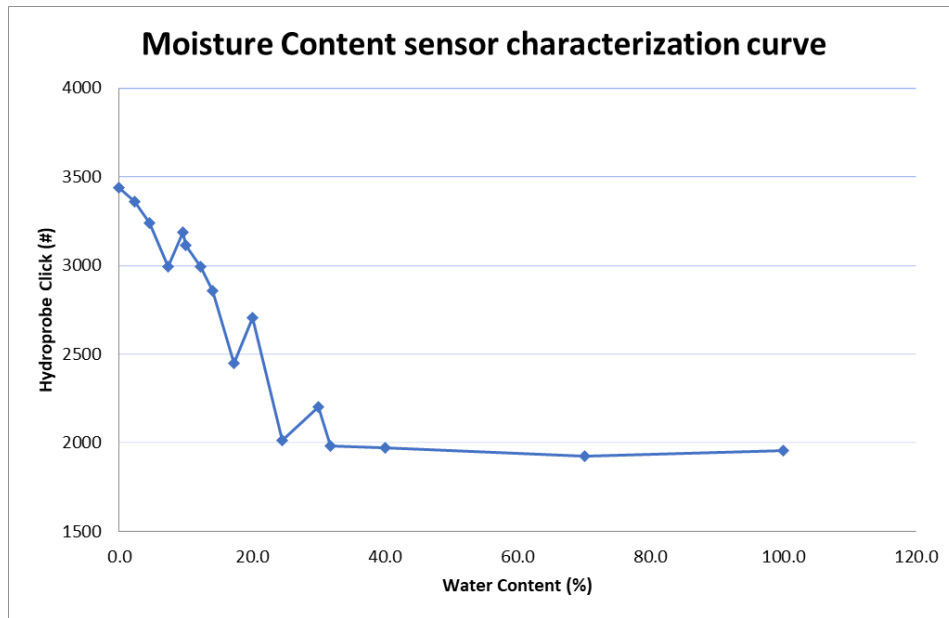


Figure 5-10: Comparing the measured moisture content with the reference measurements (This Study)

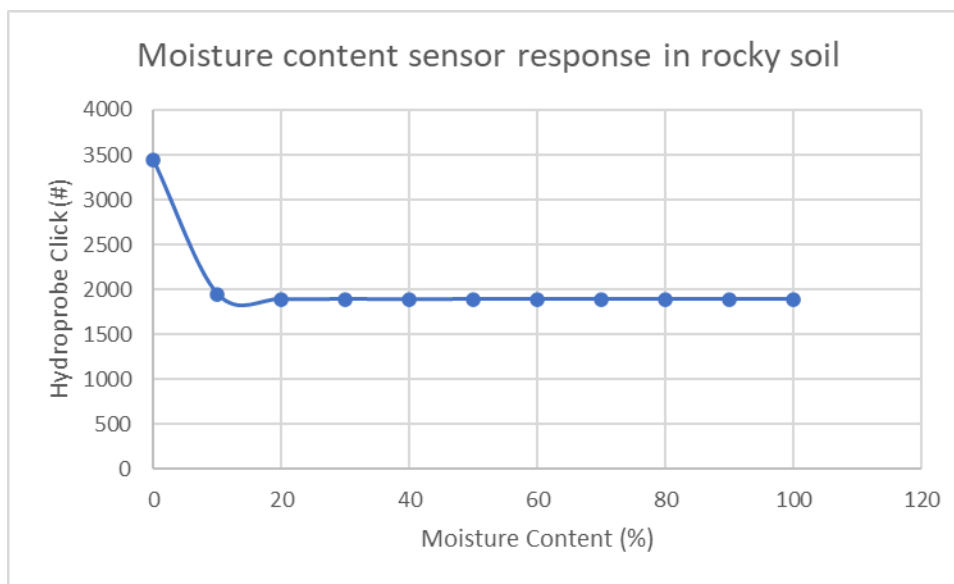


Figure 5-11: Moisture Content sensor response in rocky soil (This Study)

5.4.1.5 Discussion

Examining the curve depicted in Figure 5-10 reveals a distinct pattern: the sensor's response shows a linear trend at first but flattens after reaching a 40% moisture content. Notably, this plateau value (y-axis)

aligns with the measurement obtained when testing water alone. This indicates that the soil hits a saturation point at 40% moisture content, beyond which the sensor directly measures the water content, with minimal influence from the soil itself. Once saturated, the sensor's capacitance reading signifies the highest moisture level detectable within this soil mix. To further investigate this observation, tests were conducted on soil types with lower saturation points, like rocky soil. As illustrated in Figure 5-11, the sensor promptly reaches its maximum moisture content reading in such cases. Consequently, the characteristic of the soil plays a significant role in the moisture levels detectable by the sensor. Therefore, the requirement arises for an alternative method, or a sensor specifically calibrated to accommodate the soil type and its unique attributes, particularly its water absorption capacity within the pavement layers.

5.4.1.6 Purpose

The purpose of this test is to create a moisture content profile of the pavement structure at a depth to confirm the functionality of the device in its intended operational environment.

5.4.1.7 Setup

The test should be conducted with the sensors installed in the test-road. A 150mm diameter and 200mm deep cavity is made in the pavement in which the in-road sensor unit should be installed. Readings from a single moisture content probe installed at a depth of 100 mm should be able to collect at hourly intervals starting at 08:00 AM and ending at 05:00 PM.

5.4.1.8 Method

- a) Install the node securely in a section of the pavement at a dedicated lane on the NWU Test-road.
- b) Record the moisture content value of the pavement and transmit the information to a local PC via the Bluetooth and/or LoRa connection.
- c) Store the data in a suitable format for further processing.
- d) Repeat steps b) and c) at hourly intervals.
- e) Create a profile of the daily fluctuations in the pavement moisture content.

5.4.1.9 Results

Like the impact of humidity levels, a relatively high moisture content adversely affects the structural integrity of the pavement and, consequently, its load-bearing capacity. Figure 5-12 illustrates the moisture levels within the pavement at a depth of 5 cm.

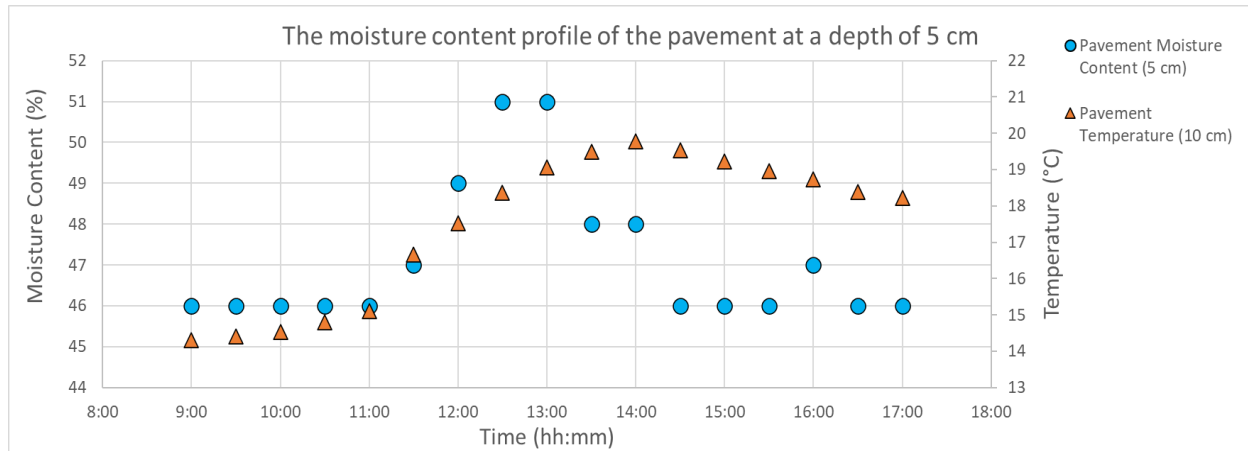


Figure 5-12: The moisture content profile for the in-road test (-26.6943, 27.0900)

5.4.1.10 Discussion

Observing Figure 5-12, a notable rise in moisture content can be observed during the time from 12:00 to 14:00. This increase indicates a potential influence of external factors such as weather conditions on the moisture levels within the pavement.

5.4.2 Conclusion

The capacitive moisture content sensor provides a somewhat linear response up to the point of soil saturation, whereafter the sensor plateaus at its maximum detectable capacitance value. The point of saturation is vastly different for different types of soils and a sensor should first be calibrated with the intended soil type. In terms of moisture content sensors, the capacitive type is known to be less accurate although inexpensive and small. For future designs, alternative sensors should be investigated that accounts for variations in soil composition.

5.5 Acceleration to Elastic deflection and/or Displacement

The elastic deflection of the pavement structure is an important parameter used in determining the performance of the pavement. To get a deflection value, readings from an accelerometer should first be converted from an acceleration value to a displacement value. Consequently, the accurate conversion of data from an acceleration to a displacement is an important task.

5.5.1 Laboratory Tests

5.5.1.1 Purpose

The goal of this test is to determine the level of accuracy with which the acceleration values obtained from an accelerometer can be converted to a vertical deflection/displacement by using various methods.

5.5.1.2 Setup

The test was carried out in the laboratory environment. Figure 5-13 below shows the testing device, which consists of a platform resting on four springs. The LVDT core, as well as the accelerometer is connected at

the centre of the platform (The LVDT is an alternating current (AC) type with a range of ± 3 mm). As the top platform is compressed by a downward force, the core moves through the LVDT body and produces a voltage at the output terminal, proportional to the displacement of the core in the body. This downward force also produces an acceleration which is recorded by the accelerometer. The LVDT body is fixed at the top of the conduit with four bolts. To displace the platform over a known reference distance, a 3D printer is used. The testing device is placed on the bed of the 3D printer and the platform displaced in the z-axis (vertical axis) by means of controlling the movements of the extruder head. This provides a reasonably good reference since the 3D printer has a resolution of 100 microns (0.1 mm).

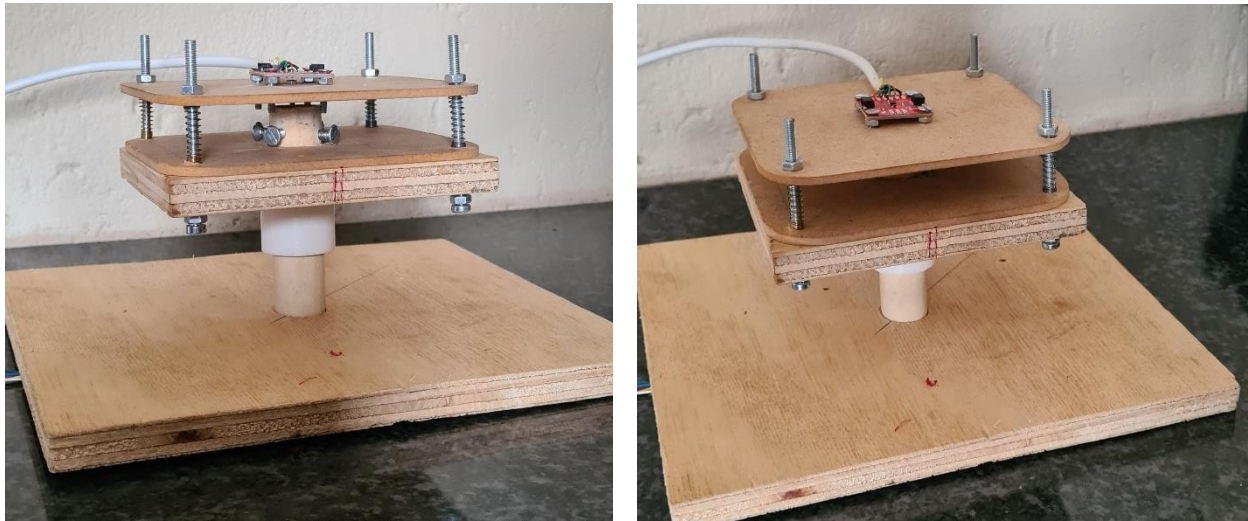


Figure 5-13: The spring-mass displacement testing device

5.5.1.3 Method

- a) The first step is to characterize the response of the LVDT, i.e. how the output voltage relates to the core's elastic deflection and/or displacement.
- b) This is done by displacing the platform over the full range of motion of the LVDT (using the 3D printer) and recording the displacement and output voltage at each measurement point.
- c) The relationship between the two measurands can then be used to infer elastic deflection and/or displacement from output voltage values.
- d) Next, the platform is displaced by a downward force, recorded by both the accelerometer and the LVDT. The first set of motions are in the form of a sine wave with a singular frequency. Thereafter, the elastic deflection and/or displacement is to represent a real-world scenario, simulating the deflection of a 2-axle vehicle driving over a measurement point.

- e) The 3D printer movement data can then be used as a reference of the relative displacement of the platform, while the acquired acceleration and LVDT data can be processed and compared to this reference.
- f) Thereafter, the accuracy of conversion from acceleration to displacement is calculated by comparing it to the reference data.
- g) Repeat steps d) to f) for different displacement values.

3D Printer Setup

The first movement is the cyclic movement of the 3D printer head. An example is shown in Figure 5-14 below, with a sine wave with an amplitude of 0.5 mm and a frequency of ~5.5 Hz. The total displacement of the 3D printer head would then be 1 mm.

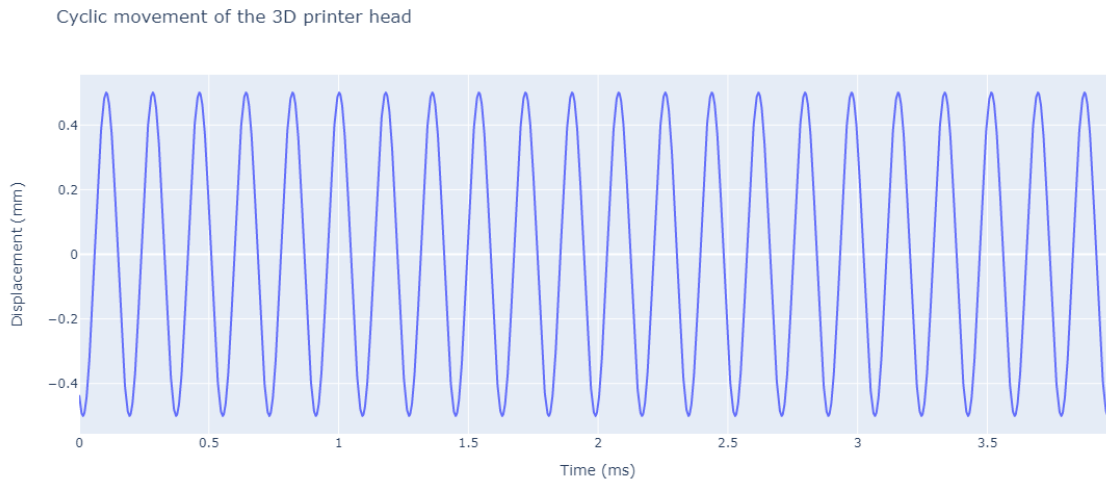


Figure 5-14: The cyclic movement of the 3D printer head (This Study)

The second movement represents a real-world scenario of a 2-axle vehicle where the displacement is recorded as the vehicle drives over the measurement point. This is shown in Figure 5-15 below. Note that the displacements are downward, but for comparative reasons it is depicted as an upward motion.

Real-world movement of the 3D printer head

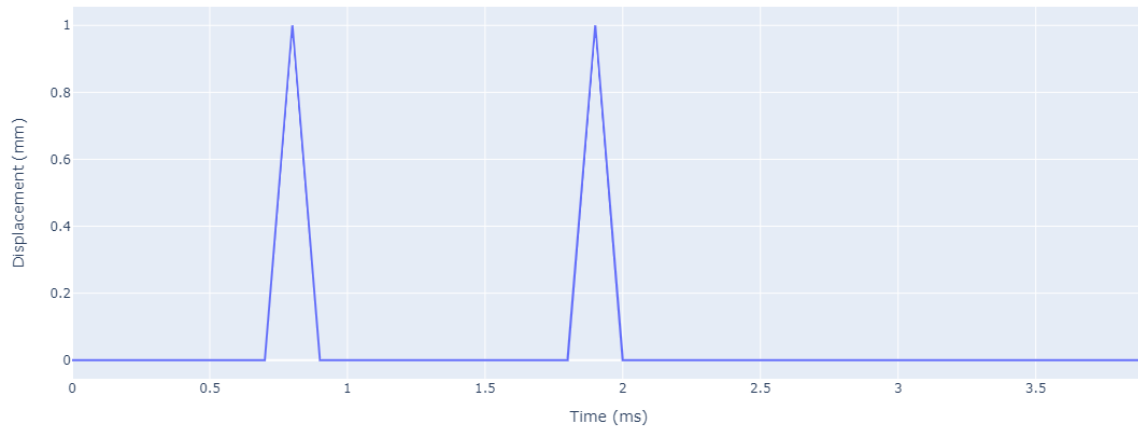


Figure 5-15: The simulated pavement displacement caused by a 2-axle vehicle (This Study)

5.5.1.4 Results

Firstly, the LVDT should be calibrated so that the core displacement can be correlated with the output voltage observed when measuring at the output of the LVDT operational amplifier. Figure 5-16 below shows the fitted linear trendline that defines the relationship between the input and output variables. As seen in the figure below, a linear relationship exists between the two variables with a coefficient of determination very close to one, revealing a strong relationship between measurands. However, notice the slight deviation from the trendline close to 0 mm displacement. This means that the accuracy of the estimation may suffer at these low displacements. This non-linear behaviour may be a result of limitations in the conditioning circuitry of the LVDT.

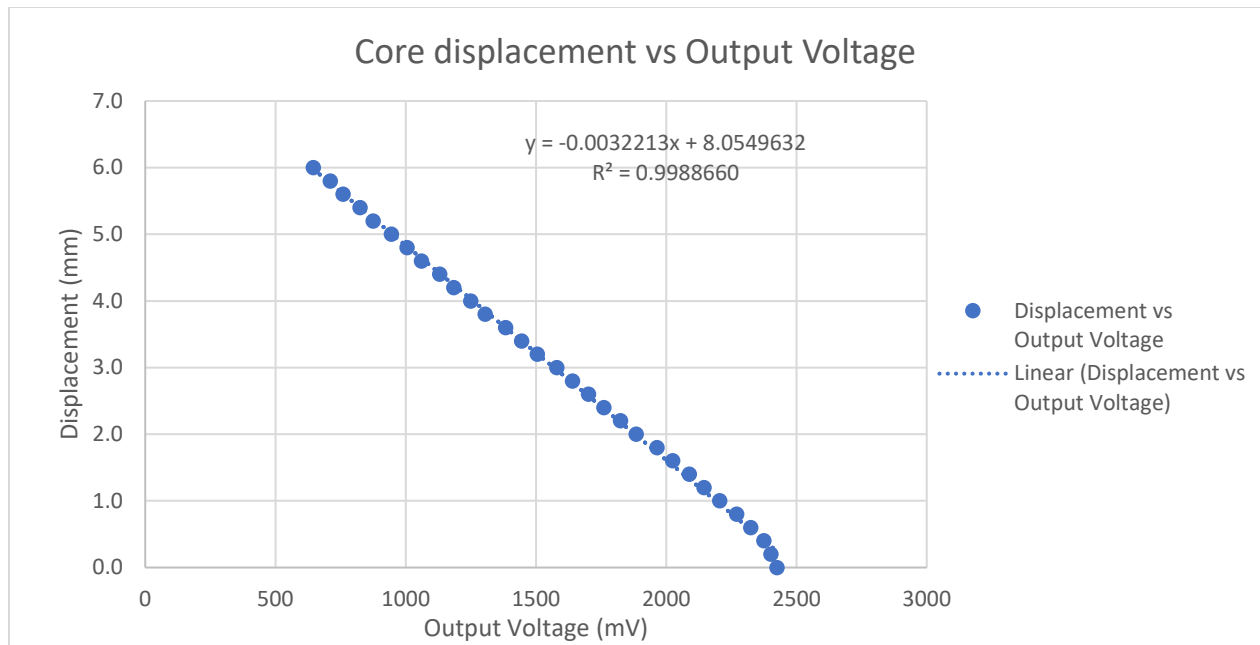


Figure 5-16: The LVDT characterization curve (This Study)

5.5.1.4.1 CYCLIC MOVEMENT TEST

With the LVDT calibrated, the actual testing phase can commence. The raw accelerometer readings for a cyclic movement are shown in Figure 5-17 below. The cyclic nature of the movement is evident in the figure, corresponding to the movement of the 3D printer head. However, there is notable noise in the raw measurements, necessitating the need for a filter.

Raw accelerometer readings

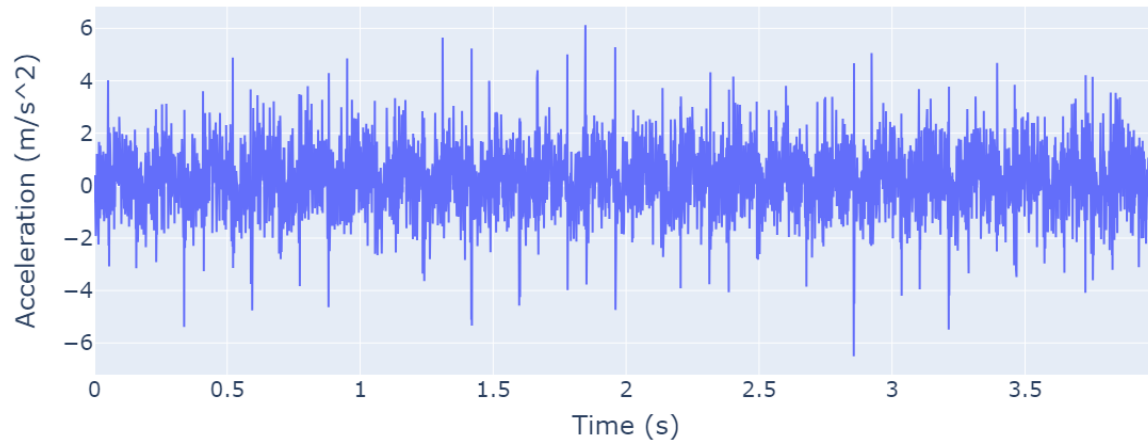


Figure 5-17: Raw accelerometer readings for a cyclic movement of the 3D printer (This Study)

Converting this signal to a displacement by means of a numerical integration method leads to a significant drift in estimations as seen in Figure 5-18 below. To compensate for this drift, baseline correction and filtering is necessary.

Calculated displacement without baseline correction and filtering

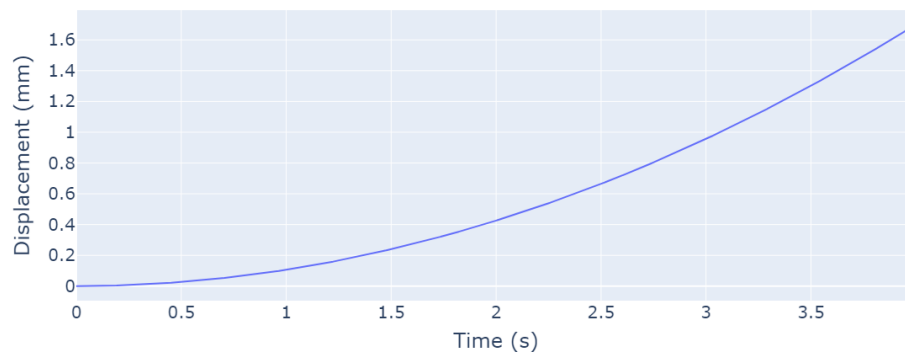


Figure 5-18: The significant drift in displacement estimations for a cyclic movement of the 3D printer head (This Study)

Once baseline correction and low-pass filtering is applied, a corrected displacement is obtained as depicted in Figure 5-19 below. Both the reference 3D printer displacement and the LVDT response is shown in the figure. The average displacement (represented by the peaks minus the troughs) is calculated and compared to that of the 1mm reference signal. This is done for a range of displacement values.

Cyclic movement of the 3D printer head

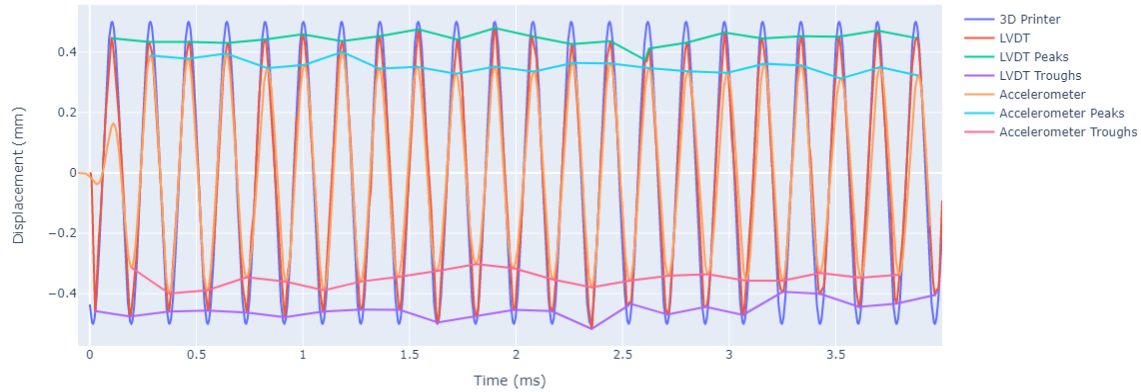


Figure 5-19: Sample test-result for a 1mm displacement (This Study)

To show the variation in measurement of the cyclic movement, 20 repetitive measurements are carried out on a single displacement value. Table 5-9 below shows statistical measures concerning this.

Table 5-9: Statistical measures of each sensor instrument for a cyclic movement

Statistic	Displacement (mm)									
	0.2		0.5		1		1.5		2	
	LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc
Mean Difference (mm)	-0.098	-0.116	-0.206	-0.256	-0.183	-0.383	-0.103	-0.330	-0.169	-0.388
Standard Deviation of the differences (mm)	0.005	0.005	0.032	0.025	0.084	0.058	0.014	0.061	0.024	0.173
Average Error (%)	48.86	57.86	41.12	51.16	18.31	38.33	6.86	22.03	8.47	19.39
Maximum Error (%)	53.20	61.36	49.13	60.75	48.72	57.70	9.01	30.38	10.66	37.02
Coefficient of Variation (%)	4.70	5.74	10.92	10.26	10.32	9.34	1.00	5.21	1.32	10.76

5.5.1.4.2 REAL-WORLD MOVEMENT TEST

For this test, the 3D printer movement resembles that of the pavement as a 2 -axle vehicle passes over it, as seen in Figure 5-15. The raw accelerometer reading for a single pulsed movement is shown in Figure 5-20 below. Two prominent pulses are evident in the figure, corresponding to the movement of the 3D printer head.

Raw accelerometer reading

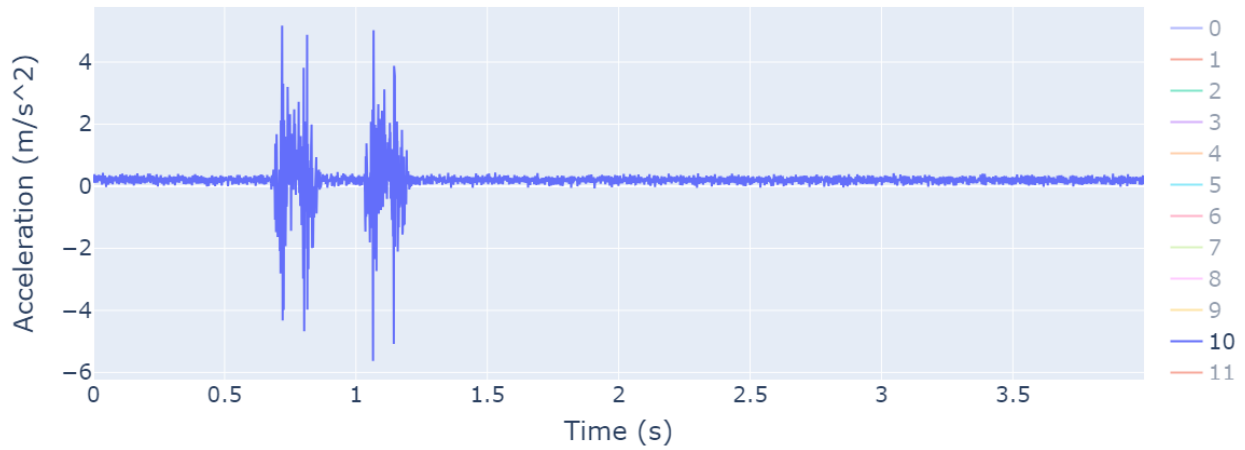


Figure 5-20: Raw accelerometer readings for a pulsed movement (This Study)

Converting this acceleration signal to a displacement using double integration causes a significant drift in the results as seen in Figure 5-21. To compensate for this drift, baseline correction and filtering is necessary.

Calculated displacement without baseline correction and filtering

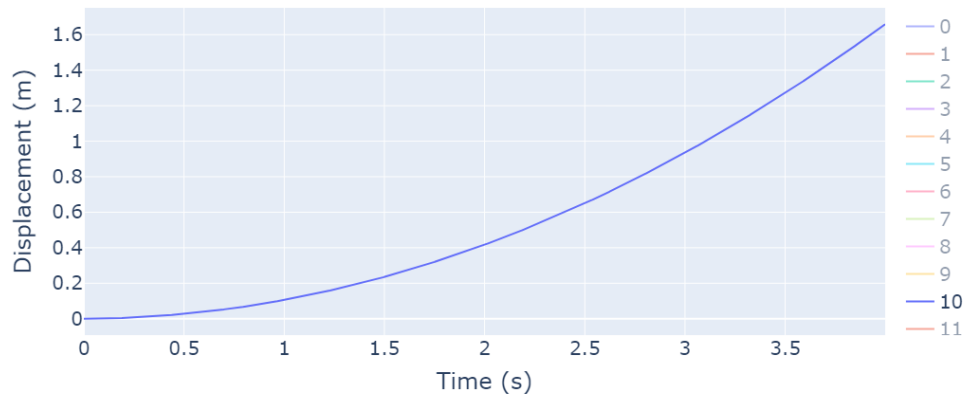


Figure 5-21: The significant drift in displacement estimations for a pulsed movement of the 3D printer head (This Study)

To eliminate the significant drift as observed above, baseline correction can be applied by subtracting a second order polynomial fit from the signal. A second order polynomial was chosen since a linear baseline correction is not adequate to estimate the random drift after double integration is done, as stated in [32].

Higher-order polynomials were also tested and did not have a significant impact on the result. Figure 5-22 below shows the baseline corrected signal. Note the units of the vertical axis is in meters.

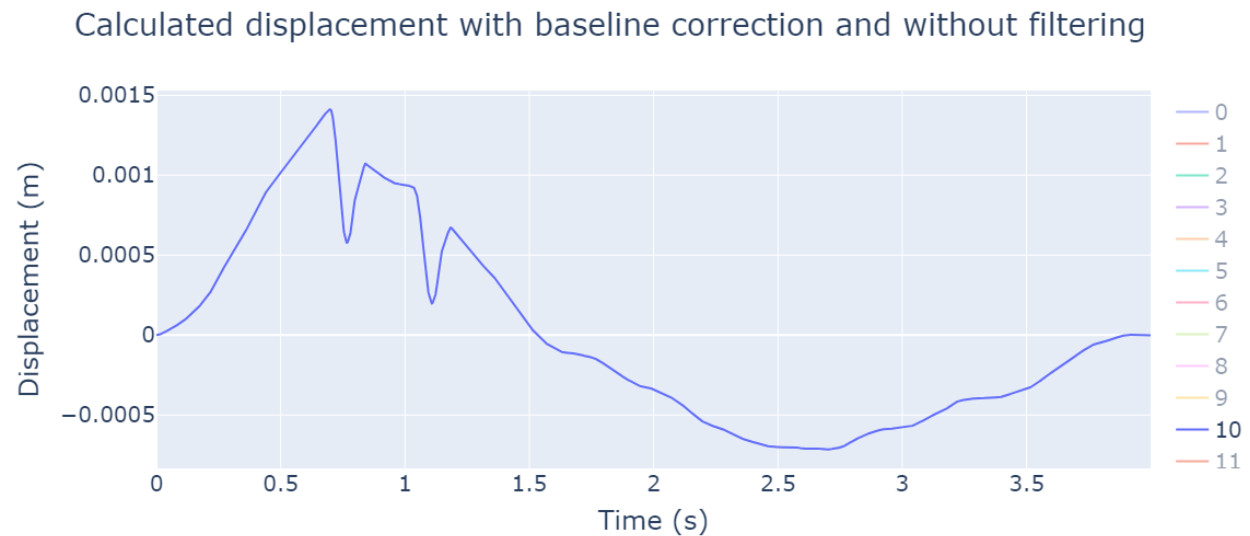


Figure 5-22: The signal after baseline correction (This Study)

When observing the figure above clear peaks can be identified, but the signal seems to be superimposed on a low-frequency signal. This low frequency signal is a result of the integration process which emphasizes the low-frequency components of a signal. Therefore, a Butterworth band-pass filter is used to deliver a clean signal. Figure 5-23 below shows the signal after filtering. Note the vertical axis unit has changed to mm. Taking a closer look at the signal, an oscillatory behaviour is evident leading to seemingly negative displacements. This is however not a true representation of the actual displacement, which only saw a positive displacement. To remove these oscillations, [24] suggests a Hilbert Transform, which gives the envelope of the original signal. This envelope is then combined with the original signal (by subtracting the envelope of the signal from the original signal) to remove the oscillations. Figure 5-24 shows the signal with the oscillations removed and shifted to align the first peak at the 2-second interval. Some oscillations are not removed as seen in the small peaks in between and after the main peaks.

Calculated displacement without shift

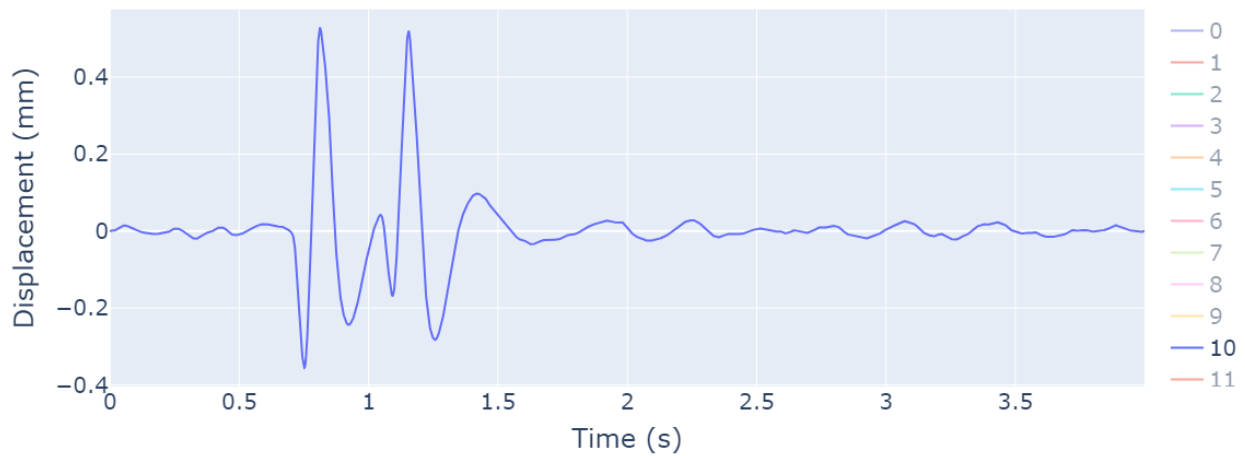


Figure 5-23: The displacement signal after filtering (This Study)

Accelerometer repeated measurement

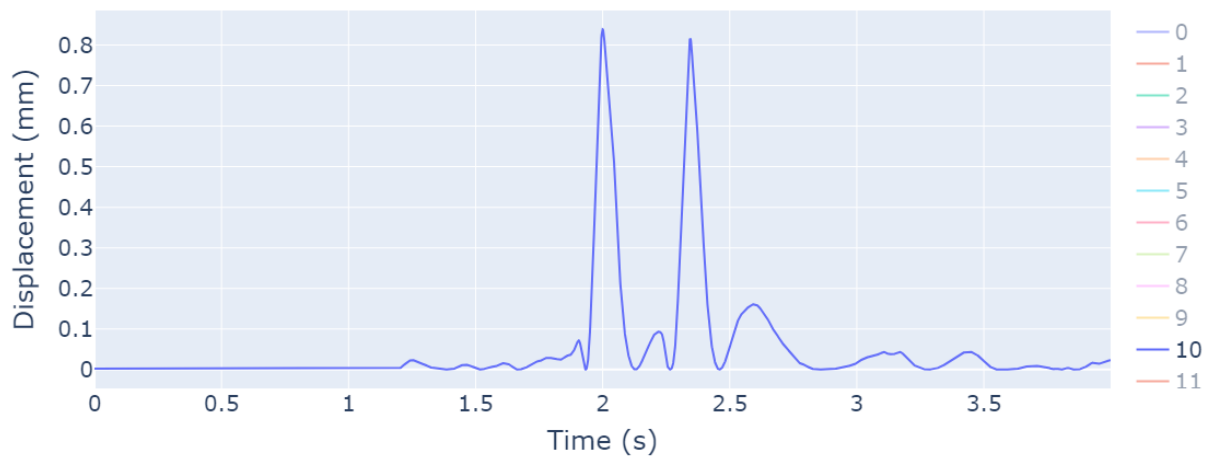


Figure 5-24: The final displacement signal after applying the Hilbert Transform (This Study)

SENSOR VARIATION

To show the variation in measurement of the pulsed movement, 20 repeated measurements are carried out on a single displacement value. Figure 5-25 below shows a 1 mm reference signal created by the 3D printer, and the mean estimations by both the LVDT and the accelerometer. Table 5-10 below shows

statistical measures over all the displacement values. As evident in the figure, the LVDT has a significantly higher amplitude than the reference measurement. On the other hand, the accelerometer has a consistently lower amplitude compared to the reference, like what was found in [19] and [24]. Therefore, a calibration can be done to correct the systematic errors.

Comparing the mean accelerometer and lvdt estimations

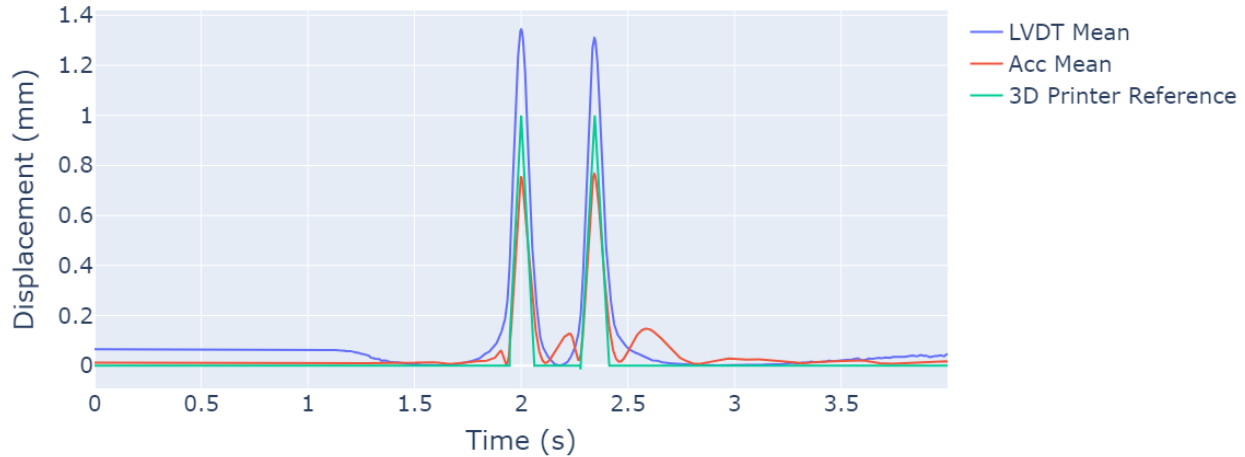


Figure 5-25: The average displacement for both sensors compared to the reference displacement of the 3D printer head (This Study)

When observing Table 5-10 below, there is a clear bias in both the LVDT and the accelerometer response. This bias can be removed through calibration discussed later. This bias is created by the decreased amplitude as seen in the figure above.

Table 5-10: Statistical measures of the variation in sensor outputs

		LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc
	Reference Displacement (mm)	0.2		0.5		1		1.5		2	
Statistic	Mean Difference (Ref. - Estimate) (mm)	-0.016	-0.085	0.009	-0.195	0.337	-0.196	0.611	-0.517	0.832	-0.458
	Standard Deviation of the differences (mm)	0.017	0.028	0.091	0.080	0.050	0.092	0.029	0.128	0.083	0.243
	Mean Signed Error (Bias) (mm)	0.016	0.085	-0.009	0.195	-0.337	0.196	-0.611	0.517	-0.832	0.458
	RMSE (mm)	0.023	0.089	0.089	0.210	0.340	0.216	0.612	0.532	0.836	0.515
	Coefficient of Variation (%)	9.338	24.725	17.802	26.111	3.712	11.471	1.378	13.068	2.945	15.725

To increase the accuracy of the estimations, a calibration factor is applied to the data to eliminate the systematic error in the estimates. The calibration is to be performed on the pulsed motion data only since it represents a real-world pavement displacement. A linear calibration curve as seen in Figure 5-26 and Figure 5-27 below can be used to calibrate the accelerometer and LVDT, respectively. As seen in the graph,

a linear relationship exists between the reference and estimated displacements, with a goodness of fit (R^2) close to 1. Note that both linear equations have an offset.

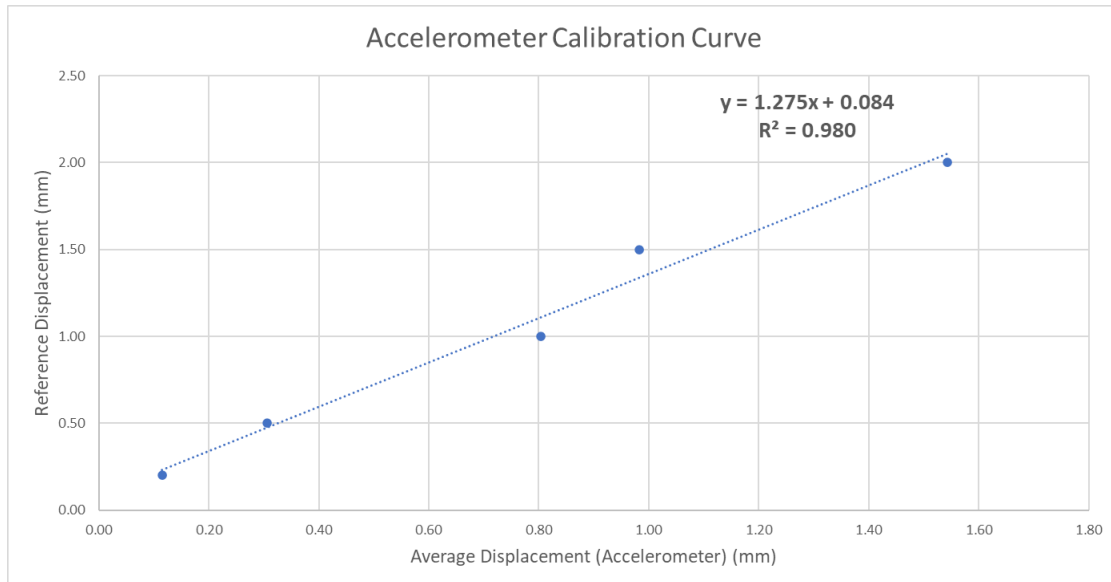


Figure 5-26: Accelerometer calibration curve (This Study)

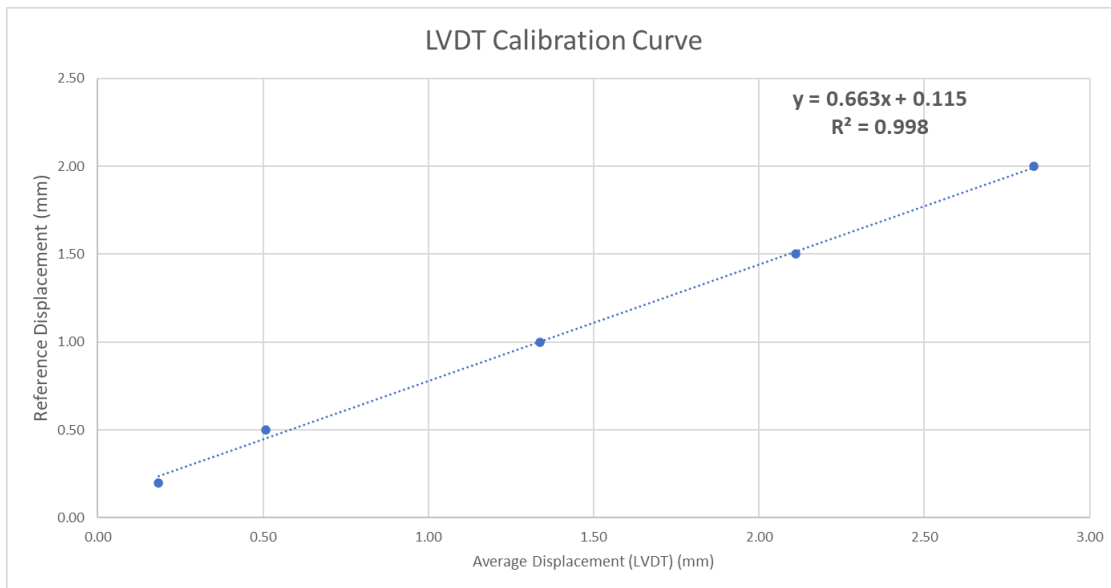


Figure 5-27: LVDT calibration curve (This Study)

After a calibration is done to remove the biases in the sensor response, a new elastic deflection and/or displacement estimate is calculated and shown in Figure 5-28. Additionally, Table 5-11 below shows the statistical measures of the calibrated estimates. Note that in the figure and subsequent depictions of displacement measured by the sensors, the offsets specified in the calibration formulas were deliberately omitted from the displayed signals. This deliberate omission aimed to ensure a consistent zero-starting reference point for all signals. The addition of the offset only occurred after the extraction of amplitudes, ensuring accuracy in the depiction of deflection amplitudes. When considering the statistics, the accuracy of estimation is significantly improved as expressed by the RMSE, with the accelerometer error reduced by almost half in all measurement ranges. The calibration also significantly reduced the LVDT error except at 0.2 mm displacement which sees a slight increase in the RMSE value.

Comparing the mean accelerometer and lvdt estimations

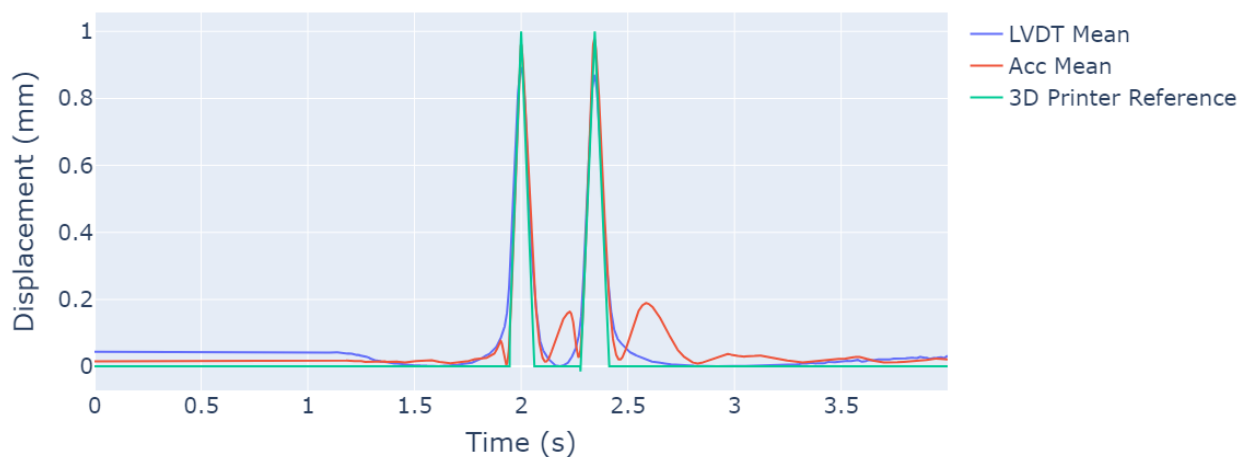


Figure 5-28: The calibrated accelerometer and LVDT estimates for a 1mm reference pulse (This Study)

When considering the mean difference between the reference and the calibrated estimates, this difference is significantly reduced for the calibrated accelerometer over all displacements. However, the standard deviation is slightly increased since amplitude adjustment also amplifies the possible errors. When comparing the Mean Signed Error or bias before and after calibration, a significant decrease in bias is evident in the accelerometer response. This indicates that the systematic error in the estimates have been minimized and that the calibration has addressed the consistent deviation in estimates. However, the LVDT bias in the lower displacement ranges increased. This may be a result of its inaccuracy in the lower displacement ranges as mentioned previously. Since the calibration increased the mean of the estimates significantly, the Coefficient of Variation decreased.

Table 5-11: The statistical measures after calibration

		Sensor									
		LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc	LVDT	Acc
	Reference Displacement (mm)	0.2		0.5		1		1.5		2	
Statistic	Mean Difference (Ref. - Estimate) (mm)	0.037	0.031	-0.047	-0.027	0.001	0.109	0.015	-0.163	-0.007	0.050
	Standard Deviation of the differences (mm)	0.011	0.036	0.060	0.102	0.033	0.118	0.019	0.164	0.055	0.309
	Mean Signed Error (Bias) (mm)	-0.037	-0.031	0.047	0.027	-0.001	-0.109	-0.015	0.163	0.007	-0.050
	RMSE (mm)	0.038	0.047	0.075	0.103	0.032	0.158	0.024	0.228	0.054	0.306
	Coefficient of Variation (%)	4.801	15.720	13.278	21.478	3.286	10.602	1.273	12.248	2.775	15.081

5.5.1.4.3 RESPONSE OF THE SENSORS WITH VARYING FREQUENCY

As vehicle speed changes in a real-world scenario, it is necessary to test the response of the sensors over varying frequencies. Since the important content lies more in the lower part of the spectrum, as discussed in Chapter 2, only frequencies below 15 Hz need to be considered. Figure 5-29 below shows the response of the LVDT and accelerometer for a sinusoidal movement of 1 mm. The frequency of movement is determined by the 3D printer, which has an upper limit of 15 Hz for 1 mm displacements or otherwise 1900 mm/min.

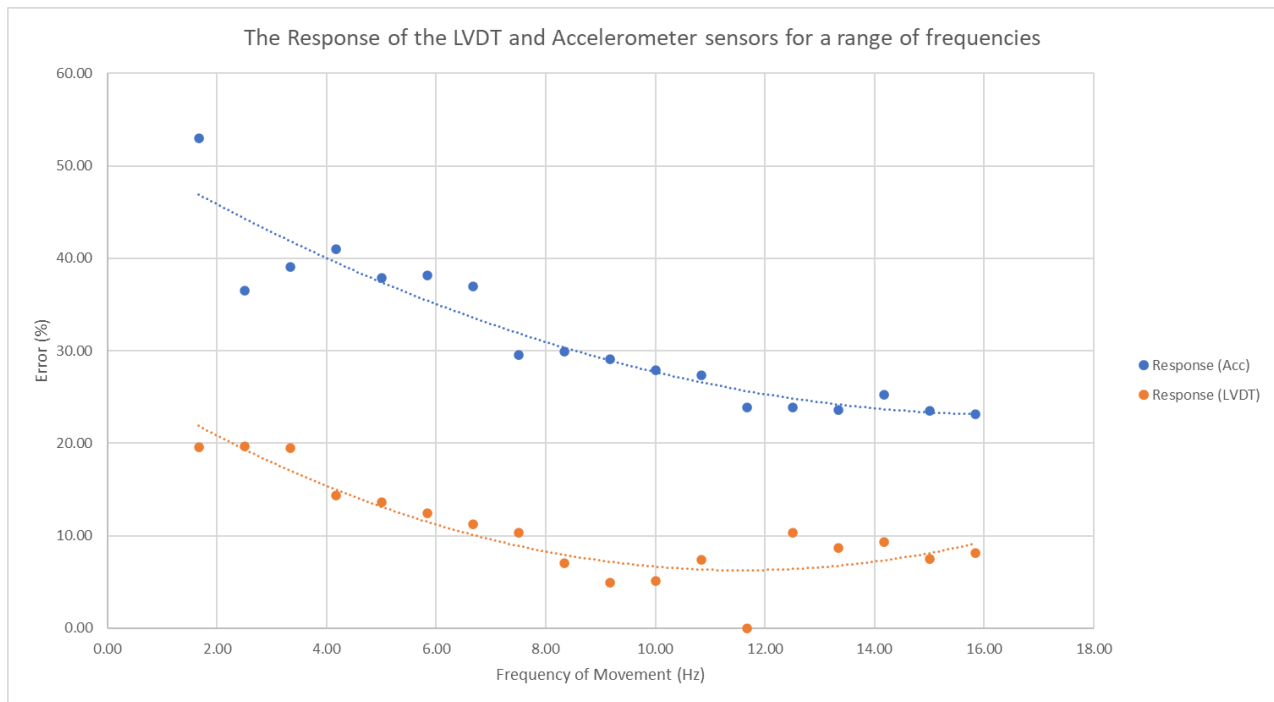
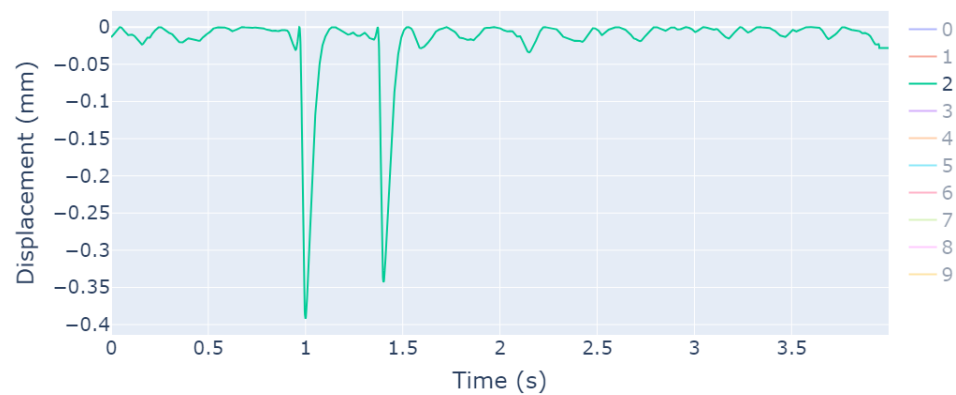


Figure 5-29: The response of the sensors over a range of frequencies (This Study)

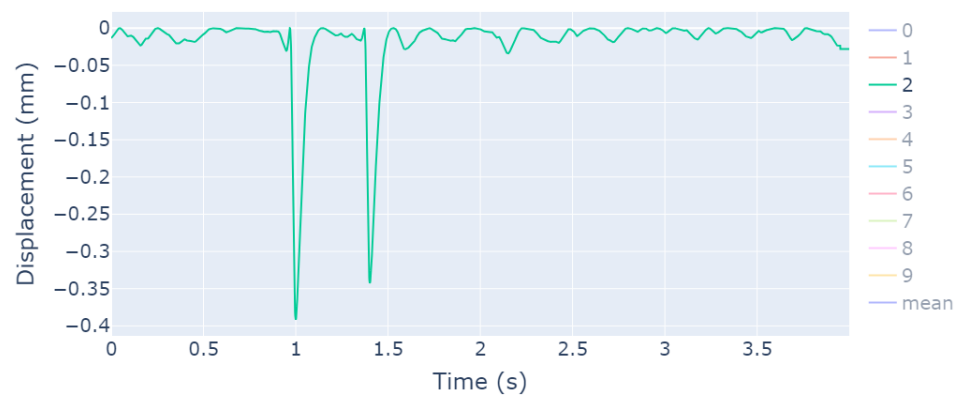
5.5.1.4.4 ACCELERATION CONVERSION METHODS

The various methods for converting acceleration to elastic deflection and/or displacement, as mentioned in the literature study above are compared in Figure 5-30 below. A 1 mm pulsed signal is used. As seen in the figure, all methods deliver almost the same result, with a slight variation in the transient phase of the signal. In all the other test cases a similar result was achieved. Therefore, the various methods need not be compared with one another since the slight variation should not affect the results. The baseline correction method was used for all tests.

Frequency Domain Integration



Baseline Correction Method



Consecutive Fit Subtraction

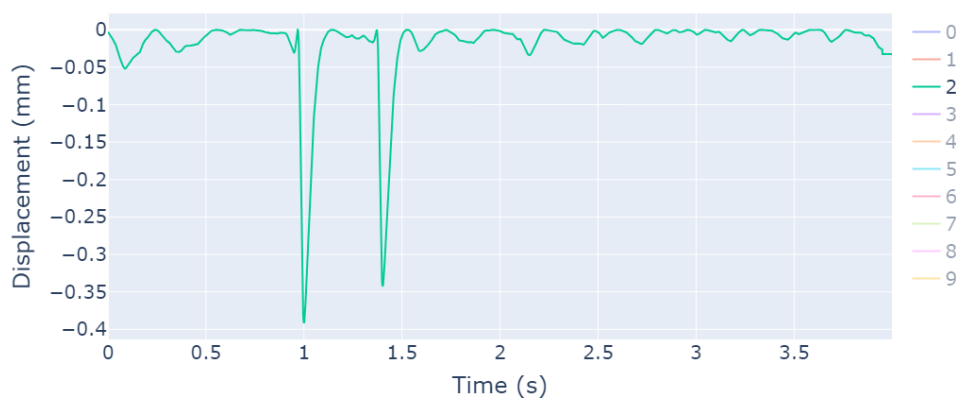


Figure 5-30: Comparison of acceleration conversion techniques

5.5.1.5 Discussion

The purpose of the laboratory test was to determine the accuracy and precision with which the displacement of the 3D printer head could be estimated by the data gathered from the accelerometer and the LVDT sensors. Firstly, consider the acceleration to displacement conversion method. Accelerations are converted to displacements using baseline correction implementing a least-squares fit detrending method as well as a Butterworth bandpass filter and a Hilbert Transform. As per reference [19], the effectiveness of the detrending method depends significantly on the selection of the drift polynomial and is less successful when applied to measurements characterized by a low signal-to-noise ratio (SNR). However, as observed in practical testing, if the polynomial fit is recalculated on each set of acceleration values, the accuracy of the trend removal is good. To understand the reliability of the accelerometer and the abovementioned conversion method, certain statistics can provide additional insight and are discussed below.

5.5.1.5.1 PRE-CALIBRATION DISPLACEMENT ESTIMATION RESULTS

Considering the uncalibrated displacement estimates for the impulse movement (real-world scenario) of the 3D printer, a large average amplitude difference between the reference and the estimates can be observed. This is true for both the accelerometer and the LVDT. However, this significant amplitude difference can be reduced by eliminating the systematic errors in the estimates by means of a calibration procedure. This calibration was also done in [65, 69], which attributed the reduced amplitude of the accelerometer estimate to the installation methods, the material used to fixate the device to the pavement, and the chosen cut-off frequencies of the band-pass filter. Considering the latter, a lower cut-off frequency does not effectively suppress the low-frequency noise in the data, leading to a disfigured signal. Increasing the cut-off frequency improves the appearance of the signal but decreases the amplitude thereof. Therefore, signal amplification is necessary after the filtering process, and in this case an amplification factor of 1.275 was used for the accelerometer (1.14 was used in [19]) and an attenuation factor of 0.6 for the LVDT. The calibration curve of both the LVDT and the accelerometer shows a linear fit to the datapoints with goodness of fit value (R^2) close to one for both sensors, indicating a good fit. The calibration significantly increased the accuracy of the estimates by minimizing the systematic errors as seen in the reduced Mean Signed Error (Bias) in Table 5-10 above.

5.5.1.5.2 POST-CALIBRATION DISPLACEMENT ESTIMATION RESULTS

After a calibration the results improved significantly, with the RMSE halving in the case of the accelerometer. For the LVDT the RMSE also improved drastically in the larger elastic deflection and/or displacement ranges. Looking at the other statistics presented in Table 5-11, some interesting conclusions can be made. The LVDT has a relatively constant RMSE over the displacement ranges (38 μm for 200 μm displacement and 54 μm for a 2 mm displacement), indicating that the variability across the measurement range is low. This is confirmed by the standard deviation which is also relatively constant over the measurement ranges. Furthermore, the mean difference or mean of the differences between the reference and the LVDT is much lower in the higher displacement ranges supporting the fact that the LVDT suffers in the lower displacements. For the accelerometer, the RMSE seems to increase as the displacement is increased (from 47 μm for 200 μm displacement to 306 μm for a 2 mm displacement), revealing higher variability for the larger displacements. This is expected as measurements at values in

the upper part of the measuring range of a sensor usually have more variability. Furthermore, the mean difference between the accelerometer estimates and the reference is relatively constant over the measurement range, however, increases slightly at 1 mm and 1.5 mm displacements.

5.5.1.5.3 THE EFFECT OF A CHANGE IN MOVEMENT FREQUENCY

Considering the response of the sensors with a varying frequency, the accelerometer errors are significantly lower above 5 Hz. However, below 5 Hz the error increases rapidly. The error increases from 35 % to 55 % from 5 Hz to 2 Hz, and from 25 % to 35% from 15 Hz to 5 Hz. This shows the limit in bandwidth of the accelerometer. For the LVDT, the error over all frequencies is expected to be constant since the bandwidth of the LVDT is from 0 Hz to 500 Hz. However, the response above shows a slight improvement in accuracy with increased frequency. Possible explanations for this may be that the LVDTs resolution increases with an increase in frequency. At higher frequencies, the signal-to-noise ratio improves, leading to an improved resolution and consequently a higher accuracy in LVDT measurements. Hysteresis may also play a role in the reduced accuracy at lower frequencies. The hysteresis effect is reduced at relatively higher frequencies, which increases the accuracy of measurements.

5.5.1.6 Conclusion

The conversion from an acceleration to a displacement proves to be possible, with reasonably good accuracy and precision. Consequently, the accelerometer seems to be adequate to be used as a elastic deflection and/or displacement measuring instrument. Furthermore, it is quite good at measuring smaller displacements when compared to the LVDT, however lacks the consistency that the LVDT has across the whole range of displacements.

The discrepancies between the reference signal and that of the sensors may be partly due to the build quality of the testing device. The springs on which the platform rests do not all have the same tension, leading to a slight tilt in the direction of the lower tension springs when the platform is compressed. This was compensated for by applying an off-centre pressure to the platform, however it may still affect readings. The testing device is also not exactly level with the ground, meaning accelerations in the x and y-axis of the accelerometer may also be present. This reduces the magnitude of acceleration in the z-axis, leading to a lower amplitude displacement signal. Furthermore, the large errors in the LVDT response at small displacements are caused by the inaccuracy in the characterization of LVDT response as discussed above.

As seen in Figure 5-29, the accelerometer produces large errors in the lower frequency range. Consequently, slow movements at very low frequencies fall outside of the bandwidth of the accelerometer. Practical implications are that pavement elastic deflections produced by slow moving vehicles cannot effectively be captured by the accelerometer. Furthermore, an accelerometer measures vibration, and with slow moving vehicles the vibrations might be minimal leading to lower accelerations, which fall below the sensitivity threshold of the accelerometer. Therefore, in choosing an accelerometer it is necessary to ensure that its bandwidth stretches to zero hertz, and that the sensitivity of the device is high.

5.5.2 In-road testing

In this section we outline the process of installing and conducting on-site tests for the device. Figure 5-31 illustrates the device's placement within a section of pavement located on the North-West University campus. This section consists of a 40 mm thick layer of asphalt concrete positioned on compacted brown earth soil. The device is situated within a cavity that measures 200 mm in depth and 150 mm in diameter. The slot (5 mm thick and 5 mm deep) integrated into the pavement serves to connect the LVDTs conditioning circuitry to the LVDT itself. It is important to note that this slot is a temporary addition since the final design proposed in this thesis will not incorporate a wired LVDT and solely relies on wireless methods.



Figure 5-31: The in-road sensor installation (-26.6943, 27.0900)

5.5.2.1 Pavement deflection with an accelerometer and a small vehicle

Two experiments were carried out to measure the deflection of the asphalt layer and the casing. In the first experiment, the accelerometer was attached to the underside of the asphalt layer to record its deflection, while the LVDT was used to measure the deflection of the casing. The focus of this experiment was to evaluate the impact of vehicle speed on displacement estimations. In the second experiment, the lateral distance between the wheel path and the accelerometer was increased to assess its effect on the estimations. Both sensors were sampled at a rate of 1 kHz. Figure 5-32 shows the raw sensor readings of the accelerometer (a) and the LVDT (b) for a vehicle passing over the sensor at a speed of 30 km/h. The axis for the accelerometer readings is acceleration in m/s^2 and time in seconds. The y-axis for the LVDT is in milli-volts. As seen in the figure, two prominent spikes are captured by both sensors, which corresponds with the two wheels of the vehicle passing over the sensor. Furthermore, the readings of the LVDT show an elastic deflection and a deformation of the casing. This is in fact the casing being embedded further into the pavement structure. These raw sensor readings can be converted to a displacement as shown above.

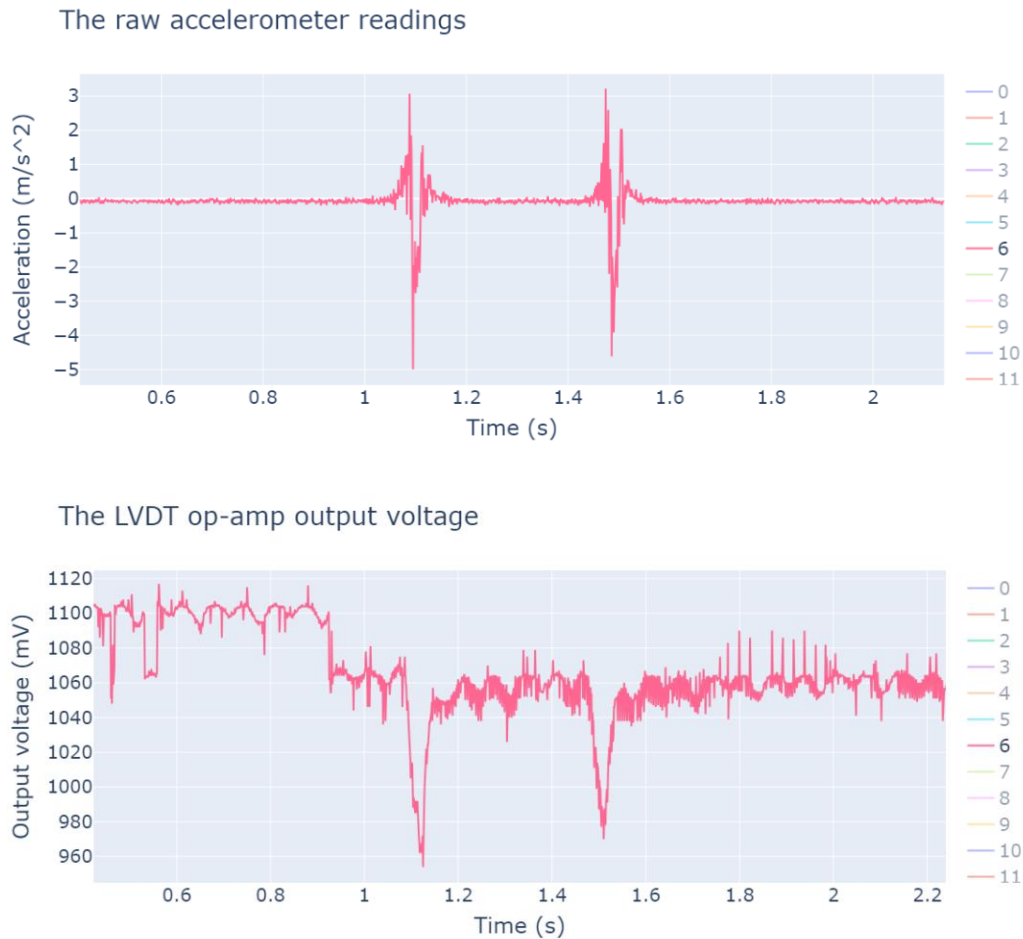


Figure 5-32: The raw measurements for a) Accelerometer and b) LVDT as a two-axle vehicle drives over the device

The displacement estimates for multiple vehicle passings are shown in Figure 5-33 below. Figure 5-33 a) shows the accelerometer estimates, revealing a quite stable and repeatable output. Figure 5-33 b) depicts the LVDT estimates for the permanent displacement of the casing. Note from the figure that the first spike is significantly larger compared to the second, revealing that the casing undergoes a significant initial permanent deformation. This means that the casing must be slowly returning to its original position when no load is applied. The average displacement estimates for both sensors are shown in Figure 5-33 c), with the LVDT estimate just mirrored over the x-axis to depict a downward deflection. Note that for this experiment the LVDT and accelerometer do not measure the same displacements, with the LVDT measuring the displacement of the casing while the accelerometer measures the displacement of the pavement.

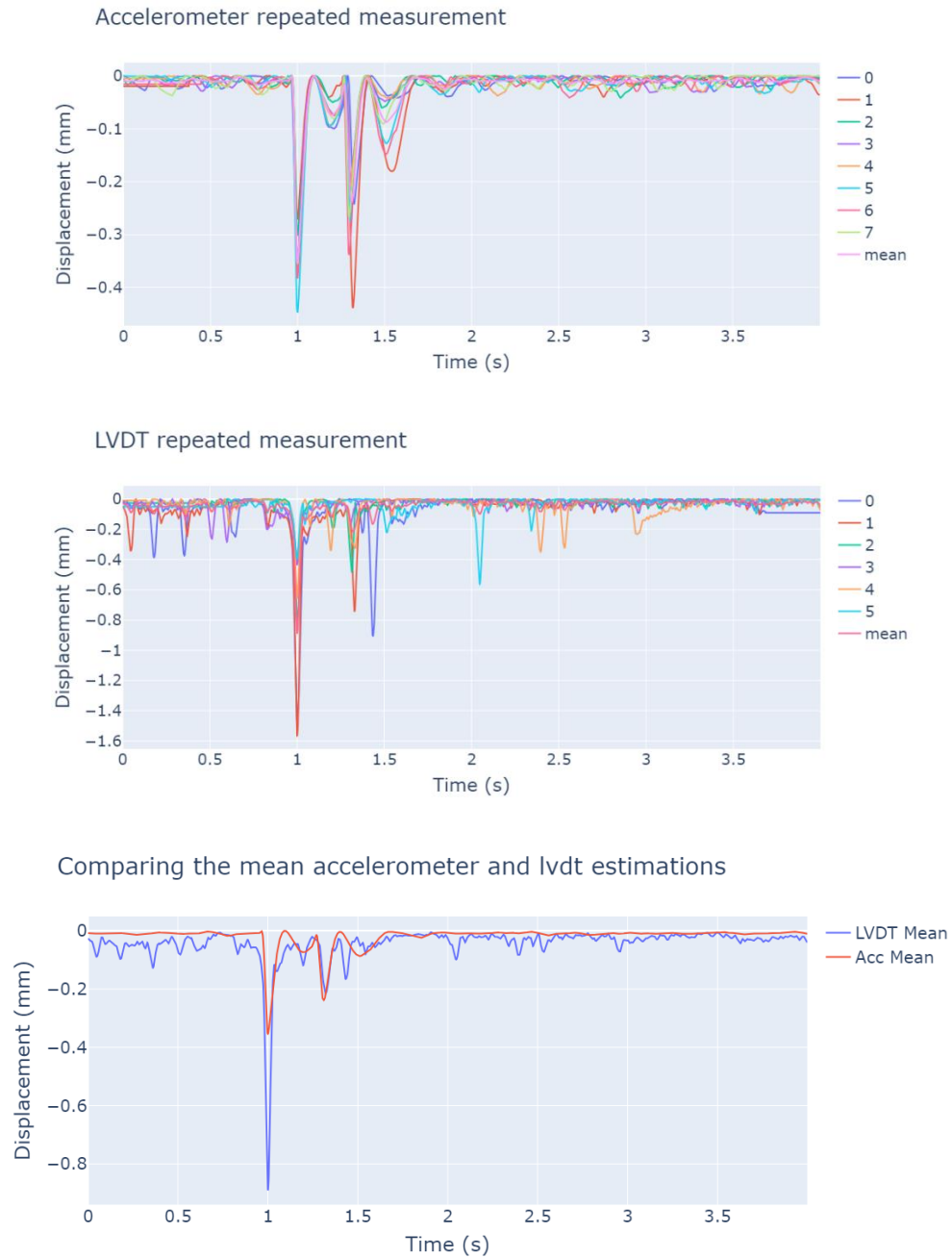


Figure 5-33: The estimated displacement from a) the accelerometer b) the LVDT and c) the means of both sensors .

5.5.2.1.1 VARIATION IN VEHICLE SPEED

In this test, a Daihatsu Sirion with a mass of 915 kg (2017 lbs) is utilized as the test vehicle. The experiment involves varying the vehicle speed as it passes over the installed device, ranging from 10 km/h to 70 km/h. Table 5-12 below presents the accelerometer displacement estimates and LVDT measurements at different incremental speeds. The table illustrates a notable variance in LVDT measurements: a stark shift is evident between the initial two speeds and the subsequent ones. This considerable deflection drop can be traced to the casing's change in position post the 20 km/h mark. As the LVDT core is affixed to the casing, it detected this permanent shift.

Table 5-12: Displacement measurements at varying speeds (-26.6943, 27.0900)

Speed (km/h)	Accelerometer Estimate (mm)	LVDT Measurement (mm)
10	0.330	1.723
20	0.320	1.874
30	0.380	0.640
40	0.337	0.557
50	0.319	0.557
60	0.343	0.431
70	0.277	0.415

5.5.2.1.2 VARIATION IN THE DISTANCE FROM THE WHEEL PATH TO THE SENSOR

To accurately measure the deflection bowl caused by a passing load, it is necessary to use multiple sensors positioned longitudinally and laterally within the pavement. These sensors are responsible for detecting the pavement deflection at different positions. Therefore, the displacement sensor employed must have the capability to measure the pavement deflection even when the wheel does not directly pass over it. In this specific test, the distance between the accelerometer position and the wheel path is adjusted to determine the maximum distance at which the accelerometer can effectively sense deflection. This information aids in determining the appropriate spacing for sensors within a pavement section. Table 5-13 presents the deflection measurements obtained at various distances. It is observed that detectable deflection occurs only up to 10 cm. Beyond this point, the signal becomes indistinguishable from noise. In this test the LVDT measurements were excluded since the LVDT core was fixed to the casing of the device and would not accurately reflect/detect the pavement deflections as the load moves away from the centre of the casing.

Table 5-13: Deflections measured at varying wheel-to-accelerometer distance

Wheel distance from the accelerometer (cm)	Accelerometer Estimate (mm)
0	0.380
5	0.199
10	0.186
15	-

5.5.2.2 Pavement deflection measured by both the LVDT and the accelerometer for a large vehicle

In this experiment the LVDT core was mounted to the bottom of the asphalt concrete layer of the pavement (previously mounted to the casing) to measure its response alongside the accelerometer. The mounting is shown in Figure 5-34 below.

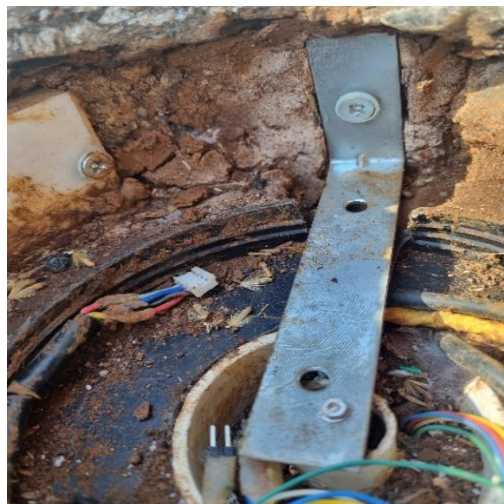


Figure 5-34: The LVDT core mounted beneath the asphalt concrete layer with a steel bracket (-26.6943, 27.0900)

With this configuration, it is possible to compare the measurements of both sensors. Figure 5-35 below shows a single response of the LVDT and the accelerometer for a 2-tonne pick-up truck driving at 30 km/h over the sensor unit. The effect of the 2 axes of the vehicle is clear in the figures.

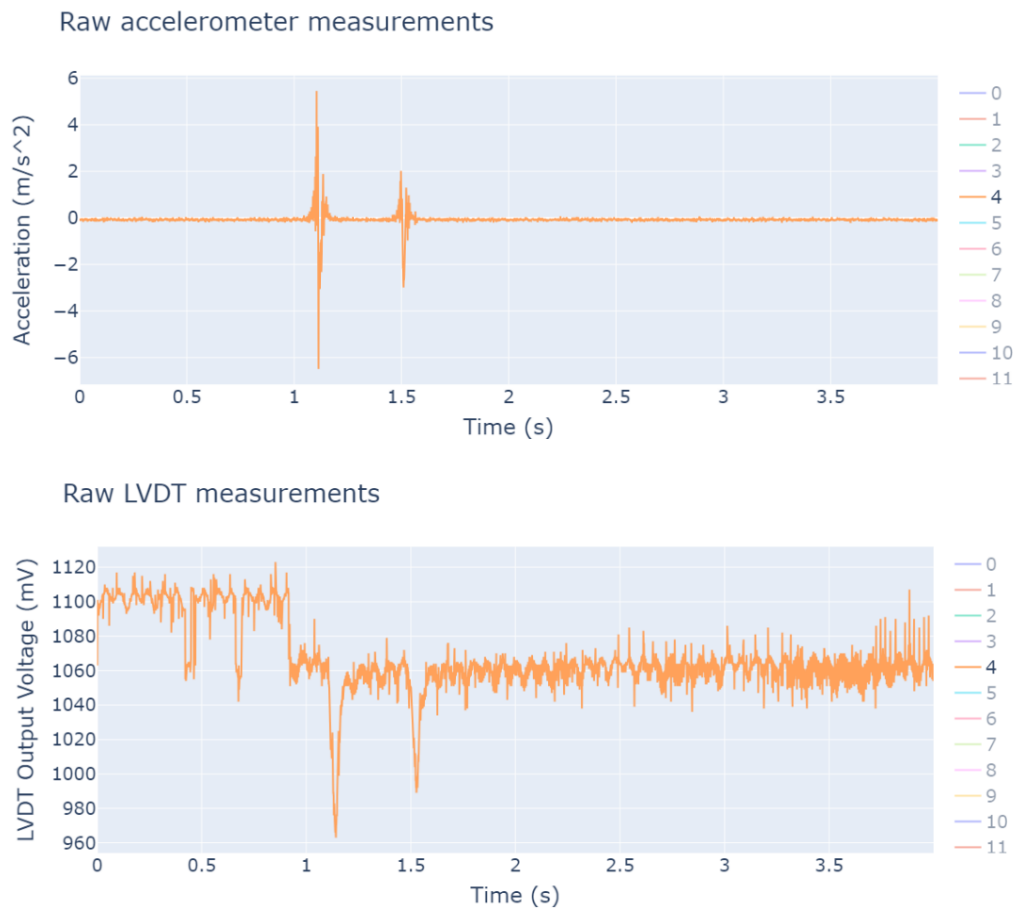


Figure 5-35: The raw readings from (a) the accelerometer and (b) the LVDT (-26.6943, 27.0900)

These raw measurements are then converted to a displacement estimate and is shown in Figure 5-36 a) and b) below. The average of these measurements is illustrated in Figure 5-36 c). These measurements are calibrated using the calibration equation calculated during the laboratory tests. As seen in the figures below, the front axle of the vehicle causes a much higher deflection compared to the rear axle. This is expected since the front axle has a higher downward axle load (5.4 kN vs 3.6 kN).

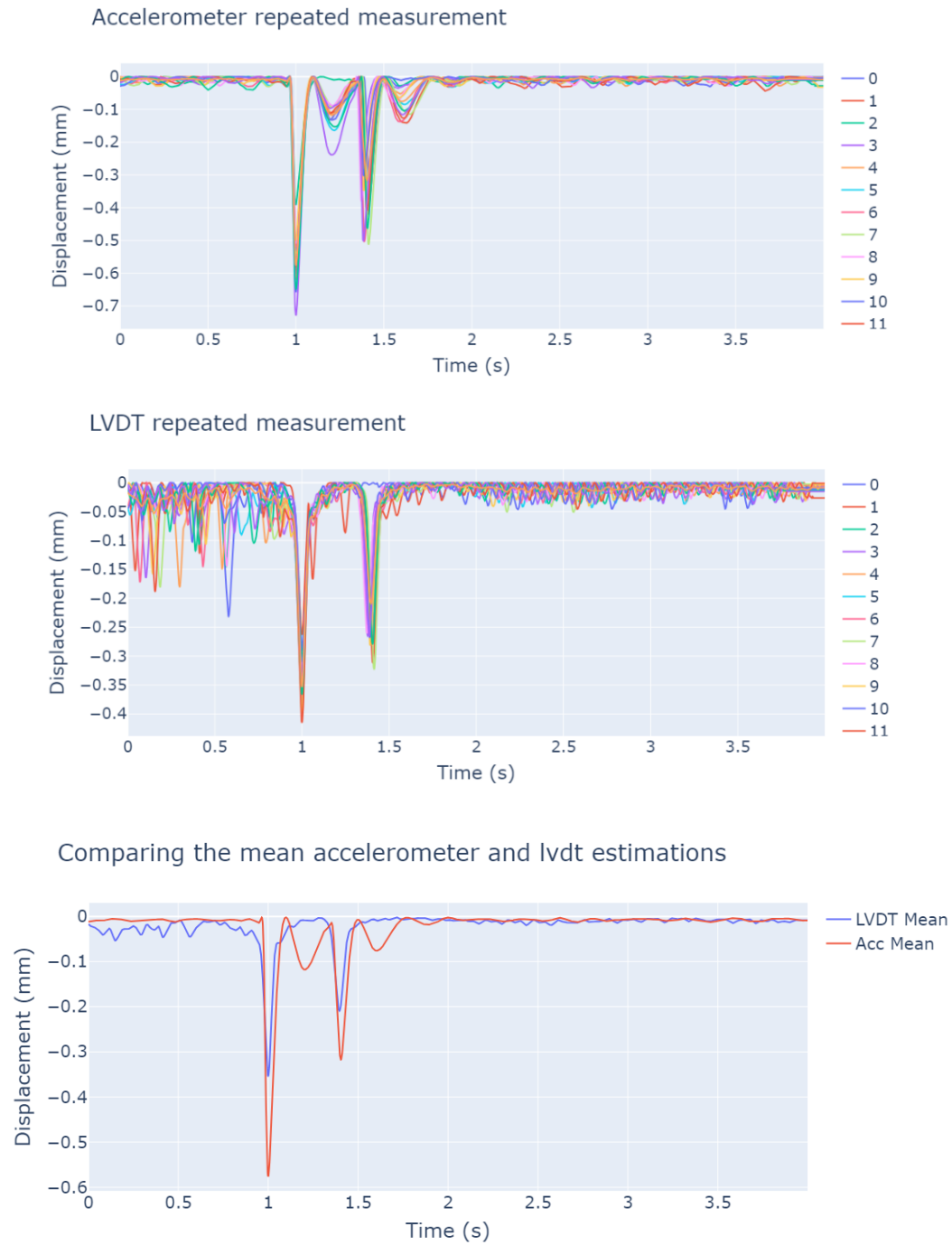


Figure 5-36: The estimated displacement of (a) the accelerometer (b) the LVDT and (c) the average of both sensors

5.5.2.2.1 VARIATION IN VEHICLE SPEED

In this test, a Mazda BT50 pick-up truck with a mass of 2 051 kg (4 522 lb) is utilized as the test vehicle. The experiment involves varying the vehicle speed as it passes over the installed device, ranging from 30 km/h to 60 km/h. Table 5-14 below presents the accelerometer displacement estimates and LVDT measurements at different incremental speeds. Figure 5-37 shows a graph of this data and reveals a slight decreasing trend in the estimates.

Table 5-14: Displacement measurements at varying speeds

Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)	LVDT Measurement Front Axle (mm)	LVDT Measurement Rear Axle (mm)
30	0.584	0.450	0.460	0.419
40	0.568	0.486	0.453	0.421
50	0.498	0.464	0.474	0.447
60	0.433	0.347	0.454	0.391

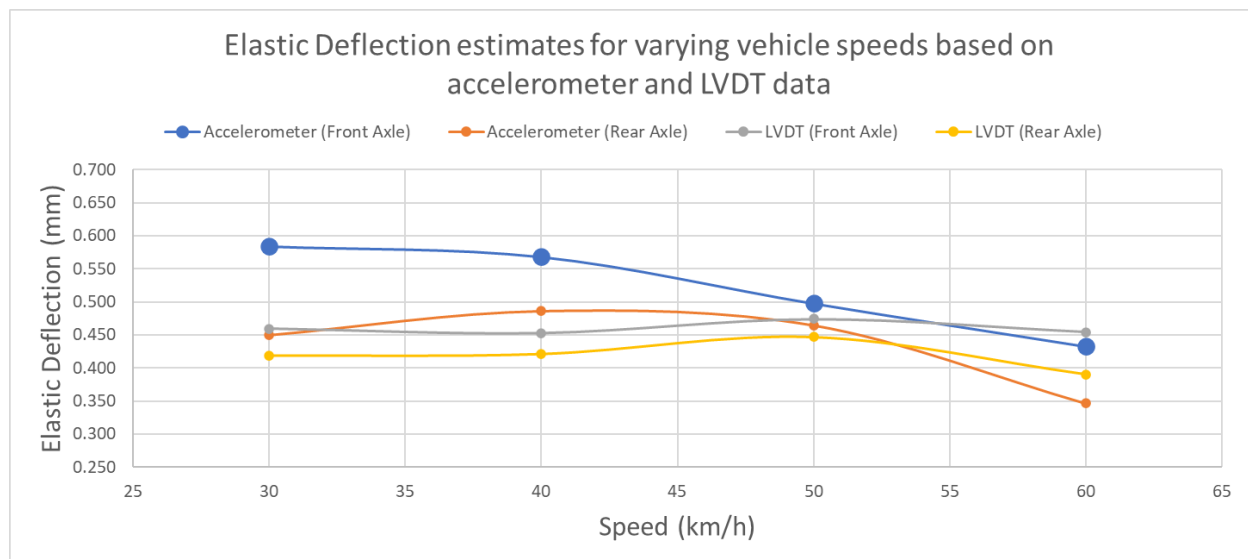


Figure 5-37: The deflection of the pavement with varying speed (-26.6943, 27.0900)

5.5.2.2.2 VARIATION IN THE DISTANCE FROM THE WHEEL PATH TO THE SENSOR

Like the first test, the distance between the wheel centreline of the Mazda pickup-truck and the centreline of the in-road device was increased. Table 5-15 presents the deflection measurements obtained at various distances for the front-axle of the vehicle. Pavement deflection is shown up to 15 cm, after which the peaks are indistinguishable from noise. However, if the trend as seen in Figure 5-38 is extended by means of an exponential function to where the elastic deflection is very close to 0 ($\gamma = 0.001$), the deflection bowl has an estimated radius of 64 cm. The deflection as measured by the LVDT is consistently lower than that of the accelerometer, as seen in the previous test as well. The radius of the deflection bowl as measured by the LVDT has an estimated radius of 70 cm.

Table 5-15: Deflections measured at varying wheel-to-sensor distance

Wheel distance from the accelerometer (cm)	Accelerometer Estimate (mm)	LVDT Estimate (mm)
0	0.584	0.437
5	0.313	0.265
10	0.189	0.184
15	0.126	-

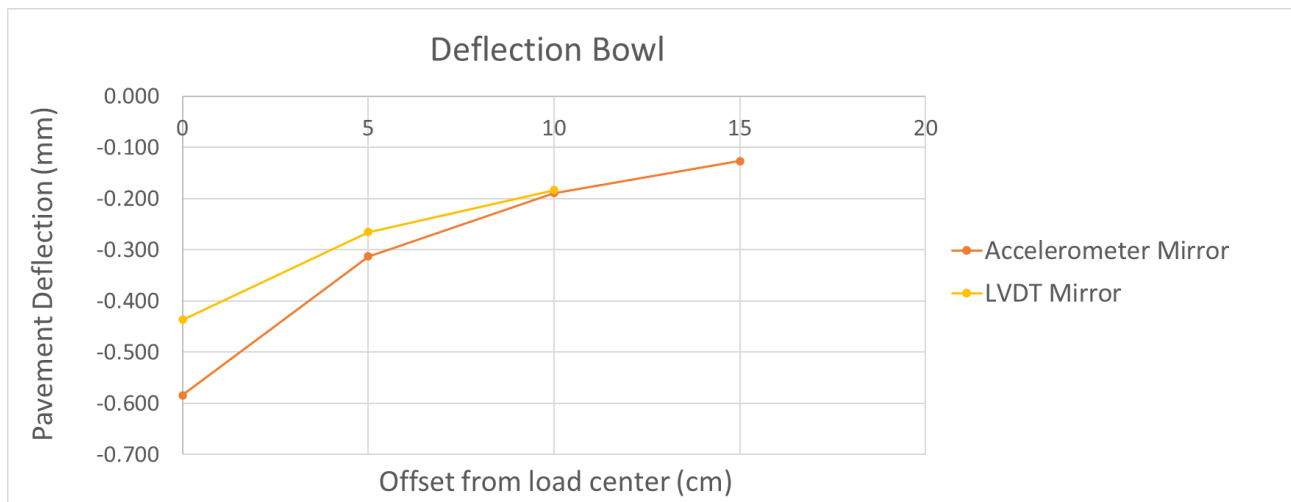


Figure 5-38: The deflection bowl created by the 2-axle pickup truck as measured by both sensors

5.5.2.3 Pavement deflection measurements on thicker asphalt concrete layers

5.5.2.3.1 UNIVERSITY OF PRETORIA ENGINEERING 4.0 TEST SECTION

In this test a road rail vehicle (RRV) weighing 10 tonnes is used as the test vehicle. The pavement consists of an 80 mm thick asphalt concrete layer seated on top of a compacted granular base layer. The test section is located at the University of Pretoria Engineering 4.0 facility. Additionally, measurements obtained from a lightweight deflectometer (LWD) provided a good reference pavement deflection measurement. Furthermore, only the speed variation test was conducted as it was significantly more difficult to consistently keep the test vehicle's wheel path at a set distance.

The test conducted on the 80 mm pavement showed a significant decrease in pavement deflection with speed compared to the previous tests with only a 40 mm thick AC layer. Figure 5-39 shows a single reference measurement on this specific pavement. Pavement deflections at various points ranged from 144 micron to 271 micron for a 20 kN force. The red curve in the figure shows the force applied by the Light Weight Deflectometer (LWD), and the blue curve shows the recorded deflection of the asphalt layer.

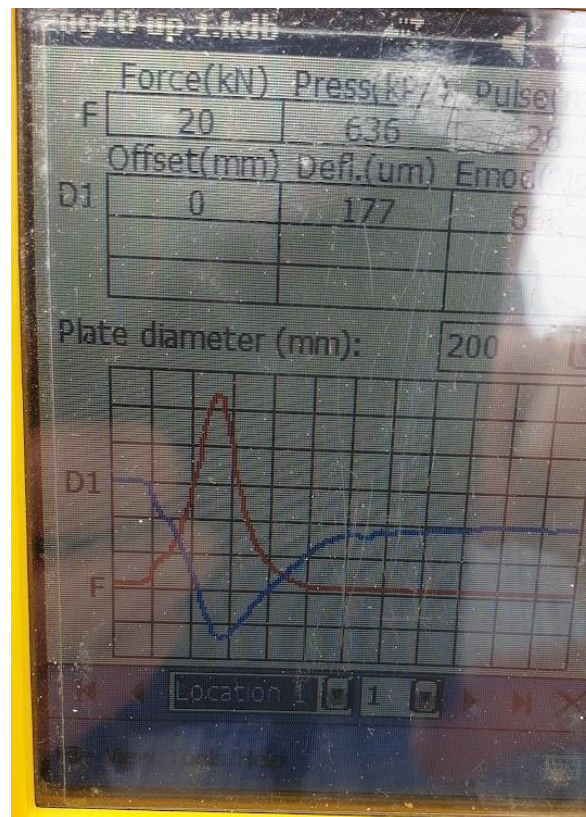


Figure 5-39: A sample reference deflection recorder by the LWD

Note that the LWD has a maximum force of 20 kN while the RRV (with no extra load) has a maximum downward force on a tire of almost 29 kN (rear-axle) and 23 kN (front-axle). Figure 5-40 shows the deflections of the pavement estimated from the accelerometer data as the RRV passes over the device at a speed of 30 km/h. As seen in the figure, the second peaks are not aligned, indicating a slight variation in the speed of the vehicle across repetitions. Furthermore, the amplitude of the second peaks seems to be lower than the first even though the rear axle of the vehicle is heavier. This is because the rear axle has a dual wheel configuration, resulting in the downward force being distributed between the two wheels, leading to a lower concentrated downward force and a lower deflection result.

Accelerometer repeated measurement

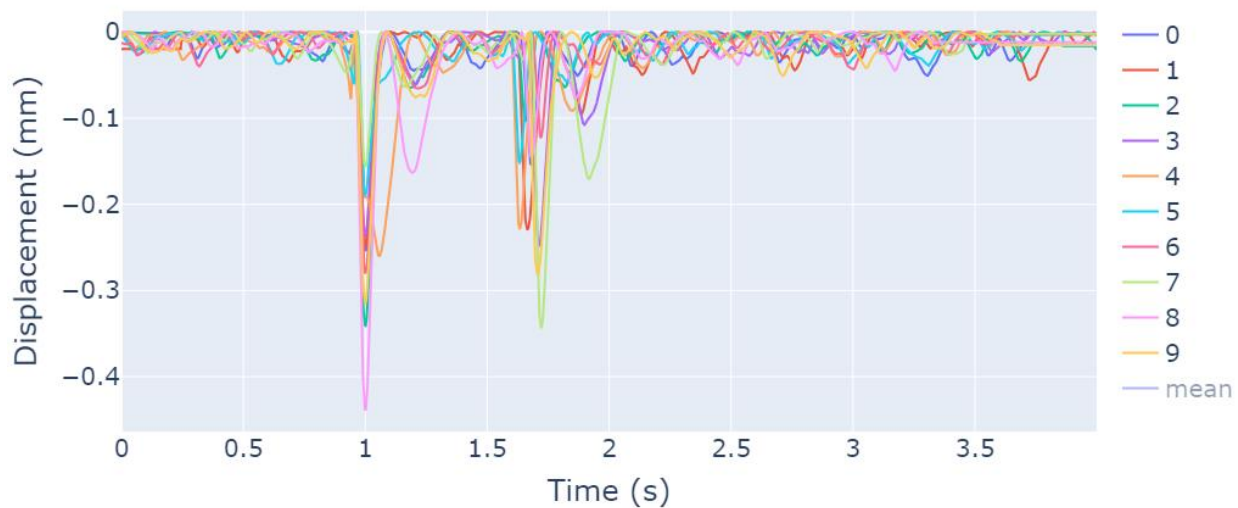


Figure 5-40: 80 mm Pavement deflection caused by the 10 tonne RRV

The mounting technique as seen in Figure 5-34 seemed to be less effective in the relatively thick asphalt layer and caused the LVDT to deliver inconsistent results. Therefore, the LVDT deflection estimates are not shown here. Varying the speed of the RRV seems to influence the estimates as seen in Table 5-16 and visually depicted in Figure 5-41. The RRV could only achieve a speed of 30 km/h. It was observed that there is an increasing trend in the deflection with increase in speed opposed to the decreasing trend as observed in earlier tests, and what is normally expected.

Table 5-16: The pavement deflection estimates based on the accelerometer data for various vehicle speeds

Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)
10	0.315	0.245
20	0.296	0.229
30	0.321	0.259

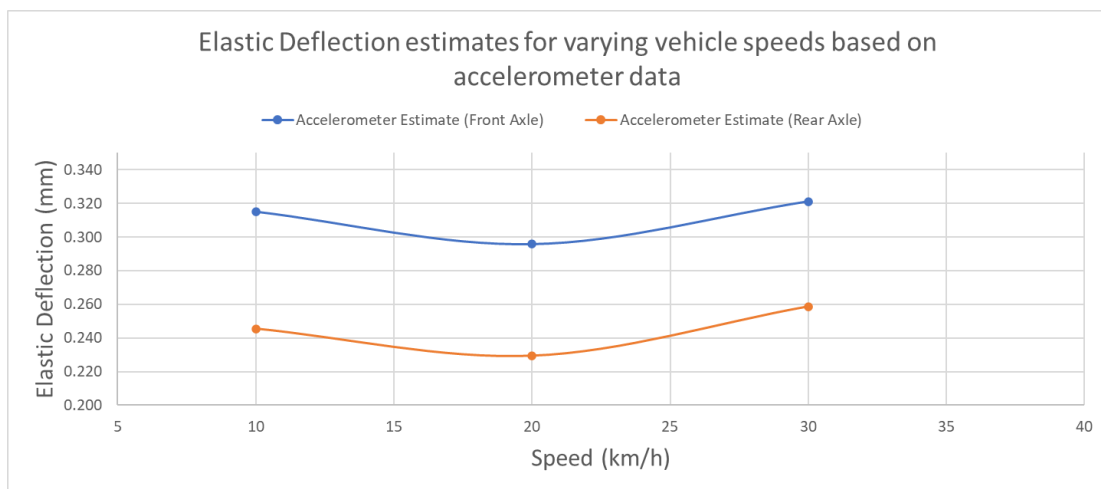


Figure 5-41: The deflections experienced by the 80 mm thick asphalt layer derived from measured accelerometer and LVDT data for varying vehicle speeds

5.5.2.3.2 N4 TEST SECTION

In this test a road rail vehicle (RRV) weighing 10 tonnes is used as the test vehicle. The pavement consists of a 200 mm thick asphalt concrete layer. Additionally, measurements obtained from a lightweight deflectometer (LWD) provided a good reference pavement deflection measurement. Furthermore, only the speed variation test was conducted as it was significantly more difficult to consistently keep the test vehicle's wheel path at a set distance. In this test, the RRV could reach speeds of up to 60 km/h.

With this test a new mounting technique was used as shown in Figure 5-42. It consists of a u-shaped bracket, firmly fixated to a shoulder in the AC layer by means of HBM X60 cold curing glue (used for stain gauge installations).



Figure 5-42: The u-shaped bracket mounting

The LWD measured a pavement deflection between 50 microns and 100 microns for a 20 kN load. With this new installation technique, the LVDT measurements could also be captured. Table 5-17 shows the resulting pavement deflection estimates on the N4 test section and Figure 5-43 shows a visual depiction of the data.

Table 5-17: The pavement deflection estimates based on accelerometer and LVDT data for various vehicle speeds

Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)	LVDT Measurement Front Axle (mm)	LVDT Measurement Rear Axle (mm)
20	0.158	0.148	0.155	0.145
40	0.166	0.142	0.168	0.150
60	0.290	0.319	0.151	0.152

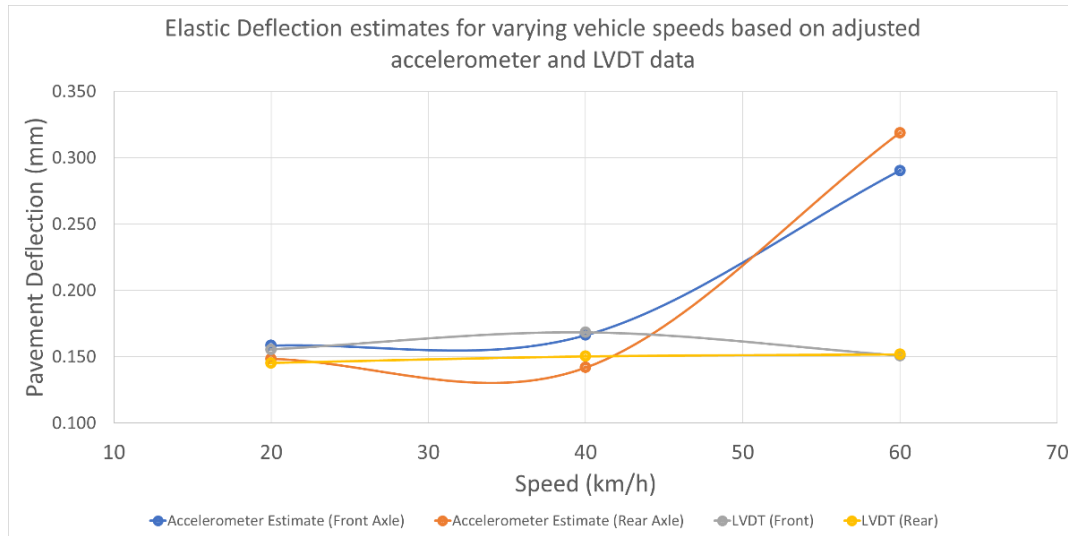


Figure 5-43: The deflections experienced by the 200 mm thick asphalt layer derived from measured accelerometer and LVDT data for varying vehicle speeds

5.5.2.4 Discussion

The goal of the in-road tests was to determine, firstly, if the deflection estimates were consistent over a range of vehicle speeds, and secondly, if a visible deflection bowl can be observed as a vehicle passes over a section of pavement.

5.5.2.4.1 NORTH-WEST UNIVERSITY 40 MM AC LAYER PAVEMENT

In the first round of tests on the 40 mm AC road at the North-West University, the LVDT was mounted to the casing of the device, which did not provide adequate results as the casing seemed to deflect significantly more compared to the pavement. For this reason, only the accelerometer data was used to estimate the true deflection of the pavement. Furthermore, for this test a 915 kg hatchback was used as the test vehicle, which results in an approximate downward force of 2.25 kN per wheel. This force deflected the 40 mm thick AC layer by an average of 330 μm . Comparing the deflection to that found in other sources, similarities can be observed. In [24], a force of 45 kN deflected the pavement by 400 μm , and in [19] a force of 80 kN resulted in a mere 150 μm deflection. This smaller deflections at higher forces highlights the difference in pavement designs. In this case, the pavement is 40 mm thick and seated on top of a sub-grade layer, whereas in [24] the AC layer has a thickness of 110 mm and is seated on a UGB layer. Tests in [19] also used a 110 mm thick AC layer, however, it was seated on top of a 178 mm thick concrete layer which gives the extra rigidity and impact resistance.

In the second in-situ test on the 40 mm AC road, which uses a 2-tonne vehicle (5.5 kN on front wheel and 4.2 kN on back wheel), an average pavement deflection of 521 μm (Accelerometer - Front Axle), 437 μm (Accelerometer - Rear Axle), 460 μm (LVDT - Front Axle), and 419 μm (LVDT - Rear Axle) can be observed across various speeds. The vehicle has twice the load per wheel compared to the first test and results in an increase of between 100 and 200 μm in average pavement deflection measured by the accelerometer

and LVDT. For this test a new mounting technique was used for the LVDT, fixating it to an L-shape bracket that is fastened to the AC pavement layer delivering better results compared to the LVDT core fastened to the device housing. Consequently, the results of the accelerometer and the LVDT can be compared. In the laboratory tests, the LVDT and the accelerometer delivered closely related displacements, however, with the in-road tests the LVDT seems to show a consistently lower pavement deflection compared to the accelerometer except at 60 km/h speeds (see Figure 5-37). The average difference between the two sensors is 40 μm . This discrepancy can partly be explained by the interpretation in [32], which attributes the difference to the accelerometer measuring the deflection of the pavement structure as a whole, whereas the LVDT solely measures deflection in relation to a reference point. Another possible reason for the discrepancy may be related to the installation method of the LVDT, which uses an L-bracket to mount the core at the centre of the cavity (see Figure 5-34). Inadequately securing this L-bracket to the pavement could potentially diminish the deflections detected by the LVDT, affecting the sensitivity of the device.

5.5.2.4.2 UP ENGINEERING 4.0 80 MM AC LAYER PAVEMENT

Considering the third set of tests conducted on the UP Engineering 4.0 test-section with a 80 mm thick asphalt layer, a number of additional insights are gained. Firstly, since a reference measurement from the LWD was available, the accuracy of the estimations could be determined. For the UP test-section, the deflections estimated by the accelerometer seemed to correlate with the reference measurements. The accelerometer estimated an average deflection of 278 μm over the various speeds against an average deflection of 178 μm for the LWD. This difference could be attributed to the additional weight of the RRV which has an average of 6 kN of force more than the LWD. Analysing the data presented in Table 5-16, it is evident that despite the rear wheel exerting a greater downward force, the front wheel causes a more pronounced deflection on the pavement. This discrepancy arises due to the rear axle's configuration with a double wheelset on each side, which distributes the downward force more evenly.

5.5.2.4.3 N4 200 MM AC LAYER PAVEMENT

In the last test on the N4 test section with a 200 mm thick asphalt layer, the speed of the RRV was increased to 60 km/h, and the resulting average deflection estimated by the accelerometer is 204 μm . This is significantly higher than the reference measurement average of 50 μm leading to a significant error in the estimates. The LVDT however, shows a much more constant deflection but also has a significantly higher amplitude than the LWD. This could be due to the construction of the asphalt concrete layer, or the type of force exerted by the LWD compared to the force exerted by an actual vehicle that drives over the pavement. Furthermore, the offset added to the sensor estimates as a result of the calibration action limited their ability to measure down to very low deflection levels.

The speed at which a vehicle travels also seems to have a slight effect on the pavement deflection. A slight decrease in the magnitude of deflections for the first two test cases can be observed for both sensors as the speed of the vehicle increases. This observation aligns with the findings reported in [24, 39], which also identified this trend. A possible explanation for this occurrence can be derived from the behaviour of the asphalt layer under load. The modulus of elasticity of the asphalt concrete layer tends to increase with higher loading rates, such as faster vehicle speeds. This increase in modulus suggests a greater resistance to deformation under rapid loading, resulting in relatively smaller deflections. However, this relationship between the speed of the vehicle and the modulus of the asphalt layer is more complex being greatly

influenced by the temperature of the asphalt layer, the viscoelastic properties thereof, and the design of the pavement. Consequently, this behaviour might not necessarily generalize to or hold true for different types of pavements. This can be clearly seen in the tests conducted on both the UP test-section and the N4 test section, with both pavements having a much thicker asphalt layer. In these tests the increase in speed seemed to increase the pavement deflections. In the UP tests, a subtle fluctuation in the trend is noted: a slight decrease in deflection from 10 km/h to 20 km/h followed by an increase from 20 km/h to 30 km/h. However, in the N4 tests, a far more pronounced increase in deflection is evident between speeds of 40 km/h and 60 km/h. This sharp increase in deflection at higher speeds contradicts findings in similar studies, demanding thorough investigation.

To ensure this anomaly wasn't influenced by the Butterworth filter's specification, the lower cut-off frequency was varied extensively across for each speed, from a value below 3 Hz to one exceeding 17 Hz. Notably, the overall trend persisted consistently: a steep spike in deflection at 60 km/h. Additionally, an alternative filter, the elliptical filter, theoretically superior due to its more accurate approximation of the ideal filter response, was explored. Regrettably, its allowed ripple in the passband instigated deflection oscillations, rendering it unsuitable for this application. Hence, the filtering process is ruled out as the cause for the substantial deflection surge observed at 60 km/h on the N4 pavement.

Another plausible factor contributing to this discrepancy could be linked to sensor calibration procedures. While calibration relied on data derived from movements of a 3D printer, it failed to account for varying movement speeds encountered in practical scenarios. This limited calibration might be the root of the observed discrepancy, emphasizing the necessity for speed-adjusted calibration in future research endeavours.

During practical testing it was necessary to adjust the cut-off frequencies of the band-pass Butterworth filter as the speed increased to ensure that the deflection signal is not disfigured. For a speed of 30 km/h the lower cut-off frequency was set to 4.5 Hz and increased to 17 Hz for a speed of 60 km/h. This adjustment can only be made when the speed of the vehicle is known. Consequently, in practise, the speed of the vehicle should be determined as the vehicle passes over the device. Techniques to achieve this is highlighted in Chapter 4. One alternative solution could involve choosing a cut-off frequency that accommodates both high-speed and lower-speed scenarios. This would however increase the error in the estimates.

5.5.2.4.4 LATERAL WHEEL-TO-SENSOR DISTANCE VARIATION

Varying the lateral distance between the wheel and the device reveals the sensitivity of the sensors as well as the deflection bowl, discussed in Chapter 2. When observing the deflection bowl in Figure 5-38, the accelerometer once again shows a consistently higher deflection compared to the LVDT when the wheel's centre is close to the device. The shape of the deflection bowls is consistent with that found in practice; however, the sensitivity of the devices limits the distance at which the bowl is still detectable. The accelerometer measures a distinguishable deflection up until 15 cm after which the peaks are not clearly recognized. When the trend of the deflection bowl of the accelerometer is extrapolated to a y-value near the x-axis crossing ($1 \mu\text{m}$ deflection), the radius of the bowl can be estimated to be approximately 64 cm. For the LVDT, the last detectable deflection occurred at 10 cm, meaning the LVDT

is less sensitive compared to the accelerometer. The distance of detectable deflection is limited by the sensitivity of both devices; however, another factor also has an influence on it. One drawback of the calibration technique, particularly evident in these tests, is the constant offset on the calibration equations. This offset limits the elastic deflection measuring range of the device to a value above the constant offset value. This means that a deflection below 84 μm for the accelerometer and 115 μm for the LVDT will therefore not be detected.

A summary of the tests conducted above can be found in Appendix A.

5.5.2.5 Conclusion

5.5.2.5.1 INSTALLATION METHOD

Considering the first installation method, it seems to be impractical to mount the LVDT core to the casing, as it may deflect significantly more compared to the pavement. However, if the casing can be designed in such a way that it moves in unison with the pavement, this installation method could deliver accurate results. Furthermore, the L-bracket used for the LVDT provides adequate fixation to the pavement if it is securely seated. A possible improvement could be the use of a U-shaped bracket that is fixed to both walls of the cavity.

5.5.2.5.2 THE INFLUENCE OF SPEED VARIATION

The speed at which the vehicle travels has an effect on the deflection of the pavement, which can be accurately detected by both sensors. However, the manual selection of the band-pass filter cut-off frequencies as the speed of the vehicle changes gives room for human error in the conversion process and may affect the accuracy thereof. Therefore, the speed of the vehicle should be determined as it passes the device and used to adjust the cut-off frequencies of the filter.

The differences in pavement design and type of force exerted on it make it difficult to evaluate the accuracy of deflection estimates observed by the sensors and the reference instrument.

5.5.2.5.3 THE INFLUENCE OF WHEEL-TO-DEVICE DISTANCE VARIATION

Finally, in the event that a vehicle passes the device with its wheel at a lateral offset from the sensors, the sensors possess the capability to detect deflections up to 15 cm away from the wheel for a 2-tonne pick-up truck. For a smaller vehicle weighing 1 tonne, this detection range reduces to 10 cm. Employing a more sensitive sensor could significantly enhance this distance. Additionally, an array of sensors installed laterally across the road can be used to estimate the overall deflection of the pavement and give an indication of the sway of the vehicle across the road.

5.6 Power supply

As discussed in chapters 1 and 2 of this document, a key feature of the in-road sensor is its ability to operate wirelessly. This not only refers to the communication subsystem, but also to the power supply system as well. Since the power supply is limited to a small battery and solar panel, power management is necessary to achieve the desired performance.

5.6.1 Purpose

The purpose of this test is to determine if the energy demand of the system can be met by the energy supply into the system.

5.6.2 Setup

The test can be carried out in the laboratory environment in which the complete device and accessories are used. For this test, the in-road device should be set up similar to the way it would operate in a real-world test scenario. A multi-meter was used to measure the current consumption of each component of the system.

5.6.3 Method

- a) Ensure that the device is powered on and set up on a stable surface.
- b) Connect all the sensor modules that would be used in a real-world environment.
- c) Run the associated software routine on the microcontroller.
- d) Connect the multi-meter in series with the power line of the component to be measured and record the current reading.
- e) Calculate the effective power of the component by using equation 4 below. The run time and idle times is obtained from the software routine of the components, such as time in sleep mode.
- f) Repeat steps a) to e) for each component of the system to calculate the total daily consumption of the device.
- g) To calculate the total daily production of the device, the solar panel should be connected to the power card with the control card connected as well.
- h) Once connected, measure the current into the battery by using the multi-meter and record the reading.
- i) Repeat these steps hourly to obtain a production profile as in Figure .

5.6.4 Results

The energy consumption (E_n) of the device can be calculated using (14), where $P_{(effective)}$ is the average daily power of the device in watts, and t_{on} is the time that the device is active per day. The average power is calculated as shown in (15), where V_n is the device voltage, I_{run} is the run current, T_{run} is the fraction of time that the component is active per day, I_{idle} is the standby current, and T_{idle} is the fraction idle time per day. A summary of the energy consumption of each component of the device is given in Table 5-18.

$$E_{daily} = P_{n(effective)} t_{on} \quad (14)$$

$$P_{(effective)} = V(I_{run} T_{run} + I_{idle} T_{idle}) \quad (15)$$

Table 5-18: The daily energy consumption of the components of the device

	P_{effective} (mW)	Daily Consumption (Wh)
Accelerometer	6.600	0.158
Humidity and Temperature sensor	0.252	0.006
Moisture content sensor	3.300	0.079
LoRa	2.263	0.054
ESP32 (@80 MHz)	32.218	0.773

Not mentioned in the table above is the duty cycle of each component, which determines its active and sleep times. The temperature, humidity, and moisture content sensors perform hourly readings. Meanwhile, the accelerometer remains active continuously to detect passing vehicles. Estimating the duty cycle for the ESP32 and LoRa device involves certain assumptions. For instance, considering a daily traffic volume of 50 000 vehicles, the ESP32 samples accelerometer data for approximately 300 milliseconds per vehicle to capture loading effects. This results in the ESP32 being active for about 250 minutes daily, in addition to the 18 minutes for other sensors. As for the LoRa device, the 50 000 vehicles generate approximately 500 KB of data in deflection estimates, coupled with an extra 120 bytes from other sensors. Transmitting this data in 100-byte packets, the LoRa device operates just under its 1% duty cycle limit, requiring around 14.5 minutes of daily active transmission. During the remaining time, all subsystems remain in sleep mode, consuming minimal power. The daily consumption of the device is can then be calculated as 1 071 mWh per day. Furthermore, to ensure that enough power is supplied to replenish the battery, the solar input is also measured. Table 5-19 shows the energy production throughout the day during a warm autumn day. The maximum production occurred at mid-day as expected. Figure 5-44 shows the expected solar production cycle throughout the day. In total 1 964 mWh of energy can be produced by the solar panel.

Table 5-19: Solar energy production throughout the day

Hour of day	7:00	8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
Voltage (V)	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Current (mA)	24	40	58	88.7	90	100	93	88	63	58	43	28
Power (mWh)	93.6	156	226.2	345.93	351	390	362.7	343.2	245.7	226.2	167.7	109.2

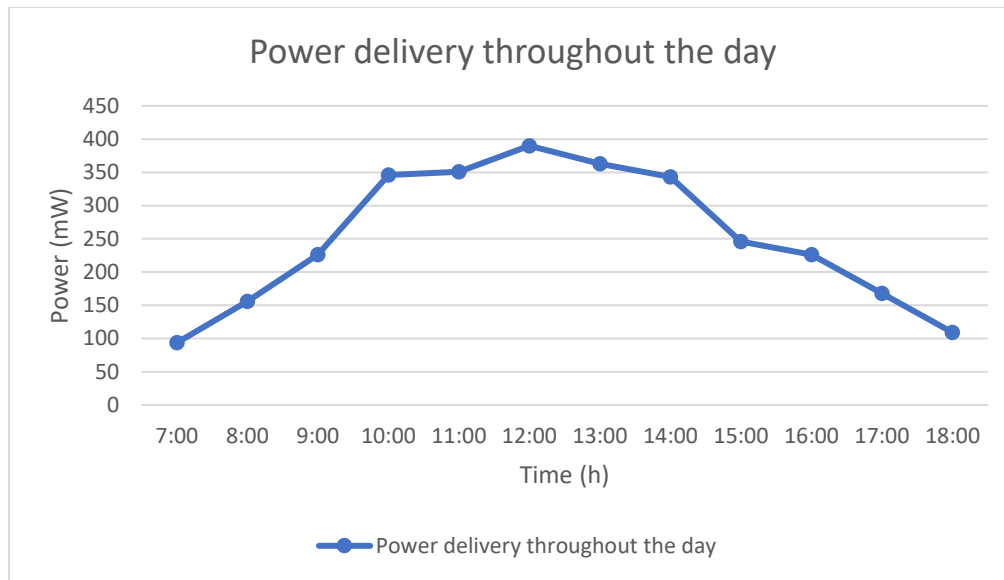


Figure 5-44: The energy production from the solar panel throughout a typical summer day. (This Study)

5.6.5 Discussion

The daily consumption of the in-road device is affected by the ESP32's power consumption by it being a factor 10 more than the other components of the system. Furthermore, the moisture content sensor does not have a sleep mode, meaning that it will continue to draw 1 mA of current even while it is not used. It accounts for almost 100 mWh of energy consumption per day. The accelerometer has a higher than stated current draw (2 mA vs 148 μ A), and since it is continuously active it accounts for a significant portion of the in-road device power consumption. This needs further investigation as accelerometers typically consume less than 1 mA of current.

On the energy production side, the solar panel, connected to the full load, provides a maximum of 100 mA to the battery and in total produces 1 964 mWh per day. This was achieved during a warm autumn day with a bright sky. The panel produces twice the energy that is being consumed in a day with a surplus energy of 893 mWh per day. However, during raining or winter seasons, this current production decreases significantly. The location of the sensor also plays a significant role in practise, with high-rise buildings potentially blocking the sun's rays. In unfavourable conditions, a 5 000 mAh battery should keep the device powered for approximately 15 days.

5.6.6 Conclusion

The energy consumption of the device can be significantly reduced by making use of the sleep modes of the microcontroller unit. However, this can be further reduced by implementing a low-power MCU. Furthermore, a lower power accelerometer can be used as well as a moisture content sensor that features a sleep mode.

In favourable conditions the solar panel seems to provide adequate power to the system to keep it running continuously without battery drain. However, if unfavourable conditions persist, the battery would be able to keep the device powered for almost fourteen days with normal operation according to this study.

5.7 Experimental Equipment

Table 5-20 shows the equipment that was necessary to conduct the tests above.

Table 5-20: The experimental equipment used for the tests above

Equipment	Quantity	Description
Computer/Laptop	1	Connects to the server/analyse data/Runs IDE
Distance measuring wheel	1	Measures the distance between transceivers
In-road sensor software	1	Software to read/write/process sensor readings/communicate to gateway
In-road sensor	2	Sensor node under test
Code B vehicle	4	Present in the operating environment
In-road sensor casing	3	Casing for the in-road sensor with various alternatives
SD card	1	Used to store sensor data during testing
Oscilloscope	1	Used to analyse results of time/frequency domain samples
Measuring tape	1	Measures distance between sensor and wheel/height of container

Traffic cones	4	Mark off area of experiments/Alert traffic
Electrical Extension Cord	1 x 40m	Supplies power from outlet
Calibrated thermometer	1	Used as reference temperature measurement device
Sodium Nitrate	1 x 100 ml	Used to create standard humidity environment
Ziplock bags	10	Container
Precision Scale	1	Used to measure soil sample mass
Oven	1	Removes moisture from soil samples
Pavement Soil samples	1	Measurand
Code C vehicle	1	Present in operating environment

6 Concluding Remarks

This thesis investigated the feasibility of an in-road device used for pavement condition monitoring that improves on the traditional monitoring systems pertaining to cost, coverage, and the frequency of assessments. This chapter concludes the thesis by addressing the research questions outlined in Chapter 1, presenting a comprehensive summary, and offering recommendations for future research endeavours.

6.1 Research Questions

- How does the utilization of a low-cost, wireless, self-powered in-road sensing device enhance the frequency and accuracy of pavement condition assessments compared to traditional monitoring techniques?

The embedded solution discussed in this thesis offers a continuous stream of information, ensuring constant accessibility without disrupting traffic flow. Employing wireless data collection enables real-time availability, unlike the intermittent reports typical of other systems. The LoRa communication system facilitates substantial data transmission—over 500 KB per day—significantly amplifying assessment frequency compared to alternative methods. Moreover, the cost-effective components allow for denser installations, ensuring more precise data collection over specific road sections. The device's extended battery life, coupled with a built-in solar panel, ensures prolonged or even indefinite operation under favourable conditions. Its wireless nature also eliminates the need for cabling which causes additional damage to the road. Moreover, the integration of multiple sensors into a single embeddable package offers a streamlined, all-in-one solution, eliminating the necessity for a diverse set of instruments to independently collect, process, and display data, ensuring synchronous and efficient operation. Overall, this solution excels in providing frequent, relatively accurate pavement assessments while maintaining uninterrupted road functionality.

- What are the challenges and limitations of using accelerometers to convert pavement acceleration to elastic deflection and/or displacement for assessing pavement health. How can these limitations be addressed or minimized?

One of the primary measurements for assessing pavement health is deflection caused by loading. This study aimed to utilize accelerometers for cost-effective, low-energy data collection with simplified installation. However, as accelerometers do not directly measure deflection, converting their data into elastic deflection and/or displacements involves complex processing. Consequently, this method presents several limitations. Firstly, as discussed in Chapter 3, the filter's lower cut-off frequencies which are set to eliminate the components added by the integration calculation require manual adjustments based on vehicle speed. In practice, determining vehicle speed on-the-go might involve using an additional accelerometer or estimating speed from consecutive peak time differences. However, the result is highly sensitive to slightest adjustments to the filter specifications, making this process very delicate. Furthermore, as indicated in the discussions above, the accelerometer estimates may require a speed-adjusted calibration, and not just calibration at constant deflections.

Another challenge arises when using accelerometers in rigid pavement structures. Identifying deflection peaks becomes more difficult as pavement stiffness increases, with peaks blending into random signal spikes. Human intervention becomes necessary to pinpoint vibration detections and correlate them with deflection signal peaks.

- Can the system accurately measure the state and behaviour of the pavement structure in real-world conditions?

Firstly, assessing the sensors that provide a pavement status profile: In in-road tests, the temperature profile accurately reflects pavement temperatures at specific times of the day. Laboratory tests confirmed temperature measurement accuracy, noting a minor time-delay in sensor response. Secondly, relative humidity lab measurements and in-road pavement humidity profiles, post-calibration, show reasonable accuracy, although a single standardized reference limited accuracy verification. Moisture content measurement accuracy was restricted due to soil sample saturation limitations and an inability to cover the full moisture content range. A soil-specific calibration is crucial for enhancing moisture content measurement accuracy. Regarding accelerometer measurements and displacement estimation, satisfactory accuracy was observed during 3D printer lab tests. Notably, the calibration substantially improved elastic deflection and/or displacement estimation accuracy. However, in-road tests presented challenges in accurately estimating pavement deflection, lacking reference measurements for the initial two tests. The third set of tests conducted on the 'stiffer' 80 mm asphalt layer located at the Engineering 4.0 facility exhibited deflection estimates closely correlated with reference instruments. Yet, accuracy diminished notably in the final tests conducted on the 200 mm asphalt layer located on the N4 test section, particularly at higher speeds. The speed dependence of the pavement deflection estimates was not accounted for in the sensor calibration procedure due to limited information on the cause of this dependency, making the conversion process less accurate in real-world scenarios. This dependency needs to be thoroughly investigated in future research endeavours. The accuracy of the deflection estimates plays a crucial role in accurately reproducing the deflection bowl resulting from a passing load. This relies heavily on the precision of these estimates.

6.2 Summary

This section serves as a concise summary of each thesis chapter.

6.2.1 Chapter 1 Summary

The thesis starts by framing the problem definition, offering background insights into pavement health monitoring and current system limitations. A proposed solution initiates the study's scope, clearly outlining its objectives and research questions.

6.2.2 Chapter 2 Summary

Chapter 2 presented some of the most relevant research on pavement health monitoring and in-road wireless sensing. The chapter first considered intelligent transportation systems as a whole and then focused on pavement health monitoring. Much focus was given to the study of using accelerometer as deflection measuring sensors which included the software algorithms used in previous research to convert accelerations to displacements. Furthermore, critical aspects of real-world pavement monitoring and

installation was discussed, which set out a few requirements for the in-road device. A large portion of this chapter was also dedicated to the power management of the device and the communication network needed to relay the pavement's status to the linked network. This chapter concluded with important design questions, such as a cost analysis for the device, setting the stage for the third chapter.

6.2.3 Chapter 3 Summary

Chapter 3 includes the preliminary design of the device, explaining its functional aspects and evolving into a comprehensive system architecture encompassing all requisite components. The chapter also highlights the diligent process of selecting components that align with system requirements.

6.2.4 Chapter 4 Summary

Chapter 4 discussed the detailed design of the system, which included the PCB design of the in-road sensor, the software design, as well as the casing design and the various installation techniques. The software design includes the embedded software running on the in-road device, as well as the acceleration to displacement conversion algorithm operational on a PC.

6.2.5 Chapter 5 Summary

Chapter 5 explores the feasibility of the device by evaluating the critical aspects of the system, both in the lab and in the road. It started off by testing the functionality of the communication subsystem, after which each sensor was tested individually. Specific focus was given to the pavement deflection testing. The accelerometer and LVDT sensors were first tested and calibrated in a laboratory environment to ensure adequate operation prior to field testing. Once proven to be effective, in-road tests confirmed the functionality of the acceleration to elastic deflection and/or displacement algorithm over different pavement designs. This chapter concluded with a power supply test to ensure uninterrupted operation.

6.2.6 Chapter 6 Summary

Chapter 6 aims to answer the design questions set out at the start of the study and concludes this thesis by recommending future research actions to improve the current system.

6.3 Future research

This study was undertaken as part of a three-year research and development project which may continue into the next few years. Therefore, it is important to highlight some of the focus areas for the continuation of this study.

- **Hardware Revision:** A recommended next step involves a secondary revision of the device's hardware. Presently, the device's form factor exceeds the recommended size, primarily constrained by the PCB dimensions. Reducing the PCB size inherently reduces the footprint of the device. This involves the removal of redundant components and scaling down the size of the remaining elements. Notably, the microcontroller unit constitutes the primary power consumer. To extend battery life and reduce overall power usage, opting for a low-power MCU is crucial. However, the trade-off between processing capabilities and power efficiency remains pivotal.
- **Software Integration:** Software integration of all aspects of the system is needed, which includes the power management algorithm, communication management algorithm, data collection and

processing algorithm. Additionally, transitioning the acceleration to displacement conversion algorithm from the PC to the embedded microcontroller software is needed.

- **Speed-Based Filter Adjustments:** Thirdly, speed estimation is necessary to adjust the filter cut-off frequencies, as seen in the design chapter of this thesis. A suitable method to achieve this needs to be investigated along with the associated software routines.
- **Deflection Anomalies Investigation:** Anomalies detected during testing on a relatively “stiff” pavement section on the N4 and UP test areas. The increase in measured deflections as the speed increases need to be investigated further, with possible adjustments to the calibration procedure being the starting point.
- **Improved Moisture Content Measurement:** To increase the accuracy of moisture content measurements an alternative sensor technology should be further investigated, with the capacitive type being prone to large errors.
- **Evaluate permanent pavement damage:** Conduct a test to assess permanent pavement damage by subjecting it to sustained excessive loads. Verify the in-road device's capability to detect and identify any resulting damages within the pavement.
- **In-road sensor installation techniques:** Pavement structures vary significantly in layer composition and thickness, posing a challenge for installing the in-road device. It is recommended to investigate a method that eases the installation process for a range of pavement types.

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Appendix A: Comprehensive pavement deflection test results

* No filter adjustment done		
Test No:	1	
Location of Sensors:	Acc cemented to AC, LVDT fixed to casing	
System Bracket Type:	No bracket	
Loading Type:	Hatchback - 1000 kg (2.45 kN per wheel)	
Axle distance:	2.43 m	
Method of calibration:	Linear Fit (Amplitude adjustment & Offset)	
Num. Runs per speed:	10	
Tyre centreline distance from instrument centerline:	0 cm to +/- 2 cm	
Road Surface Temperature Estimate:	38 °C	
New with Hilbert Transform after calib		
Speed (km/h)	Accelerometer Estimate (mm)	LVDT Measurement (mm)
10	0.246	1.608
20	0.236	1.759
30	0.296	0.525
40	0.253	0.442
50	0.235	0.442
60	0.259	0.316
70	0.193	0.300
New with Hilbert Transform after calib + offset		
Speed (km/h)	Accelerometer Estimate (mm)	LVDT Measurement (mm)
10	0.330	1.723
20	0.320	1.874
30	0.380	0.640
40	0.337	0.557
50	0.319	0.557
60	0.343	0.431
70	0.277	0.415
Average	0.329	0.885
Std Deviation	0.029	0.583

Figure A - 1: The first in-road speed test results on the NWU campus using a small hatchback as test vehicle (-26.6943, 27.0900)

Test No:	2				
Location of Sensors:	LVDT mount to bracket at centre, Acc screw to wall				
System Bracket Type:	L-shaped bracket, single wall fixation				
Loading Type:	Bakkie - 5.5 kN (Front wheel), 4.2 kN (Backwheel)				
Axle distance	3 m				
Method of calibration:	Linear Fit (Amplitude adjustment & Offset)				
Num. Runs per speed	10				
Tyre centreline distance from instrument centerline	0 cm to +/- 2 cm				
Road Surface Temperature Measurement	20 °C				
* Note filter cut-offs					
New with Hilbert		*Only amplitude calibrated			
Filter Cut-off	Speed (km/h)	Accelerometer Estimate (mm)	LVDT Measurement (mm)		
[3.5,40]	30	0.4748	0.3218		
[4.25,40]	40	0.5077	0.3318		
[7,50]	50	0.4720	0.3304		
[11,70]	60	0.3834	0.3077		
Final		* Adds offset			
	Speed (km/h)	Accelerometer Estimate (mm)	LVDT Measurement (mm)		
	30	0.559	0.437		
	40	0.592	0.447		
	50	0.556	0.445		
	60	0.467	0.423		
New Cut-off frequencies below					
New with Hilbert		*Only amplitude calibrated			
Filter Cut-off	Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)	LVDT Front Axle (mm)	LVDT Rear Axle (mm)
[6,499]	30	0.4999	0.3659	0.34466	0.30382
[8.5,499]	40	0.4840	0.4020	0.33764	0.3063
[11,499]	50	0.4137	0.3805	0.35915	0.33198
[17,499]	60	0.3488	0.2628	0.3394	0.27553
Final		* Adds offset			
	Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)	LVDT Front Axle (mm)	LVDT Rear Axle (mm)
	30	0.584	0.450	0.460	0.419
	40	0.568	0.486	0.453	0.421
	50	0.498	0.464	0.474	0.447
	60	0.433	0.347	0.454	0.391

Figure A - 2: The second in-road speed test results on the NWU campus using a large pick-up truck as test vehicle (-26.6943, 27.0900)

Test No:	3	
Location of Sensors:	Mount to bracket at centre	
System Bracket Type:	L-shaped bracket, single wall fixation	
Loading Type:	RRV - 23 kN (Front) and 29 kN (Back)	
Axle distance	6 m	
Method of calibration:	Linear Fit (Amplitude adjustment & Offset)	
Num. Runs per speed	10	
* No LVDT data		
Tyre centreline distance from instrument centerline	0 cm to +/- 5 cm	
Road Surface		
Temperature Estimate	47 °C	

! With old filter cut-offs		
Amplitude Calibrated		
Cut-off Freq. (Hz)	Speed (km/h)	Accelerometer Estimate (mm)
[3,40]	10	0.1218
[3.5,40]	20	0.2002
[3.5,40]	30	0.2471
Final Displacement		* Offset adjusted
Speed (km/h)		Accelerometer Estimate (mm)
10		0.206
20		0.284
30		0.331

New with Hilbert		*Only amplitude calibrated	
Cut-off Freq. (Hz)	Speed (km/h)	Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)
[2,499]	10	0.2311	0.1615
[4.5,499]	20	0.2118	0.1454
[6,499]	30	0.2372	0.1746
Final		* Adds offset	
Speed (km/h)		Accelerometer Estimate Front Axle (mm)	Accelerometer Estimate Rear Axle (mm)
10		0.315	0.245
20		0.296	0.229
30		0.321	0.259

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Test No: 4 Location of Sensors: Mount to bracket at centre, Left wheelpath System Bracket Type: U-shaped bracket, double wall fixation Loading Type: RRV - 23 kN (Front) and 29 kN (Back) Axle distance: 6 m Method of calibration: Linear Fit (Amplitude adjustment & Offset) Num. Runs per speed: 10 Tyre centreline distance from instrument centerline: 0 cm to +/- 5 cm Road Surface Temperature Estimate: 47 °C						Deflections for each individual run 20kmph Acc Avg LVDT Avg Front Axle Rear Axle Front Axle Rear Axle - 0.047334 0.047334 - 0.03855 0.07279 0.08609 0.07944 0.0445 0.02956 0.03703 0.09996 0.12369 0.111825 - 0.02251 0.04224 - 0.04224 0.03195 - 0.03191 0.0657 0.048805 - - - 0.04279 0.04279 0.0424 - 0.0424 - 0.05108 0.05108 - - 0.13815 0.0608 0.099475 0.0408 - 0.0408 0.03371 0.0666 0.050155 - - 0.10238 0.03633 0.069355 0.04269 - 0.04269 0.074449 0.06449 - 0.040468 0.030207 0.04073 Avg. 0.037793 0.02523 0.004418 0.006564 Std. Dev. 0.02523 0.004418 0.006564 40kmph Acc Avg LVDT Avg Front Axle Rear Axle Front Axle Rear Axle - - - - 0.07528 0.07189 0.073585 - 0.03529 0.03529 0.15399 0.12208 0.138035 0.05637 - 0.05637 0.01759 0.01746 0.017525 - - - 0.12412 0.12412 - - 0.0993 0.0373 0.0683 0.04964 - 0.04964 0.0401 0.01939 0.029745 0.0541 - 0.0541 0.04515 0.02506 0.035105 - - 0.1667 0.04547 0.106085 - - 0.06 - 0.06 - - Avg. 0.082264 0.057846 0.0725 0.05337 0.03529 0.04885 Std. Dev. 0.050555 0.041042 0.002796 0 60kmph Acc Avg LVDT Avg Front Axle Rear Axle Front Axle Rear Axle 0.02647 - 0.02647 - - 0.03976 0.25196 0.14586 - 0.0254 0.0254 0.0281 0.08292 0.05551 - - 0.3592 0.2207 0.28995 0.0506 - 0.0506 0.5011 0.24403 0.372565 0.036 - 0.036 0.1494 - 0.1494 0.0277 - 0.4 0.0747 0.23735 - - 0.2767 0.3354 0.30605 0.0288 0.0411 0.03495 - 0.2724 0.2724 - - 0.0755 0.3958 0.23565 - 0.044 0.044 0.206248 0.234739 0.229415 0.035775 0.036833 0.03819 Avg. 0.171573 0.104123 0.009134 0.008171 Std. Dev. 0.171573 0.104123 0.009134 0.008171
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Figure A - 4: The fourth in-road speed test results on the N4 test road using the RRV as test vehicle (-25.7423, 28.2588)

Test No: 5 Location of Sensors: LVDT mount to bracket at centre, Acc screw to wall System Bracket Type: L-shaped bracket, single wall fixation Loading Type: Bakkie - 5.5 kN (Front wheel), 4.2 kN (Backwheel) Axle distance: 3 m Method of calibration: Linear Fit (Amplitude adjustment & Offset) Num. Runs per speed: 10 Tyre centreline distance from instrument centerline: 0 cm to 20 cm Road Surface Temperature Measurement: 20 °C					
Mirror (x-axis)	Mirror (y-axis)	Wheel distance from accelerometer (cm)	Accelerometer Estimate (mm)	LVDT Estimate (mm)	LVDT Mirror
15	-0.126	0	-0.584	-0.437	
10	-0.189	-5	-0.313	-0.265	-0.184
5	-0.313	-10	-0.189	-0.184	-0.265
0	-0.584	-15	-0.126		-0.437

Figure A - 5: The results of the distance offset test on the NWU campus using a large pick-up truck as test vehicle (-26.6943, 27.0900)

Test No:	6		
Location of Sensors:	Acc cemented to AC, LVDT fixed to casing		
System Bracket Type:	No bracket		
Loading Type:	Hatchback - 1000 kg (2.45 kN per wheel)		
Axle distance:	2.43 m		
Method of calibration:	Linear Fit (Amplitude adjustment & Offset)		
Num. Runs per speed:	10		
Tyre centreline distance from instrument centerline:	0 cm to 15 cm		
Road Surface Temperature Estimate:	38 °C		
New with Hilbert and calib+offset			
Distance from Acc (cm)	Acc (mm)		
0	0.296	0.380	
5	0.115	0.199	
10	0.102	0.186	
15	no detectable signal		
Mirror	Mirror	Wheel distance from accelerometer (cm)	Accelerometer Estimate (mm)
15		0	-0.380
10	-0.186	-5	-0.199
5	-0.199	-10	-0.186
0	-0.380	-15	

Figure A - 6: The results of the distance offset test on the NWU campus using a small hatchback as test vehicle (-26.6943, 27.0900)