Development of an air-quality solution for taxis and taxi ranks.

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Abstract

English

Minibus taxis are a popular mode of transport in the public sector of South Africa, but they may contribute to air pollution and pose health risks to drivers, passengers and bystanders. This thesis report aims to develop a solution to measure the levels of CO2, VOC, particulate matter and NOx both inside minibus taxis and at taxi ranks, to estimate the air quality. It also investigates the potential health risks associated with exposure to air pollution in minibus taxi ranks and within minibus taxis, particularly for passengers, drivers and potential third parties.

Afrikaans

Minibus-taxis is ’n gewilde vervoermiddel in die openbare sektor van Suid-Afrika, maar dit kan bydra tot lugbesoedeling en gesondheidsrisiko’s vir bestuurders, passasiers en omstanders. Hierdie skripsie poog om ’n oplossing te ontwikkel om die vlakke van CO2, VOC, deeltjiesmateriaal en NOx binne minibus-taxis en by taxistaanplekke te meet, om sodoende die lugkwaliteit te beraam. Dit ondersoek ook die potensiële gesondheidsrisiko’s wat verband hou met blootstelling aan lugbesoedeling by minibus-taxistaanplekke en binne minibus-taxis, veral vir passasiers, bestuurders en moontlike derde partye.

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Nomenclature

Acronyms and abbreviations

PM	Particulate Matter
VOC	Volatile Organic Compounds
UART	Universal Asynchronous Receiver / Transmitter
i2c	Inter-Integrated Circuit
UFP	Ultrafine Particle
LPG	Liquefied Petroleum Gas
CNG	Compressed Natural Gas
PPM	Parts Per Million
PPB	Parts Per Billion
NDIR	Nondispersive Infrared
PID	Photoionisation Detector
FID	Flame Ionisation Detector
MOS	Oxide Semiconductor Sensor
UV	Ultraviolet
AQI	Air Quality Index
IO	Inputs and Outputs
HAT	Hardware Attached on Top
USB	Universal Serial Bus
STA	Station
AP	Access Point
SD	Secure Digital
FS	File System
NMEA	National Marine Electronics Association
PPS	Pulse Per Second
SPI	Serial Peripheral Interface
GPS	Global Positioning System
PPS	Pulse Per Second

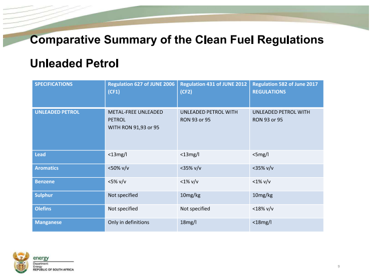
Chapter 1

Introduction

1.1. Background

In South Africa, millions of commuters use taxis frequently and depend on them for all of their mobility needs [8].

The South African government has recognised the impact of taxi emissions on air quality and has taken steps to address the issue. In 2006, the government gazetted regulations that required taxi operators to convert their vehicles to run on cleaner fuels, such as liquefied petroleum gas (LPG), compressed natural gas (CNG), or diesel with lower sulphur content [4].

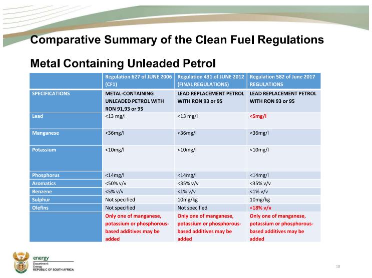


Comparative Summary of the Clean Fuel Regulations

Unleaded Petrol

SPECIFICATIONS	Regulation 627 of JUNE 2006 (CF1)	Regulation 431 of JUNE 2012 (CF2)	Regulation 582 of June 2017 REGULATIONS
UNLEADED PETROL	METAL-FREE UNLEADED PETROL WITH RON 91,93 or 95	UNLEADED PETROL WITH RON 93 or 95	UNLEADED PETROL WITH RON 93 or 95
Lead	<13mg/l	<13mg/l	<5mg/l
Aromatics	<50% v/v	<35% v/v	<35% v/v
Benzene	<5% v/v	<1% v/v	<1% v/v
Sulphur	Not specified	10mg/kg	10mg/kg
Olefins	Not specified	Not specified	<18% v/v
Manganese	Only in definitions	18mg/l	<18mg/l

Figure 1.1: Unleaded [4]

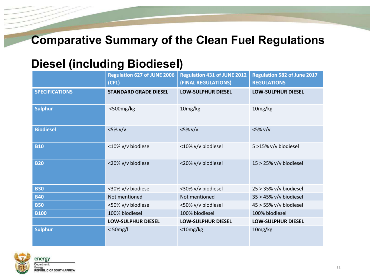


Comparative Summary of the Clean Fuel Regulations

Metal Containing Unleaded Petrol

	Regulation 627 of JUNE 2006 (CF1)	Regulation 431 of JUNE 2012 (FINAL REGULATIONS)	Regulation 582 of June 2017 REGULATIONS
SPECIFICATIONS	METAL-CONTAINING UNLEADED PETROL WITH RON 91,93 or 95	LEAD REPLACEMENT PETROL WITH RON 93 or 95	LEAD REPLACEMENT PETROL WITH RON 93 or 95
Lead	<13 mg/l	<13 mg/l	<5mg/l
Manganese	<36mg/l	<36mg/l	<36mg/l
Potassium	<10mg/l	<10mg/l	<10mg/l
Phosphorus	<14mg/l	<14mg/l	<14mg/l
Aromatics	<50% v/v	<35% v/v	<35% v/v
Benzene	<5% v/v	<1% v/v	<1% v/v
Sulphur	Not specified	10mg/kg	10mg/kg
Olefins	Not specified	Not specified	<18% v/v
	Only one of manganese, potassium or phosphorous-based additives may be added	Only one of manganese, potassium or phosphorous-based additives may be added	Only one of manganese, potassium or phosphorous-based additives may be added

Figure 1.2: Metal+ Unleaded [4]



Comparative Summary of the Clean Fuel Regulations

Diesel (including Biodiesel)

	Regulation 627 of JUNE 2006 (CF1)	Regulation 431 of JUNE 2012 (FINAL REGULATIONS)	Regulation 582 of June 2017 REGULATIONS
SPECIFICATIONS	STANDARD GRADE DIESEL	LOW-SULPHUR DIESEL	LOW-SULPHUR DIESEL
Sulphur	<500mg/kg	10mg/kg	10mg/kg
Biodiesel	<5% v/v	<5% v/v	<5% v/v
B10	<10% v/v biodiesel	<10% v/v biodiesel	5 >15% v/v biodiesel
B20	<20% v/v biodiesel	<20% v/v biodiesel	15 > 25% v/v biodiesel
B30	<30% v/v biodiesel	<30% v/v biodiesel	25 > 35% v/v biodiesel
B40	Not mentioned	Not mentioned	35 > 45% v/v biodiesel
B50	<50% v/v biodiesel	<50% v/v biodiesel	45 > 55% v/v biodiesel
B100	100% biodiesel	100% biodiesel	100% biodiesel
	LOW-SULPHUR DIESEL	LOW-SULPHUR DIESEL	LOW-SULPHUR DIESEL
Sulphur	< 50mg/l	<10mg/kg	10mg/kg

Figure 1.3: Diesel [4]

As seen in Figures 1.1, 1.2 and 1.3, South Africa's regulations on cleaner fuels are updated every five to six years. Cleaner fuels produce less greenhouse emissions. The implementation of these regulations has been slow and often poorly regulated [9], resulting in continued poor air quality in many areas.

The main sources of air pollution in South Africa are industrial activities, power generation, vehicle emissions, biomass burning, and domestic fuel use [10]. Among these sources, vehicle emissions are particularly relevant for taxi commuters, who are exposed to high levels of pollutants such as particulate matter (PM), nitrogen oxides (NOx), carbon monoxide (CO), and volatile organic compounds (VOCs) [11]. These pollutants can have adverse effects on respiratory, cardiovascular, neurological, and immune systems, as well as increase the risk of cancer and premature death [12].

1.2. Problem Statement

Despite the popularity and importance of taxis in South Africa, there is a lack of research on the air quality inside these vehicles and at taxi ranks. Air quality is a crucial factor for human health and well-being, especially for commuters who spend long hours in taxis exposed to various pollutants. Moreover, taxi emissions contribute to the overall air pollution in crowded spaces (in this case taxi ranks), which affects the environment and the quality of life of the passers by. The closest studies are concerning single cab taxis [2], road based pollution [13] and general pollution [3]. There is a need for a study on the air quality in taxis and taxi ranks and its impacts on human health and the environment, this report aims to provide a means to that end.

1.3. Objectives

The objective of the study are as follows:

- To design a device to measure the levels of:
  - CO2
  - VOC
  - NOx
  - Particulate Matter

  both inside taxis and in taxi ranks.
- To investigate the potential health risks associated with exposure to air pollution in taxi ranks and within taxis, particularly for passengers, drivers and potential third parties.
- Develop hardware that measures the above-mentioned.
- Develop software/firmware that integrates the hardware.

1.4. Scope

The scope of the project encompasses only the following:

- Design of base station and satellite module
- Design of communication network for satellite module and base station as well as data storage and backup

- Hardware development
- Software development
- Test of Hardware and Software elements

1.5. Report Overview

NEED TO DO THIS

Chapter 2

Background Study

2.1. Effects of Pollutants

2.1.1. CO_2

Exposure to CO_2 in concentrations as low as 1000 ppm can lead to adverse effects [14], this is enhanced by prolonged exposure, as would likely be experienced by the driver or passenger.
Adverse effects include [15]:

- inflammation
- reduced cognitive performance
- kidney and bone problems

2.1.2. Particulate Matter

Short-term exposure to particulate matter in the 2.5 and 10 µg range seems to to aggravate pre-existing conditions, such as respiratory and cardiovascular conditions [16], long term exposure is irrelevant in this context, as it is not measurable in the span of this study.

2.1.3. Volatile Organic Compounds

Short term exposure to VOCs can lead to eye and respiratory tract irritation, headaches, nausea and cancer [17]. The Environmental XPRT article on acceptable VOC levels in the air (2019) [18] suggests that acceptable ranges for VOC would be between 300 to 500 µg .

2.1.4. NO_x

Even at low concentrations, nitrogen oxides (NO_2, N_2O_4, N_2O_3, and N_2O_5) irritate the lungs and upper respiratory tract [19]. Symptoms from exposure to NO_2 include inflammation of the airways, increase susceptibility to respiratory infections and to allergens as well as aggravating pre-existing lung or heart conditions. The safe amount that should not be exceeded regularly is 200µg. [20]

2.2. Related Work and Existing Solutions

2.2.1. Related Work

2.2.1.1. Air quality at bus stops [1]

This article was a case study of air quality monitoring at a bus stop in an underpass on the campus of Lancaster University. The bus stop was suspected to have high levels of air pollution due to the large number of vehicles passing through the tunnel. They used an Aeroqual AQY Micro Air Quality Station to measure the concentrations of NO_2, PM_{10} and $PM_{2.5}$ at the bus stop. This study concluded that bus stops facing the roadway had higher concentrations of particulate matter, with the distribution of the particulate matter being similar regardless of the size of the particles measured. Traffic flow also impacted in the concentrations to a statistically significant degree.

2.2.1.2. Exposure to traffic air pollutants in taxicabs [2]

This study reviewed the level of pollutants present inside taxi cabs(American style taxis). The article reports that the exposure studies show that traffic related air pollutants concentrations inside taxicabs are higher than their urban background. This was a research based study.

2.2.1.3. An investigation into the environmental impact of the taxi industry in Butterworth [3]

This study analysed the environmental impact of the taxi industry in South Africa, by surveying a fleet of taxis in Butterworth, they do simple analogue measures such as dust gauges and soil and water analysis. This study concluded that the magnitude of environmental impact caused by taxis is correlated to the size of the taxi rank as well as the size of the population.

2.2.2. Existing Solutions

2.2.2.1. Aeroqual AQY

This sensor was used in a study aiming to measure similar metrics done to determine the air quality at bus stops [1]. The solution used consists of sensors for the following along with provided ranges [21]:

- Particulate matter ($PM_{2.5}$ & PM_{10}) 0-1000 µg
- Ozone

- Nitrogen Dioxide 0-500 ppb
- Temperature and Relative Humidity
- Dew point

This sensor lacks Carbon Dioxide measuring and lacks detailed specification on ranges' error.

2.2.2.2. Airthings View Plus

This sensor suite was designed for home use, it features:

- Particulate matter ($PM_{2.5}$ 0-200µg)
- Carbon dioxide 400–5000 ppm
- VOC
- Radon

This sensor was not intended to be extremely accurate and seems to be more for sensing danger than accurate measuring. It does include a handy chart for what should be considered normal levels for the different sensors as seen in Figure C.1.

2.3. Air Quality Monitoring Methods

2.3.1. Sensors

2.3.1.1. Carbon Dioxide (CO_2)

There are two main types of CO2 sensors: infrared gas sensors (NDIR) and chemical gas sensors. [22] The most common and more accurate sensor type is the NDIR sensor. Chemical sensors typically use less power and can be smaller but are less accurate and are more prone to aging effects.

2.3.1.2. VOC

VOC sensors measure volatile organic compounds in the air, such as what is found in petroleum fuels. There are three main types of sensors used to detect VOC [23] [24]:

- photoionisation detector (PID)
- flame ionisation detector (FID)
- metal oxide semiconductor sensor (MOS)

PID sensors uses ultraviolet light to ionise the VOC molecules and measure the electric current. They are typically used for low concentrations. FID sensors, are similar to PID sensors, but use a flame instead of UV light. A MOS sensor uses a heated metal oxide film that reacts with VOC and measures the change in resistance. This sensor is typically used from low to medium concentration. [23] [24]

2.3.1.3. PM

Particulate matter sensors measure the concentration and size of airborne particles. They use different methods to detect particles, such as:

- light scattering
- light obscuration
- direct imaging

Light scattering is used for smaller sized particles (< 1 µm), while obscuration is used for larger particles [25]. Direct imaging depends on the resolution and size of the sensor, but is usually prohibitively expensive.

2.3.1.4. Nitrogen Oxides

NO_x sensors measure are typically found in exhaust gases of diesel engines [26]. There are different types of NO_x sensors [27]:

- Electrochemical
- Zirconia

Electrochemical uses an electrolyte to create a current proportional to the concentration. Zirconia sensors use ceramic material and changes resistance based on concentration. Zirconia sensors typically run at lower temperatures and are more customisable. [28]

2.3.2. Air Quality Reporting

Air quality is usually reported as an index taken from various sources. We can use this standard to measure our perceived air quality of each contributing gas or particulate mater. [29]

IAQ Index			
PM2.5	VOC	CO2	
μg/m^3	μg/m^3	ppm	Hazard Level
<12	<100	<700	Good
35	200	800	Moderate
56	300	1100	Poor
150	400	1500	Unhealthy
250	500	2000	Very Unhealthy
300	600	3000	Hazardous
500	700	5000	Extreme

Figure 2.1: Air Quality index [5]

Typically, the gases used to estimate the air quality form part of an index and are weighted. The AQI was developed by the US to communicate levels of air pollution to the public [30]. It is based on the levels of different pollutants in the air, such as particulate matter (PM), ozone (O3), nitrogen dioxide (NO2), sulphur dioxide (SO2) and carbon monoxide (CO). The AQI is calculated for each gas separately so it is logical to measure each and take the highest (worst) as the index value. [31]

Chapter 3

System Design

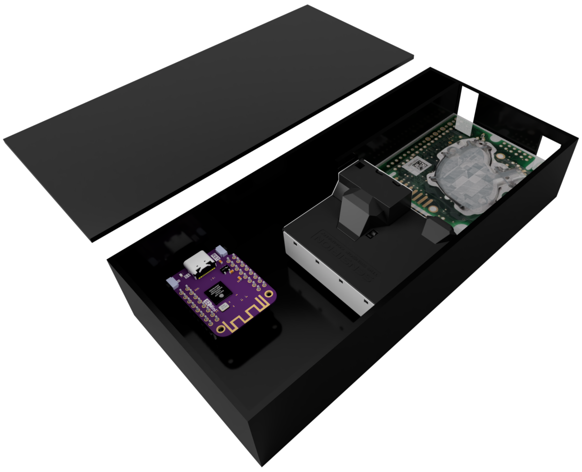


Figure 3.1: Render of design

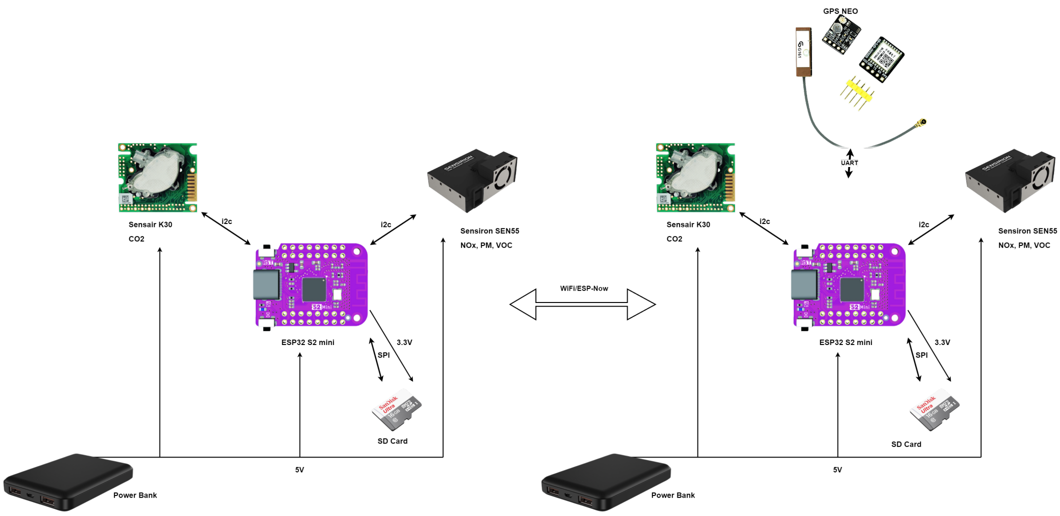


Figure 3.2: Full overview

3.1. Short summary of system

As seen in figure 3.2 the system consists of two sensors, the Sensirion SEN55, and the Senseair K30, the former measuring Particulate Matter, VOC, NO_X, Temperature, and Humidity and the latter CO_2 concentration respectively. They both share the same i2c bus. The other components in the system is the SD card used to store the data, the SD card is connected via the one of the ESP32-S2's SPI buses. The satellite station features a GPS to note the difference in values for different routes, it also functions as a home beacon, allowing the controller to know when the base station is close enough so it can attempt to transmit - this also serves to reduce power consumption since the onboard WiFi chip uses considerably more power than the GPS, thus keeping the WiFi from continuously trying to connect. The microcontroller forming the heart of the system is the ESP32-S2 MINI by WEMOS. The power source for the project is a 10000mAh power bank.

3.2. Hardware Overview

3.2.1. Microcontroller

An essential part of this project is the microcontroller, since it contains and controls many of the aspects needed for the project to work. Choosing a microcontroller comes down to its features. For this project the features considered were:

- Speed
- Communication capabilities
- Expandability / IO
- Storage
- Power draw
- Size
- Cost

A few common microcontroller boards available at the time of writing are compared in the table below along with their respective specifications:

		ESP32-S2 lolin mini	ESP8266 NodeMCU	Raspberry Pi Zero W
Speed		Tensilica Xtensa LX7 32 bit Single-Core @ 240Mhz	Tensilica LX106 32 bit @ 80 MHz (up to 160 MHz)	BCM2835 1GHz
Communication	Wifi	802.11b/g/n	802.11b/g/n max 65mbps	802.11b/g/n
Expandability / IO	I2C	2	1	2
	ADC	20 x 12bit	1 x 10 bit	8 x 17 bit
	CAN/TWAI	Y		Needs HAT
	GPIO	43	17	40
	UART	Y	Y	Y
Storage		Micro SD and USB OTG	Needs module	Micro SD and USB OTG
Power draw		190mA peak when sending WiFi	250mA peak	260mA at idle
Size		34.3*25.4mm	49*26mm	60*30mm
Cost		R99	R94	R320.85

Table 3.1: Microcontroller option and Specifications

From Table 3.1 the ESP32 S2-mini is power efficient, contains enough expandability to implement the necessary sensors, has wireless capabilities and is more affordable than the alternatives.

3.2.2. ESP-NOW/WiFi

When considering data transfer between the basestation and satellite station, speed, power consumption and range need to be accounted for. According to an article done by Dani Eichhorn from thingpulse, the runtime of a typical ESP32 running on a standard 2.5A h battery can be increased from an estimated 6.9 months on a WiFi gateway to up to 3.7 years on ESP-NOW, a sixfold increase [32].

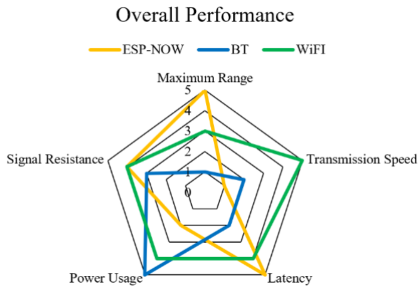


Figure 3.3: Overall Performance of each Protocol

In figure 3.3 extracted from a study done regarding the performance of the various wireless aspects of the ESP32 [33] it can be seen that the transmission range of ESP-NOW is superior to that of WiFi making it a valid option for transmission, while also keeping power consumption low. Tests will have to be done to see if the transmission speeds are fast enough to enable transmission of data when the satellite station reaches base.

3.2.3. Sensors

3.2.3.1. CO_2

For the CO_2 sensor a sensor with at least 5000ppm measuring capability was needed, as that was the top end of exposure for AQI. It also needed a suitable interface and an acceptable power consumption and fast enough response time. After looking at a few options on the market, the Senseair K30 FR (Fast response) NDIR sensor was chosen. This sensor features both UART and I2C communication, has a 70 mA average power consumption when powered, has a 0-5000 ppm sensing capability and is a fast response sensor, meaning it does not need a fan and can use the pre-existing fan from the other sensor since it uses diffusion. This enables accurate and fast sensing.

3.2.3.2. PM, NO_x, VOC

The sensor chosen for the various needed values needed to comply to the various parameters needed to determine air quality. For the air quality index, the values indicated are VOC and PM2.5, these values needed to have a range of at least 100-700 µg/cm^3 and 0-1200 µg/cm^3 respectively.
The sensor chosen is an all in one sensor, the Sensirion SEN55, it measures Temperature, Humidity, Particulate matter in the ranges 1, 2.5, 4, and 10 µm Both the VOC and NOx values are given as an index from a given baseline, so the information gathered from it will be in the form of a qualitative measurement based on what would be considered to be normal values, any deviation from the baseline represents a change in air quality. The particulate matter is given in precise measurements, so that will be helpful to identify the possible types of pollutants as well.

Parameter	Conditions		Value	Units
Mass concentration specified range	-		0 to 1000	ug/m3
Mass concentration size range	PM1.0		0.3 to 1.0	um
	PM2 5		0.3 to 2.5	um
	PM4		0.3 to 4.0	um
	PM10		0.3 to 10.0	um
Mass concentration precision for PM1 and PM2.5	0 to 100 ug/m3		±5 ug/m3 AND 5 % m.v.	
	100 to 1000 ug/m3		±10	% m.v.
Mass concentration precision2,3 for PW, PM105	0 to 100 ug/m3		±25	ug/m3
	100 to 1000 ug/m3		±25	% m.v.
Maximum long-term mass concentration precision limit drift	0 to 100 ug/m3		±1 25	ug/m3 / year
	100 to 1000 ug/m3		±1 25	% m.v. / year
Typical start-up time	number concentration	200 - 3000 #/cm3	8	s
		100 -200 #/cm3	16	s
		50 — 100 #/cm3	30	s
Sensor output characteristics	PM2.5 mass concentration		Calibrated to TSI DustTrak{TM} DRX 8533 Ambient Mode	
Additional T-dependent mass precision limit drift	temperature difference to 25C	typ.	±05	% m.v./ oc
Laser wavelength (DIN EN 60825-1 Class 1)	typ		660	nm

Table 3.2: Particulate matter sensor specifications [6]

As seen in table 3.2 [6] the precision attained is more than adequate for our measuring purposes.
Table 3.3 [6] contains the power requirements for all of these sensors, with the average being 63mA at 5V for typical use.

3.2.4. Power

From the previous section the power usage on average was found to be $70 + 63 = 133$mA consumption for the sensors alone. Depending on the draw from the ESP32 the consumption total would average around $70 + 63 + 90 = 223$mA [32]. And for the satellite station there is one more drain of power, the ATGM336H GPS, with average power consumption of 20 mA [34] bringing the satellite station to 243mA .
For the intended use, remote data gathering would be done with the help of a lithium battery pack, as lithium ion /polymer batteries are energy dense and are commonly found

Parameter	Conditions		Min	Typ	Max	Unit
Average supply current	Idle Mode (first 10 seconds)	SEN55	-	3.8	4.2	mA
		SEN54	-	7	1	
		SEN50	-	0.7	1	
	Idle Mode (after first 10 seconds)	SEN55	-	2.6	3	
		SEN54	-	0.7	1	
		SEN50	-	0.7	1	
	RHT/Gas-only Measurement Mode	SEN55	-	6.8	8	
		SEN54	-	6.5	7.7	
	Measurement-Mode (first 60 seconds)	SEN55	-	70	100	
		SEN54	-	70	100	
		SEN50	-	70	100	
	Measurement-Mode (after first 60 seconds)	SEN55	-	63	80	
		SEN54	-	63	80	
		SEN50	-	63	80	

Table 3.3: Current draw [6]

Figure 3.4: Power bank chosen

in USB power banks. Most of the sensors and the microcontroller either have native 5V input or have a voltage regulator onboard making it ideal. To calculate the size of the battery necessary, we take the typical usage, in the case of inside the taxi being 3 hours for the morning commutes and in the case of the base station 14 hours for the full day data. This gives: $223\text{mA} \times 14 = 3.122\text{A h}$ at 5V. This equates to 15.61W h. Typically battery bank capacity is given in mAh but this can be deceiving as it normally references the capacity of the cells in parallel with an average voltage of 3.7V not the 5V output. With the 15.61Wh needed, this would equate to a $4218,9$mAh Power bank needed. To ensure Full day usage, a typical power bank of 10000 mAh is chosen. This also ensures that, should the system need to, it would be able to provide 24 hour data. The power bank chosen also features Type C power delivery or PD for short, this allows it to be charged with 20W of power and thus charge quicker and avoid downtime in the sensor.

Chapter 4

Detailed System Design

4.1. Hardware

This system consists of multiple interconnecting components that will be discussed in detail in this section, namely:

- ESP32-S2
- Sensiron Sen55
- Senseair K30
- SD-card adapter
- ATGM336H GPS module
- Power bank

4.1.1. ESP32-S2

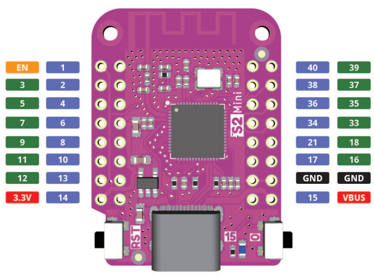


Figure 4.1: ESP32-S2 mini

The module used is the ESP32-S2 mini by WEMOS/Lolin. This module features thirty seven digital pins, three SPI interfaces with two of them fully available, two i2c buses, dual hardware UARTs, a built-in WiFi radio with antenna on board. The board runs on 3.3v power, but has an onboard voltage regulator that works on 5V. Although the board supports multiple i2c devices, it was chosen to connect both devices to one bus since they have different addresses. This also alleviates some space in memory by not having another initialisation of the i2c library instance. The board features an ultra low power co-processor capable of waking up from i2c interrupts, this could be used if deploying for longer durations. The main processor is an Xtensa® 32 bit Single Core Microprocessor that operates at up to 240MHz. Should this device be deployed with only internet capability in a data sensitive environment it also features cryptographic hardware accelerators. The board features native support for USB and does not need a serial bus bridge, making debugging much easier. It is also rated for extreme conditions, capable of working at up to 120 degrees Celsius [35].

4.1.2. Sensirion SEN55

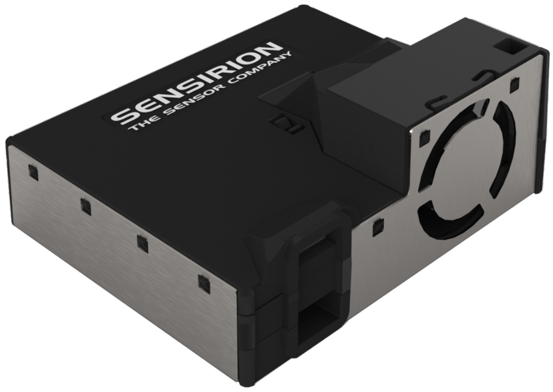


Figure 4.2: Sensirion SEN55

This sensor provides Particulate Matter, Relative Humidity, Temperature, VOC Index and NOx Index outputs. It is produced by Sensirion and uses a ACES 51452-006H0H0-001 connector interface to connect. It communicates using the i2c bus and has a library available to use to read its values, however, the NOx and VOC outputs are in the format of an index and the raw values are available but the conversion algorithm is proprietary, the index is thus used. The board uses 5v power as its VCC but communicates over i2c at 3.3V common voltage. The 5V is provided straight from the power bank in this use case. For the readings from the sensor, the particulate matter, relative humidity and temperature values are available immediately, with the VOC value following shortly behind. For the NOx and VOC values to be reliable, the sensor needs to be in operation for 1 hour for VOC and 6 hours for NOx. For extended use, as would be the case in the taxi rank, the sensor has a learning function on the VOC and NOx index, which is set by default as 12 hours. From this the sensor will estimate the mean gain for the previous 12 hours. The device also features a self cleaning mode, this runs once a week.

4.1.3. Senseair K30

The Senseair K30 FR module is an NDIR CO_2 sensor with 5000 ppm sensing range and an accuracy of 3%. It has a rate of measurement of 2 Hz and a response time of 2

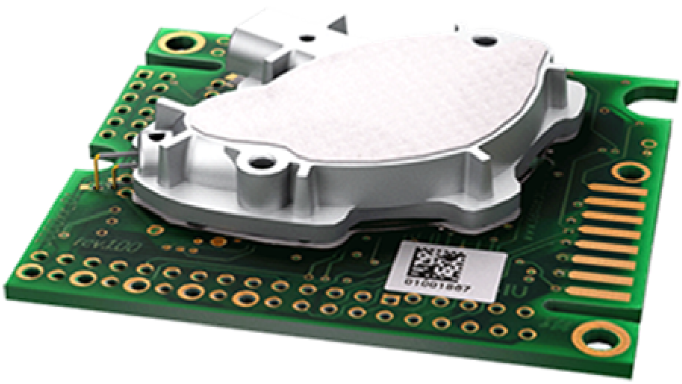


Figure 4.3: Senseair K30 FR

seconds, but since we are not using a gas tube, the diffusion time is 20 seconds which should be appropriate for the application. The sensor has a few ways to interface with the microcontroller, it features two analog outputs of 0 to 5V and 0 to 10V respectively representing 0 to 5000 ppm. It also features UART utilizing the MODBUS protocol as well as i2c communication. The sensor runs on 5 to 14V for power and has a dedicated input for the communications voltage, allowing the microcontroller to communicate at 3.3 or 5V depending on the model. The sensor communication is done using i2c and there is a detailed document by Sensair describing the protocol. The module also features the ability to change its address, this persists through power down, this negates the issue of having two sensors with the same address conflicting in the case of default addresses.

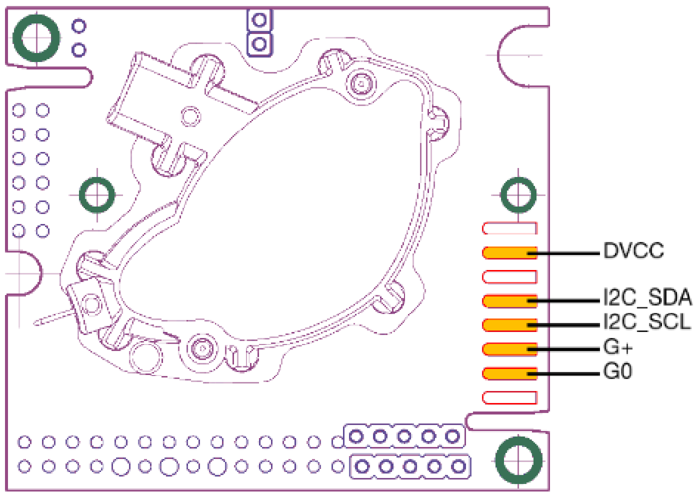


Figure 4.4: The i2c lines SDA and SDL are defined on the factory connector as well as the G+ and G0 representing VCC 5V in this case and ground along with DVCC representing the 3.3V communications voltage.

4.1.4. ATGM336H GPS module

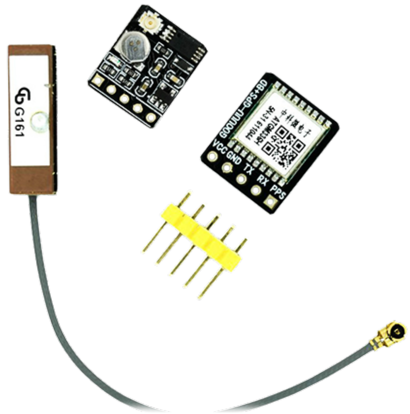


Figure 4.5: ATGM336H

Figure 4.6: GPS Antenna

The GPS module chosen for the satellite station is the ATGM336H shown in Figure 4.5, it is a small module, measuring in at only 13.1 by 15.7mm. It operates at 3.3V and consumes only 25mA when acquiring its position for the first time, and 20mA while tracking. It has an accuracy of 2.5 meters and an update rate of 10 Hz although 1 Hz is standard. The time to first fix for this module, referring to the time it needs to acquire an accurate location without the help of cell towers, is 26 seconds, this is also referred to as a cold start. Once it has the initial fix, it refreshes every second, and also supplies a PPS or pulse per second as a heartbeat. The module uses UART or Serial to communicate at a default Baud Rate of 9600bps. The standard it uses to communicate is NMEA0183, this will be further discussed in the software design. The module also includes a ceramic antenna, but another flat Molex Flexible GPS Antenna was used to allow the unit to not be as susceptible to bumps and outside interference. The GPS Antenna shown in Figure 4.6 is the antenna used in the design, it also features greater than 74% efficiency and is only 0.1 mm thick with an adhesive backing making it extremely easy to mount.

4.1.5. SD-card adapter

4.1.6. Power bank

4.1.7. Software/Firmware implementation

4.1.7.1. Overview

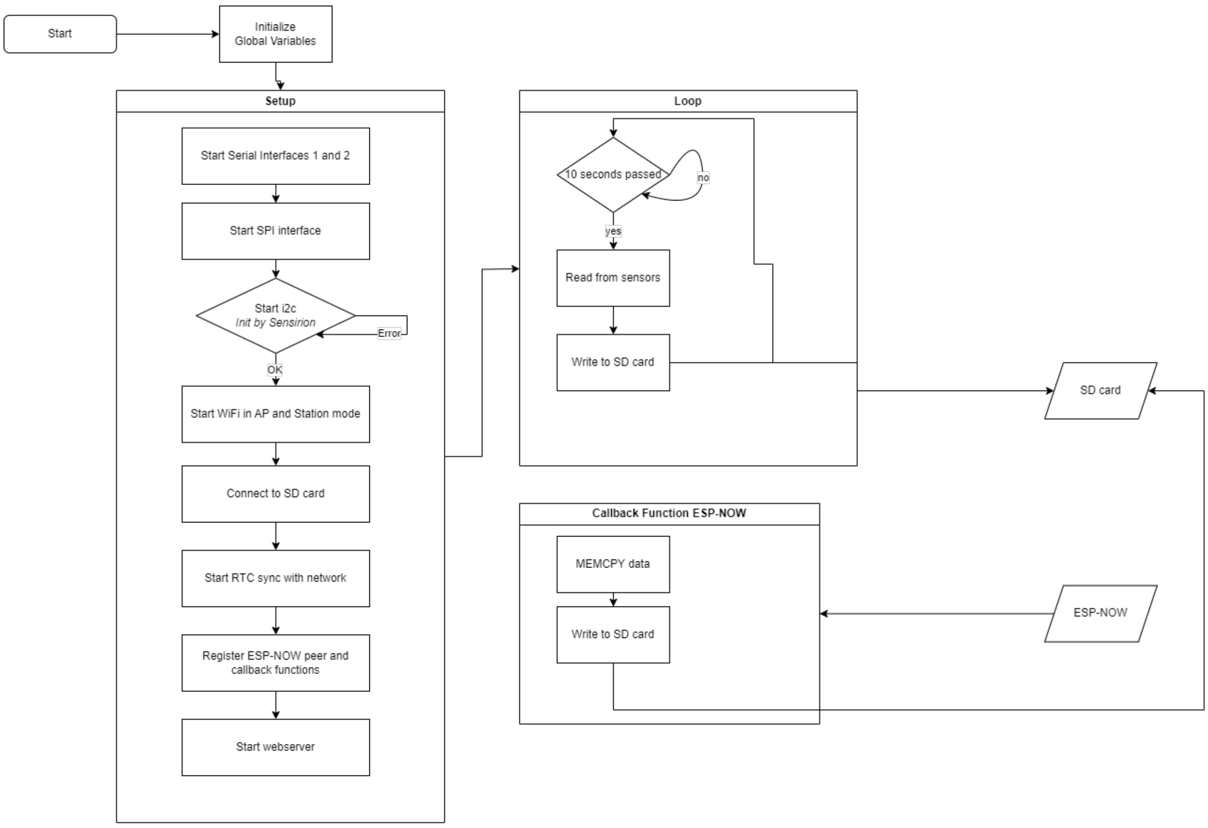


Figure 4.7: Flow diagram of software implementation

4.1.8. UART

The GPS unit uses UART Serial commands to send its data to the ESP32. The data received from the GPS module is in the format of NMEA strings. This is the standard format for most gps receivers. [36]

NMEA Sentence	Meaning
GPGGA	Global positioning system fix data (time, position, fix type data)
GPGLL	Geographic position, latitude, longitude
GPVTG	Course and speed information relative to the ground
GPRMC	Time, date, position, course and speed data
GPGSA	GPS receiver operating mode, satellites used in the position solution, and DOP values.
GPGSV	The number of GPS satellites in view satellite ID numbers, elevation, azimuth and SNR values.
GPMSS	Signal to noise ratio, signal strength, frequency, and bit rate from a radio beacon receiver.
GPTRF	Transit fix data
GPSTN	Multiple data ID
GPXTE	cross track error, measured
GPZDA	Date and time (PPS timing message, synchronized to PPS).
150	OK to send message.

Table 4.1: NMEA Sentences and their meanings [7]

This data is sent over the uart in comma delimited messages, the uart is set to default to 9600 baud. The ESP32-S2 has 2 hardware UARTs, one is used for debugging and communication with the device while developing and one for communicating with the GPS module. The first UART is set to 115200 baud and the second to 9600 baud. Each UART is initialized separately and the second UART is passed to the gps encoding library TinyGPS++. The first UART is only called when debugging or notices are needed. It is used to check sending of messages using ESP-NOW for example.

4.1.9. i2c

Both the Sensirion and Senseair sensors make use of the i2c bus to communicate.

4.1.10. ESP-NOW

Chapter 5

Results

5.1. Particulate Matter

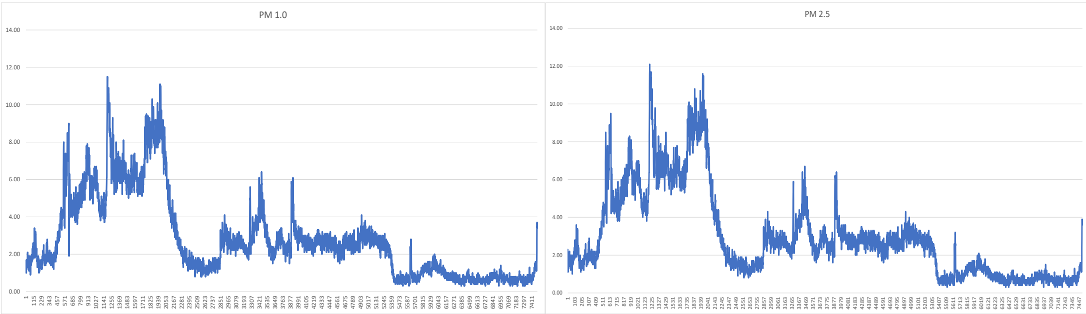


Figure 5.1: PM 1.0 (left) and PM 2.5 (right)

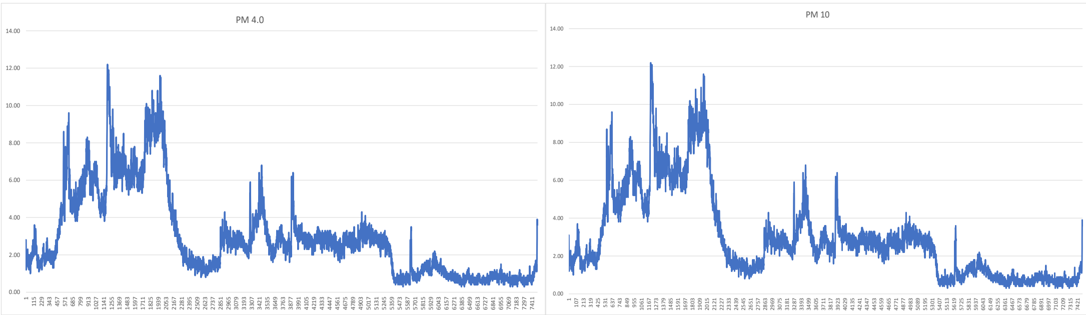


Figure 5.2: PM 4.0 (left) and PM 10 (right)

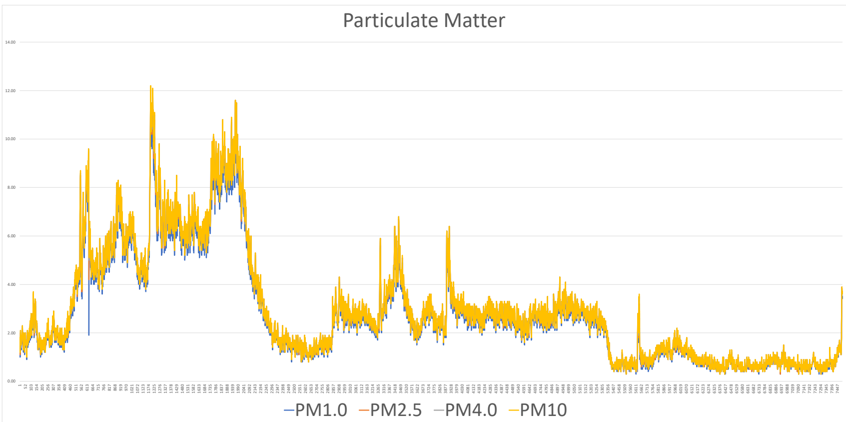


Figure 5.3: Part

The correlation between all of the different types of particulate matter concentrations is rather high, as can be seen from Figure 5.3, This means we could conceivably only use the PM 2.5 reading as is the norm.

5.2. CO2

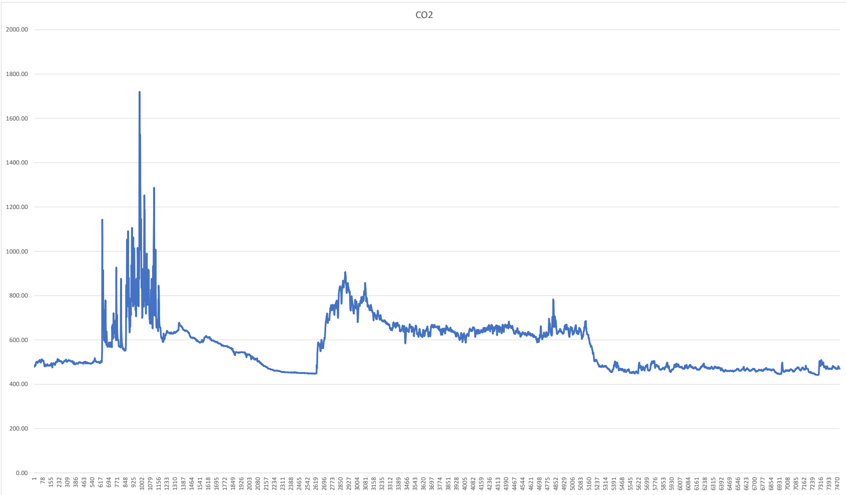


Figure 5.4: CO2 measurements

5.3. Temp and Humidity

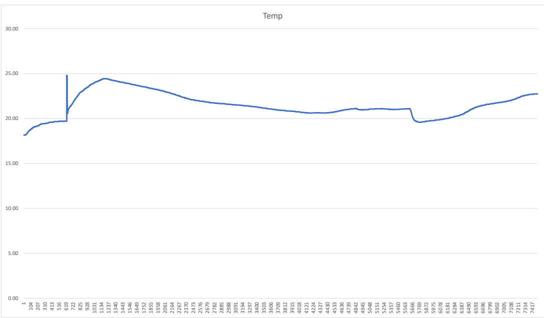


Figure 5.5: Temperature

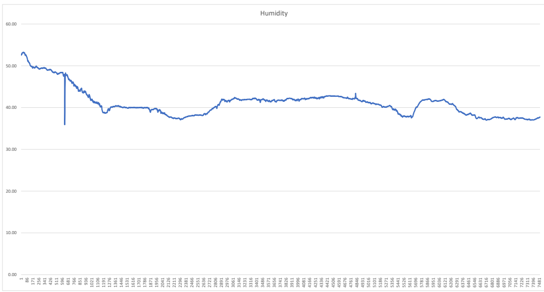


Figure 5.6: Humidity

5.4. VOC and NOx index

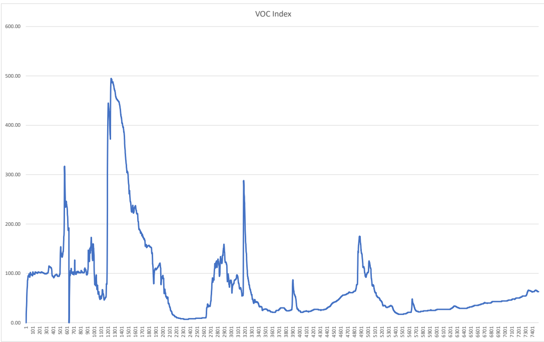


Figure 5.7: VOC

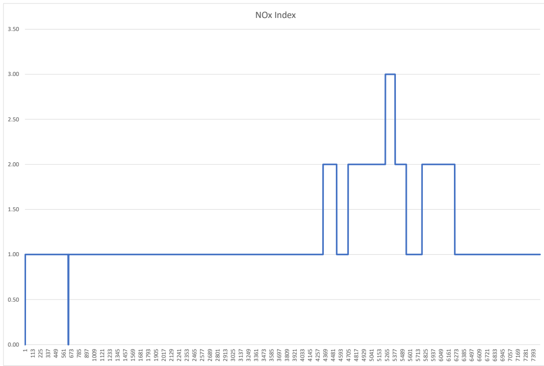


Figure 5.8: NOx

Chapter 6

Summary and Conclusion

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Appendix A

Project Planning Schedule

This is an appendix.

Appendix B

Outcomes Compliance

This is another appendix.

Appendix C

Appendix

Threshold levels

Radon (pCi/L)
- ≥4 pCi/L
- ≥2.7 and <4 pCi/L
- <2.7 pCi/L

Radon (Bq/m^3)
- ≥150 Bq/m^3
- ≥100 and <150 Bq/m^3
- <100 Bq/m^3

Particulate matter ($PM_{2.5}$)
- ≥25 µg/m^3
- ≥10 and <25 µg/m^3
- <10 µg/m^3

Carbon dioxide (CO_2)
- ≥1000 ppm
- ≥800 and <1000 ppm
- <800 ppm

Humidity
- ≥70 %
- ≥60 and <70 %
- ≥30 and <60 %
- ≥25 and <30 %
- <25 %

Temperature (°F)
- >77 °F
- ≥64 and ≤77 °F
- <64 °F

Temperature (°C)
- >25 °C
- ≥18 and ≤25 °C
- <18 °C

Airborne chemicals (VOC)
- ≥2000 ppb
- ≥250 and <2000 ppb
- <250 ppb

Figure C.1: Airthings table