Journal of Technological Sciences (JTS) Volume 1, Issue 2, 2023

Chinhoyi University of Technology
Journal of Technological Sciences
http://journals.cut.ac.zw/index.php/jts

The design of an IoT based automatic pollution monitoring system

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The design of an IoT based automatic pollution monitoring system

Abstract

Urban areas are characterized by high population density and extreme air pollution due to mobile machines and industrial activities. Automobiles are one of the main sources of air pollution. The main aim of this research was to monitor the amount of vehicle emissions and ambient air pollution levels depending on vehicle density. This research also investigates cold start emissions from petrol vehicle engines. Design science research methodology was implemented in designing the monitoring system, compatible for both ambient and onboard emission monitoring. The system was designed with emission detection sensors installed on four locations of Chinhoyi urban to monitor ambient air pollution, and on vehicle exhaust tail pipes to monitor vehicle emissions. Highest average CO level (3.27ppm) was found in a location with highest vehicle density (33 vehicles at Location 2 (CHTMBusStop)). It was also observed that Location 1 (CHEMA) had higher vehicle density as compared to location in Chinhoyi urban. However, CO concentration (0.44ppm) at Location 1 (CHEMA) is lower than CO concentrations at locations in Chinhoyi town (0.56ppm and 0.98ppm at Location 3 (CCFCRobots) and Location 4 (CKERobots) respectively). This is attributed to the driving mode of vehicles in highway driving cycle and urban driving cycle. It was found that as vehicle density increased from 15 to 18, CO concentration also increased from 0.56ppm to 0.98ppm respectively. A location furthest from town (location 1) had the minimum CH_4 concentration (2.57ppm), and as we move closer to town CBD CH_4, concentrations increased significantly (5.94ppm, 7.52ppm and 57.34ppm at location 2, 3, and 4 (Chinhoyi town CBD) respectively). The average CO emission level from vehicle exhaust tailpipes found was 78.39ppm, which is not above the set limit of 90ppm for at most 15minutes. However, the maximum concentration of CO observed from exhaust tail pipes was 988.69ppm. Nissan Sylphy (engine capacity of 1,798cm^3, engine model MRA8DE) without converter was found to emit more CO pollutants (279.97ppm) as compared to Toyota Alex2001 (engine of capacity 1496cm^3) and Toyota Runx with engine capacity of 1497cm^3 (58.57ppm and 20.91ppm respectively). The CO emission levels from vehicles with catalytic converter exist within Zimbabwean emission limits.

1. Introduction

Urbanization contributes to more air pollution in developing countries due to second hand vehicles that are being imported from developed countries. According to the Environmental Management Agency (EMA) (2015), Zimbabwe has seen a sharp rise in the number of imported cars over the years; the country's Light Driver Vehicle (LDV) count rose from 509 764 in 2005 to 1 037 643 in 2016 (Vietnam Register, 2017). According to Vietnam Register (2017), the percentage of new cars fell from 15.7% in 2005 to 3.8% in 2016. According to United Nations Environment Programme (UNEP) (2014), the importation of subpar used cars is causing the population of automobiles in African nations like Botswana and Zimbabwe to double every ten years. Such second-hand vehicles and industrial machines contribute to high air pollution. Acid rain, global warming, and the greenhouse effect might be caused by unchecked emissions. In 2012, air pollution was linked to about 7 million premature deaths globally, according to a report published by the World Health Organization (WHO) (Rinki & Karnika, 2015). This study was motivated by these emissions from vehicles' knock-on consequences.

This research aimed at monitoring ambient air pollution and vehicle exhaust tail pipe emissions. Several authors have looked at pollution monitoring. They include Mohamed (2017) who recommends the use of nanotechnology in air pollution detection stating that nanomaterials are advantageous as they can be applied in pollution remediation technologies. Iodice et al. (2016) suggests the use of moss transplants for biomonitoring in air pollution evaluation. Hernandez-Vargas et al. (2018) emphasized the importance of real-time pollution detection stating that it reduces the use of harsh chemicals and reagents that leads to high pollution. Real-time pollution detection helps in outlining anthropogenic-based pollution (Nigam & Shukla, 2015; Iodice et al., 2016; Artiola & Brusseau, 2019). Several researchers emphasized that vehicle emission detection needs to be continuous (Plashnitsa, Anggraini, & Miura, 2011; Spreen et al., 2016; Bangal, Gite, Pravin, Ambhure, & Gaikwad, 2017) since it may occur for a very short distance and/or time as a result of possibly different causes such as geographical terrain (Hitchcock & Carslaw, 2016) and driving patterns (Iodice et al., 2016; He & Jin, 2017). In this research, pollution detection MQ sensors were installed on four different locations in Chinhoyi urban and also on three petrol vehicles' exhaust tail pipes. The sensors then forwarded data to the mobile phone, which send data to the central computer located at Chinhoyi University of Technology.

2. Justification of the study

Environmental Management Agency (EMA) can make use of this research's output. This is because their mandate is maintain clean air, hence they need to monitor air pollution levels in the environment and the sources of emissions. Giannadaki et al. (2018) estimated that a 50% reduction in agricultural air emissions reduced premature deaths by protecting over 200 000 lives in 59 countries. Air pollution monitoring aids air pollution management agencies in controlling emissions, indirectly contributing to reduced premature deaths. According to Wang et al. (2018), prolonged exposure to air pollution shortens life expectancy, which is why air pollution monitoring and alerting is necessary. The technology is essential for preserving clean air since it offers automatic and real-time detection and alerting. Pollution monitoring is necessary because no one can maintain clean air without being aware of the present amounts of pollution in the environment.

This research adds value to the body of knowledge as fellow researchers will use it as they review literature. In particular, researchers working on vehicle emission and ambient air pollution monitoring and control will make use of this research. Additionally, manufacturers of emission detection devices will also make use of this research to review functionality of the sensors used in this research.

3. Related work

In addition to the negative effects of air pollution on human health, the United Nations Environment Programme (UNEP) (2014) estimated that by 2030 global losses to crops like maize (which is Zimbabwe's stable food), wheat, and soya beans caused by ground-level ozone (O3) pollutants could be estimated at US$17-35 billion annually. The World Health Organization (WHO) (2009) reported that approximately 2.4 million people die each year due to air pollution, and the statistics from UNEP (2014) indicate that more than 3.5 million people die annually due to outdoor air pollution. WHO (2017) also noted that in 2012, mortality rates in Zimbabwe were 52.9 per 100 000 population. Therefore, air pollution needs to be controlled so as to improve the quality of air, achieve food security and protect our eco-systems. As a result, monitoring air pollution is necessary to save our eco-systems, increase food security, and enhance air quality.

Environmental monitoring is of great importance (Artiola & Brusseau,2019; Luo & Yang 2019) in developing and implementing laws and regulations for the protection of human health and the environment (Mohite & Barote, 2015; Artiola & Brusseau, 2019). Nandy, Coutu, and Ababei (2018) emphasized the importance of environmental pollution monitoring to ensure safety to human beings and other living organisms. Several researchers have proposed emission monitoring systems. Jagasia et al. (2017) suggest the use of emission detection devices at traffic lights. The use of metal oxide semiconductor sensors for carbon monoxide emission detection in homes, industry, and urban areas is encouraged (Nandy, Coutu, & Ababei, 2018). Artiola and Brusseau (2019) reported that monitoring can be done through physical, chemical and biological methods. Luo and Yang (2019) accentuates the necessity of locating the source of pollution. This is the reason why in this research we selected urban areas highly populated with vehicles and people at the same time.

The presence of people contributes to high pollution levels because pollution is anthropogenic. Artiola and Brusseau (2019) emphasized the use of nascent technologies of remote sensing through mounting sensors on satellites and drones while Luo and Yang (2019) encouraged the use of sensor network systems where data collected is sent to a central server for analysis. In this work, the researchers incorporated a sensor network system for pollution data collection and analysis. Cheap semiconductor sensors were used for pollution detection. Nigam and Shukla (2015) and Hernandez-Vargas et al. (2018) advocate the use of electrochemical biosensors for pollution detection. Nigam and Shukla (2015) reported that “enzymes and biological systems” are good for pollution detection, quantification, and conversion of pollutants to non-pollutants.

Das, Sen, and Debnath (2015) reported that nanomaterials are promising in the design of pollution detection sensors and environmental pollution control. Mohamed (2017) recommends the use of nanotechnology in air pollution detection stating that nanomaterials are advantageous as they can be applied in pollution remediation technologies. Mohamed (2017) reported that nanomaterials have magnificent adsorbing, catalyzing, and sensing properties. Iodice et al. (2016) suggests the use of moss transplants for biomonitoring in air pollution evaluation. Iodice et al. (2016) supports the use of mosses on the basis that they are able to monitor a variety of contaminants. Hernandez-Vargas et al. (2018) emphasized the importance of real-time pollution detection stating that it reduces the use of harsh chemicals and reagents that leads to high pollution. Real-time pollution detection helps in outlining anthropogenic-based pollution (Nigam & Shukla, 2015; Iodice et al., 2016; Artiola & Brusseau, 2019). Carbon monoxides and hydrocarbons are the main pollutants which require attention in the environment (Artiola and Brusseau, 2019) and automobiles contribute a lot to the emission of such gases (Hedinger, Elbert, & Onder, 2017; Fan, Hou, & Yan, 2018; Carlson, Hankins, & Stein, 2019) especially in urban areas (Holnicki *et al.*, 2017).

A number of authors have looked at vehicle emission monitoring for different reasons. In this research we have developed an onboard automobile emission monitoring system for the purpose of analyzing the effects of exhaust gas temperature, geographical location terrain, and day time on vehicle emission levels. The first research to note is the one done by Marina and Mary (2016) where an IoT based system was developed to infrequently collect vehicle carbon monoxide emission level and send it to a cloud-based server hosted by Amazon. The system presented in this paper continuously monitors vehicle emissions and ambient air pollution levels. Pollution monitoring require to be continuous, however, in Marina & Mary, (2016)'s IoT based system, emission level was checked every 20km. This however, may not represent the vehicle's actual emission trend because 20km is a long distance to travel without checking emission levels. The system could be more beneficial if the same systems, which upload data for their respective countries are developed in other countries. On the other hand, emission detection needs to be continuous (Plashnitsa, Anggraini, & Miura, 2011; Spreen et al., 2016; Bangal, Gite, Pravin, Ambhure, & Gaikwad, 2017) since it may occur for a very short distance and/or time as a result of possibly different causes such as geographical terrain (Hitchcock & Carslaw, 2016) and driving patterns (Iodice et al., 2016; He & Jin, 2017).

Smit and Kingston (2019) proposed the use of remote sensing for vehicle emission detection using infrared vehicle profiles to identify conditions which contribute to high emissions (e.g., cold engine operation). However, the sensing devices are stationary, which means emission detection is not continuous, that is, each vehicle’s emission level is measured once, only when it passes through remote sensors.

Piyush and Pathrikar (2017) came up with a design for automated control of automobile emissions and rash driving. The system made use of semi-conductor sensor for emission detection, when emission level exceeds a set threshold, a notification alarm is raised and the vehicle halts automatically to stop further emissions. The main objective of the system was to instantly control emission levels. Same on board emission detection using MQ sensors was suggested by several more researchers (Chandrasekaran, Muthukumar, & Rajendran, 2013; Kulkarni & Ravi, 2014; Tiwari, Shekhar, Joshi, & Deep, 2015; Basavaraj, Chethan, Kumar, Vinay, Vinay, & Mahitha, 2017). Systems by these authors were meant for instant emission control through automated vehicle halt. Such systems could be used best for data collection, which may be used later in big data analysis. However, these systems only record data when emission levels exceed a set threshold and it may take long time to get enough data for big data analysis and some important emission values that could have been measured while emitting below threshold might be missing.

Another Internet of Things (IoT) system was made by (Abirami, Dharini, Kokilavani, & Vijayanandam, 2017) for monitoring vehicle emission trends. The system records a message when emission levels get to extreme levels and a message is sent to system administrator.

4. Methodology

The research team employed the Design Science Research Methodology (DSRM), which was adapted from guidance by Hevner and Chatterjee (2010), Wieringa (2016), and Vaishnavi et al., (2017). This study process involves the following steps: problem identification and objective setting, system design or suggestion, development and demonstration, evaluation, and communication. The first phase of the DSRM was problem identification and objective setting. The problem was identified through literature review, where air pollution is said to be contributing to adverse effects on the environment and on human lives. The research team concluded the first phase by setting goals, to monitor vehicle emissions and ambient air pollution. System design commenced after thorough literature review and section 5.2 and 5.3 shows system design. The development of the system began by assembling all hardware devices, programming them following the data flow diagram in Figure 5.9.4 and 5.9.5. The designed system was installed and demonstrations were done as the system was tested and evaluated. This paper serves as the communication last phase of the DSRM.

4.1.Hardware tools for ambient air pollution monitoring

An automated system was developed to gather pollution data in several locations of Chinhoyi urban. Pollution detection devices (MQ sensors) were installed on locations labeled 1 to 4 in Figure ***4*** map**.** MQ7 was used to measure CO concentration, MQ135 for CO_2 and MQ2 for CH_4. GPS module was used to gather GPS coordinates of the locations. LM35 temperature sensor was used to measure ambient temperature. These detection devices send pollution data to a mobile phone through a GSM module. The GSM module was being triggered by AT-Mega 2560 microcontroller to forward data to the central computer for data analysis. Data analysis was done using python programming language to generate trends and graphs using the data gathered. System architecture is shown in Figure ***1.*** System block diagram is illustrated in Figure 2

4.2.System Architecture

The system was designed with detection, central control and notification devices. Detection devices include the MQ7, MQ2, MQ135, GPS sensor, and temperature sensor. These devices were collecting data and sending it to the microcontroller, acting as the central control unit. The controller bundled all data as one message and send it to a mobile phone through the GSM module.

The data sent to the phone was then synchronized with the computer on the internet, acting as the central server for data access and analysis. Figure below shows the system architecture.

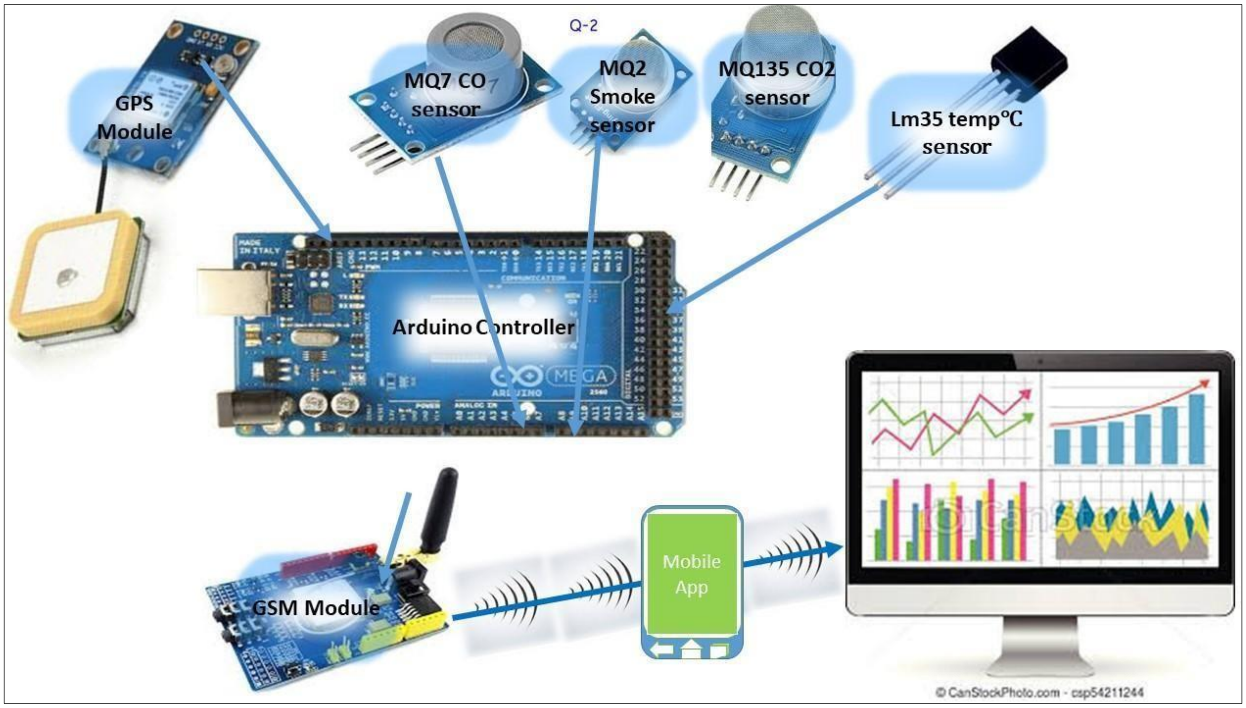

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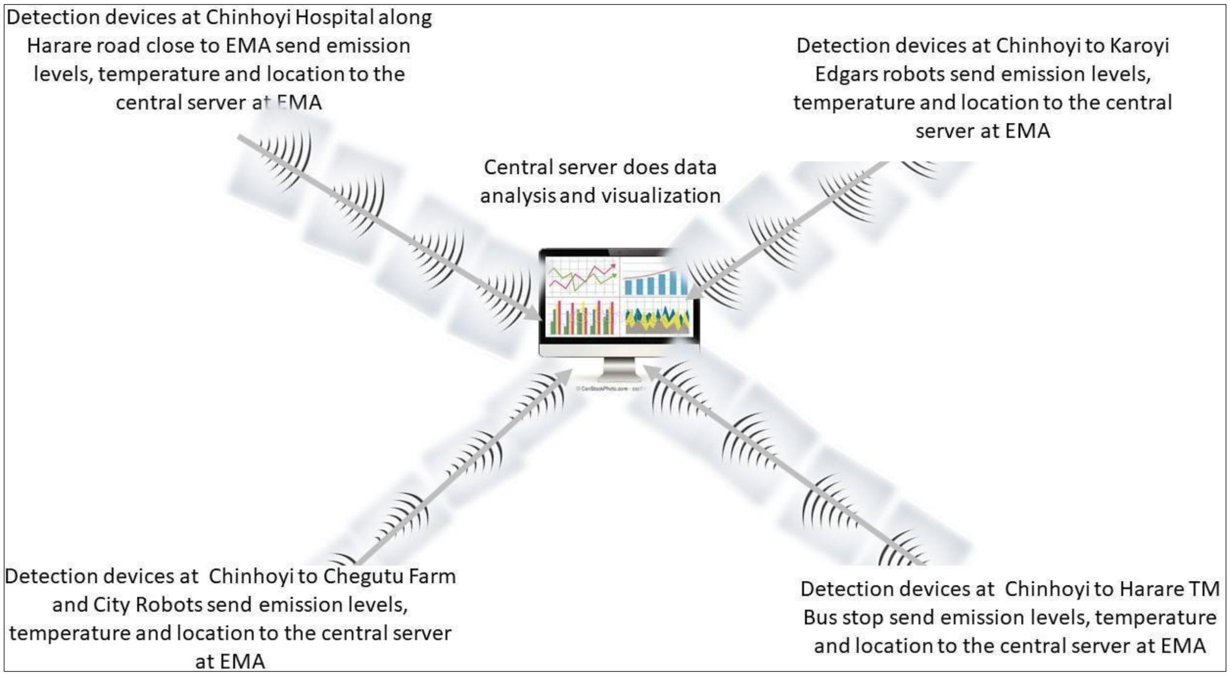
Figure 1: Ambient air pollution monitoring system architecture

4.3.System block diagram

Figure below shows an overview of the whole ambient air pollution monitoring. The figure gives details about the four locations where the detection devices where deployed and how they were sending data to the central server through wireless technology.



Detection devices at Chinhoyi Hospital along Harare road close to EMA send emission levels, temperature and location to the central server at EMA

Detection devices at Chinhoyi to Karoyi Edgars robots send emission levels, temperature and location to the central server at EMA

Central server does data analysis and visualization

Detection devices at Chinhoyi to Chegutu Farm and City Robots send emission levels, temperature and location to the central server at EMA

Detection devices at Chinhoyi to Harare TM Bus stop send emission levels, temperature and location to the central server at EMA

Figure 2: Block diagram for ambient air pollution monitoring system

4.4.GPS Module

Global Positioning System module is a device used to get latitude and longitude coordinates which define a specific location on earth. In this research, the GPS module used is GPS neo-6. The module receives the coordinates from satellites and forwards the coordinates to the microcontroller.

4.5.GSM module

Global System for Mobile Communications (GSM) module is a device that makes use of Short Messaging System (SMS) and mobile networks to send messages. The module requires having a SIM card. In this research, the module is used to forward data from onboard detection devices to a mobile phone. For the module to perform this task, it was triggered by the microcontroller.

4.6.Mobile phone

A mobile android phone was used as the medium between the GSM module and the central server.

The android phone used was an Itel A14 max running android version 8.1.0 with a total RAM of 512MB. An android application was developed to get messages from on-board emission detection and forward the message data to a central server. The device gets data from the onboard system and forwards the data to a central server using Wireless Local Area Network (WLAN). The central server and the mobile phone were using a common WLAN and could share data over the network.

4.7.Microcontroller

A microcontroller device is a minicomputer that focuses on achieving one task or few. In this research, a microcontroller is used for getting emission values from detection sensors, get vehicle location from GPS module as GPS coordinates, and getting exhaust gas temperature from connected LM35 temperature sensor. The microcontroller combines the collected data with vehicle number, mileage, make, and model and forwards the data to a GSM, which will send data to a central server through a mobile phone. Therefore, the microcontroller in this research is the center where all components are controlled. The microcontroller used here uses an AT Mega 2560 microcontroller on an Arduino Mega 2560 board.

4.8.Sensors

A sensor is a device used to detect or measure real world parameters. Sensors used in this research are MQ sensors (MQ2, MQ7 and MQ135). MQ2 sensor was used to measure CH_4, MQ7 was used to measure CO and MQ135 was used to measure CO_2. Sensors were calibrated as described in the section 5.8.1 (Sensor calibration).

4.8.1. Sensor Calibration

Sensor calibration is defined as the process of configuring an instrument to ensure that it gives out the correct output values in its domain (Babu and Nagaraja, 2018). Babu and Nagaraja (2018) noted that MQ sensors require calibration before use. Babu and Nagaraja (2018) noted that the aim of calibrating a sensor is to obtain a typical value in clean air (Visvam, 2016) and the same value can be used to determine the deviation from the typical/standard value in other scenarios. This was also concurred by Kumar, Mukherjee, and Parveen (2019) who stated that MQ sensors must be deployed to fresh air before converting the sensor value to PPM values. A constant value obtained when sensor is deployed in fresh air shall then be used in a formula to calculate a PPM value.

4.8.1.1.LM35 temperature sensor calibration

Singh, Dhar, & Roy (2017) and Chin *et al.* (2019) noted that for each one degree Celsius (°C), LM 35 temperature sensor will give an output value of 10mV. Therefore, LM 35 sensor value multiplied by ten will give the temperature value in °C (i.e., temperature in °C (temp°C) = lm35SensorValue / 10). Singh, Dhar, & Roy (2017) suggests LM 35 temperature sensor calibration using an external thermometer where LM 35 sensor value divided by ten is compared to digital thermometer's temperature values. This confirmed that temperature in °C is equal to LM 35 sensor value in millivolts divided by ten. Veerasingam, Karodi, Shukla, & Yeleti (2009), Murugan, Periasamy, and Muruganand, (2012), Mulge (2013) and Latha, Sudha, and Swati (2013) agree that LM 35 temperature sensor does not need "any external calibration or trimming" for it to give accurate temperature values with variance less or equal to ±0.25. Mulge (2013) noted of ±1/4°C for normal temperatures and ±8/4°C for -55°C to +150°C full temperature range for LM 35 (Murugan, Periasamy and Muruganand, 2012) while Latha et al. (2013) reported a variance of ±0.4 at room temperature and ±0.8 for temperature range from 0°C to 100°C. LM35 calibration was done through two-point calibration method, where ice-water bath and boiling water's temperatures are used as references. It is well known that water boils at 100°C and its triple point is 0.01°C. Therefore, reference low is 0.01, reference high is 100 and reference range is 100-0.01=99.99. LM 35 sensor's raw values for boiling water was found to be 868, raw values for ice water was found to be 848, hence the raw range is 20. Therefore, the formula to calculate temperature values in °C is shown in equation (4.1) and (4.2).

$$Temp°\mathrm{C} = \left(\frac{(RawValue - RawLow) * ReferenceRange}{RawRange}\right) + ReferenceLow \qquad \text{Equation (1).}$$

$$Temp°\mathrm{C} = RawValue - 848 * 4.995 + 0.01 \qquad \text{Equation (2).}$$

4.8.1.2.MQ sensor calibration and obtaining ppm values.

Unlike LM 35 sensor, MQ sensors are non-linear hence, it is a must for them to be calibrated properly. According to Dorcea, Hnatiuc, and Lazar (2019), the formulae below are used in converting sensor values to ppm per gas stated using MQ 2 sensor. For CH_4, Equation (3) was used. Equation (4.4) was used for CO detection and conversion.

$$\log ppm = -2.606 \log\left(\frac{Rs}{R0}\right) + 3.6301 \qquad \text{Equation (3)}$$

$$\log ppm = -2.9368(\log\left(\frac{Rs}{R0}\right) + 4.4477 \qquad \text{Equation (4).}$$

Using the same method used by Dorcea, Hnatiuc, and Lazar (2019), the equation (5) was used for MQ135 sensor value conversion to ppm.

$$\log ppm = -0.2894572 \log\left(\frac{Rs}{R0}\right) + 0.4284388 \qquad \text{Equation (5).}$$

$$Rs = \left(\frac{Vc - Vout}{Vout}\right) * RL \qquad \text{Equation (6)}$$

$$R0 = Rs/RatioAir \qquad \text{Equation (7).}$$

These equations were derived from MQ datasheets diagrams using Web Plot Digitizer and regression modeling in Python. R_s is sensor resistance in the presence of certain gas and R_0 is sensor's resistance at 1 000ppm for MQ2. According to Babu and Nagaraja (2018) and Dorcea, Hnatiuc, and Lazar (2019), equation (5.8) was used to obtain R_s, where V_c is the circuitry voltage input for the sensor, R_L is load resistance, V_{out} is the voltage for the load resistance given as sensor output, and R_s is the sensor's resistance in clean air. V_c value was measured using a current sensor, and R_L used here is 5 000Ω for MQ 2. For MQ 7, R_L value used is 10 000Ω, for MQ 135, 20 000Ω and for MQ 3, 200 000Ω was used for R_L. This is according to Babu and Nagaraja (2018) and Dorcea et al. (2019). Formula for R_0 is shown in equation (5.9). According to Dorcea et al. (2019), *Ratio Air* for MQ 2 is 9.65, for MQ 3 is 59.95 and for MQ 7 is 26.06. Parmar, Lakhani, & Chattopadhyay (2018) did MQ 135 and MQ 7 sensor calibration early in the morning. Visvam (2016) noted that the reference value for MQ 7 is 100ppm and 1 000ppm for MQ 2.

4.9.Software tools

4.9.1. Arduino IDE and C++

Arduino Integrated Development Environment (IDE) was used for microcontroller programming using C++ programming language.

4.9.2. Android Studio

Android studio is a development platform for android applications using Kotlin, Java and XML. Kotlin and Java are the languages that are used for application control while XML is used for

Graphical User Interface (GUI) design. In developing the application, Java and XML were used.

4.9.3. Notepad++

Notepad++ is a platform where web applications and scripts can be developed. Many document formats can be created and edited using Notepad++. In this research, PHP API was developed using notepad++. Inside the PHP API were SQL statements to insert data into MySQL database. The database was accessed through phpMyAdmin installed with Xampp.

4.9.4. Program flow diagram for ambient air pollution monitoring

The program that was uploaded on the At Mega 2560 microcontroller was based on the program flow diagram given in Figure 3. Once the system is started, sensors gather data from ambient air. The GPS module receives the GPS latitude and longitude coordinates while the LM35 temperature sensor measures the current temperature. Data is then sent to the GSM module which forwards data to a mobile phone after every two minutes. The mobile phone will then forward the data to a central computer where data analysis and visualization was done.

4.9.5. Ambient air pollution monitoring program flow diagram

Ambient air pollution monitoring starts by initializing detection devices and gathering pollution levels of CO, CH_4 and CO_2. After pollution levels data collection, the system senses the location at which the data is collected using the GPS sensor. The last thing to be detected was temperature and the data is combined as one message forwarded to the mobile phone after every 120seconds. This is outlined by the program flow diagram in Figure below.

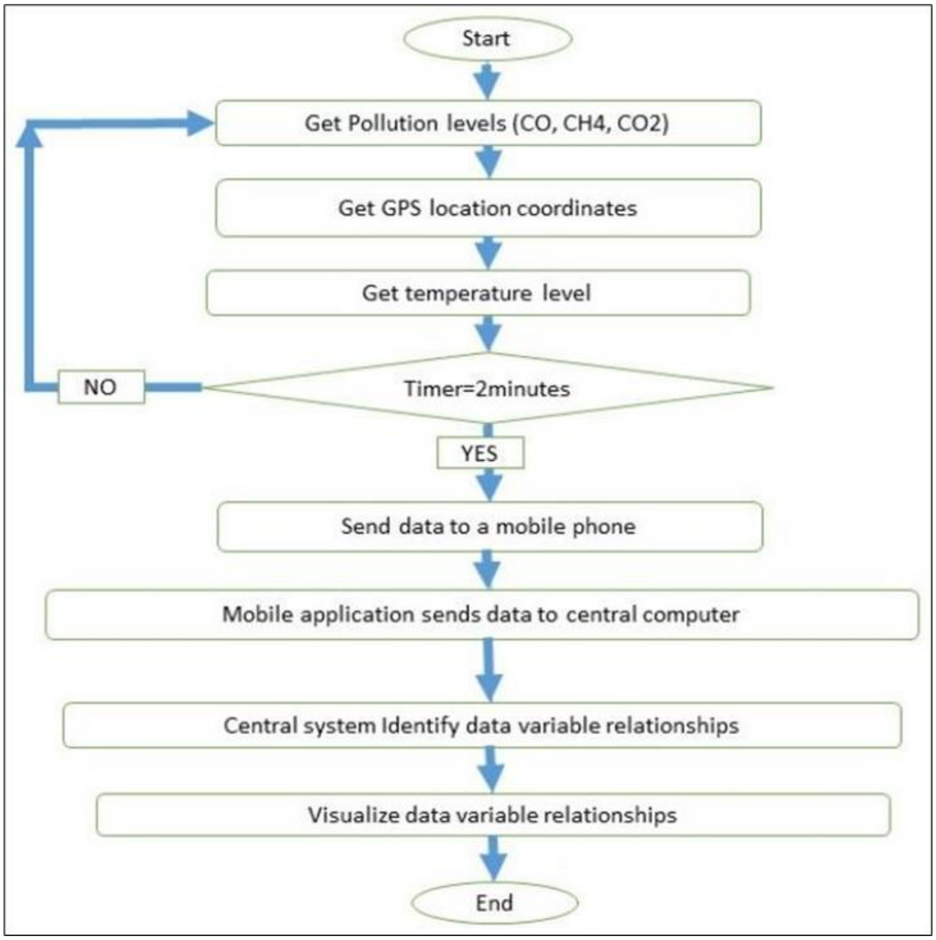


Figure 3: Ambient air pollution monitoring program flow

4.10. Location map

The designed monitoring system was installed on locations illuminated in Figure 4. The locations were selected based on their respective association with vehicle density and average speed of vehicles that passes through it. Sections that follow after Figure 4 below gives more details about each location. The research team chose to have at least one location with vehicles running at high speeds, assuming that they have attained engine light-off temperatures and the location was CHEMA. Other locations were in Chinhoyi CBD, where there were many vehicles and most of them starting from key-ON, some accelerating and decelerating at traffic lights. These locations allowed the research to explore various pollution trends from vehicles in different states of driving patterns. Two locations were on the traffic lighting intersections and the other one was at a bus stop.

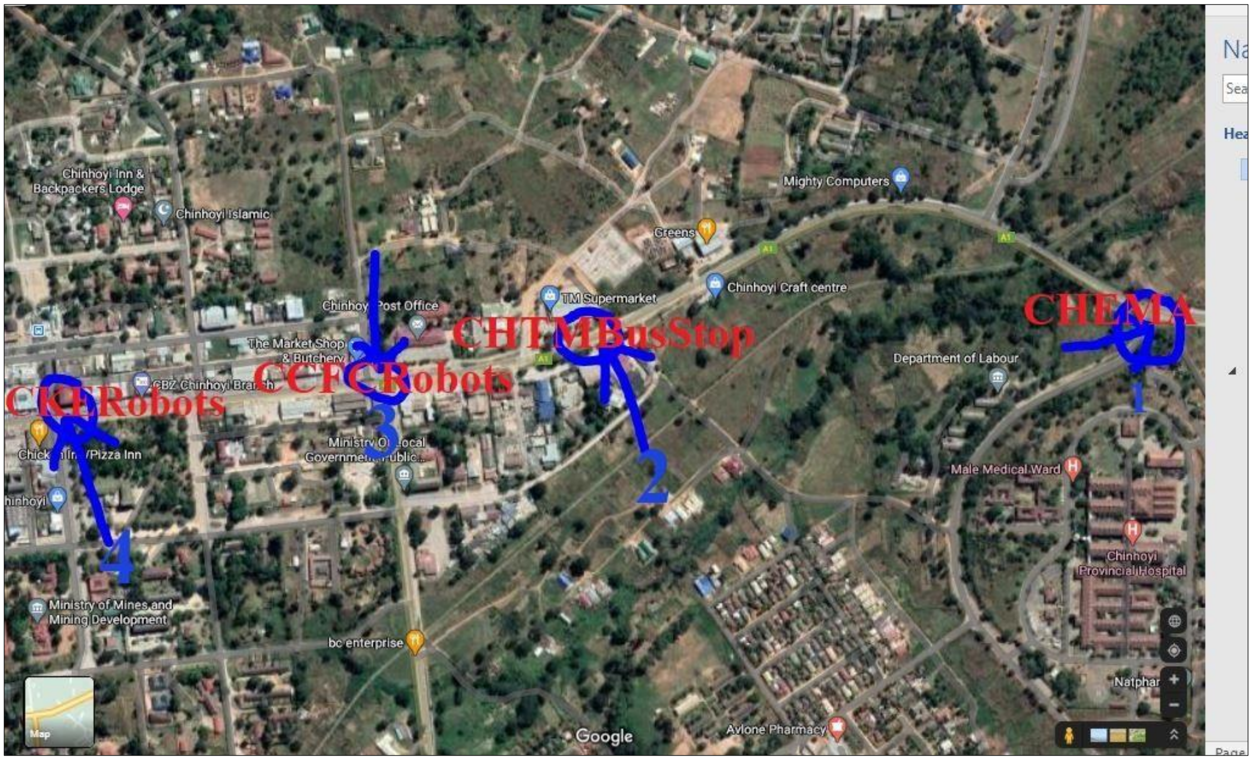


Figure 4: Locations where detection sensors were installed in Chinhoyi urban.

4.10.1. Location 1 (CHEMA)

Pollutants for vehicles plying Harare-Chinhoyi highway were measured at CHEMA checkpoint. Detection devices were installed 1 meter away from the road at an altitude of 1 m. The average number of vehicles per minute passing through location 1 was found to be 25. This average number was determined from sample vehicles counted manually for ten minutes after every one hour. Vehicles passing through location 1 were assumed to be running at 40 km/h to 60 km/h since this section of the road has a speed limit of 60 km/h.

4.10.2. Location 2 (CHTMBusStop)

This location had more vehicles as compared to other locations and the vehicles had different driving modes ranging from decelerating, accelerating, starting, and idling. Detection devices were installed 1 meter away from the road and set 1 meter high. The average number of vehicles passing through the location was 33 per minute.

4.10.3. Location 3 (CCFCRobots)

This location had an estimate of 15 vehicles passing through the area per minute. The location is an intersection controlled by traffic lights; which regulates the speed of vehicles. Since there are traffic lights, some vehicles were decelerating; some accelerating and some were idling. Detection devices were installed 1 meter away from the road and set 1 meter high.

4.10.4. Location 4 (CKERobots)

This location had an estimate of 18 vehicles that pass through the area per minute. Since there are traffic lights, some vehicles were decelerating; some accelerating and some were idling. Detection devices were installed 1 meter away from the road and set 1 meter high.

4.11. Onboard emission monitoring

Vehicle emissions were also monitored with the same detection and notification system. The detection sensors were installed on vehicle exhaust tailpipes. Sensors were feeding the microcontroller with emission levels data and the controller forwards the data to the mobile phone through a GSM module as depicted in Figure *5.2* with system architecture. The mobile phone then received messages. A mobile application can then send the data to the central server for data analysis and visualization. A sample of system demonstration was published (Masheka, 2020).

4.11.1. Vehicles description

The system was installed on three 4 cylinder petrol vehicles with engine check light on. Nissan Sylphy, with engine capacity of 1,798cm^3, engine model MRA8DE and a mileage of 172400 km was used in this research. Toyota Allex 2001 with an inline four-cylinder gasoline engine of capacity 1496cm^3 with mileage 117983 km and Toyota Runx with an inline four cylinder gasoline engine of 1497cm^3 capacity with a mileage of 212417 km were also used in this research. Mixed test cycles (highway, and urban) were employed while the system was installed. Two Toyota vehicles had a catalytic converter installed while Nissan Sylphy had no converter.

4.11.2. Hardware installation for onboard emission monitoring

Figure below shows how the system was deployed on moving vehicles for monitoring vehicle emissions. The detection devices were attached on the vehicle exhaust tail pipe, sending data to the microcontroller through a data cable. The control box containing other devices (microcontroller, GPS sensor, and display unit) was put in the vehicle boot as shown on reader's right side in Figure below.

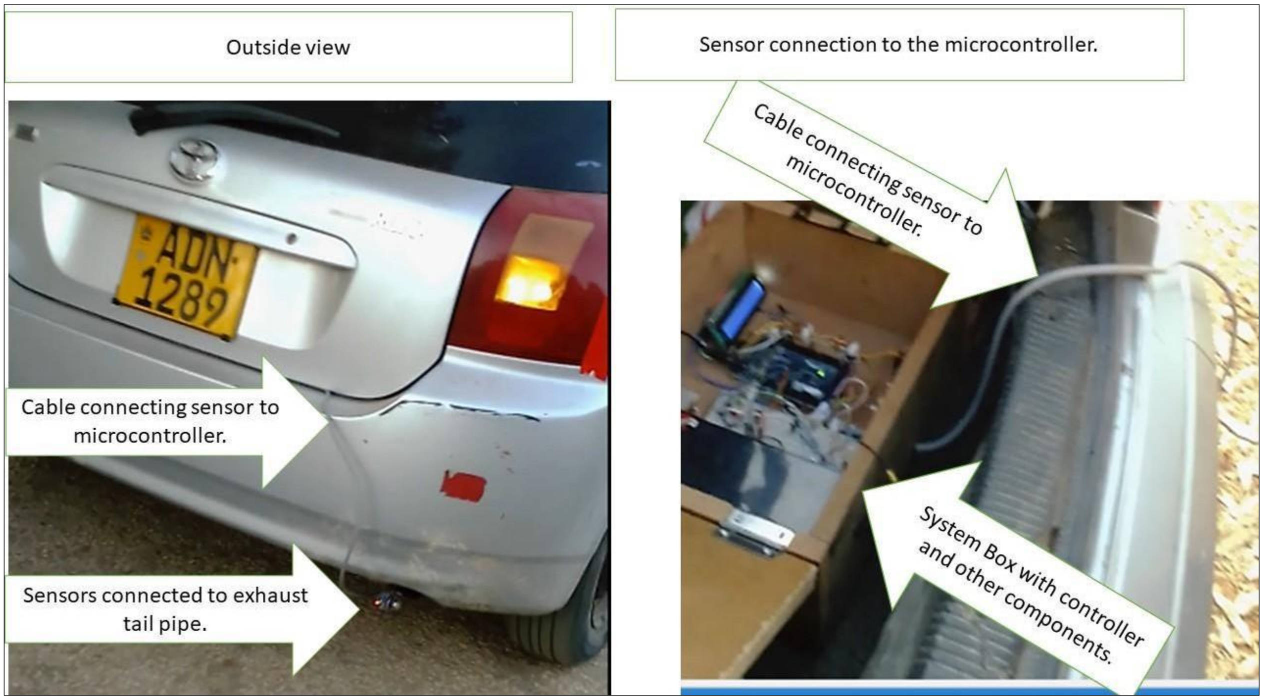


Figure 5: On-board sensor connection to exhaust tail-pipe

4.11.3. Message received on the mobile phone

Sample text messages from detection devices were structured with a primary key, vehicle details, GPS coordinates, and pollution levels. The data segments were separated by a semicolon to allow the mobile application to decode the message for insertion into the database of the central server.

```
AVPECS1119;NISSAN;SY
LPHY;AEE9117;172400;1
629 Ruvimbo Chinhoyi;-17
.395296;30.179319;https:
//www.latlong.net/c/
?lat=-17.395296&
long=30.179319;1302
.04;31524.48; NAN;
6.37;1397.79;0.08;27.89;0
.01;259.77;0.05;87.89;37.1
6;6/7/2020;6:35:23:0;4
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AVPECS1121;NISSAN;SY
LPHY;AEE9117;172400;1
629 Ruvimbo Chinhoyi;-17
.395298;30.179319;https:
//www.latlong.net/c/
?lat=-17.395298&
long=30.179319;1003
.89;32713.74; NAN;
```

Figure 6: Sample messages received on the mobile phone

4.11.4. Mobile application interface

Figure below shows the mobile phone application developed to forward data messages from data collection devices to the central server computer. The view button was used to view received messages and the data was submitted to a mobile phone's local database using the "submit locally" button. The "submit to sever" button submit data from mobile phone's messages to the server computer. "Synchronise" button was used to sync data in phone's database and data in the server computer. The synced data can be viewed through the button labelled "view synched data".

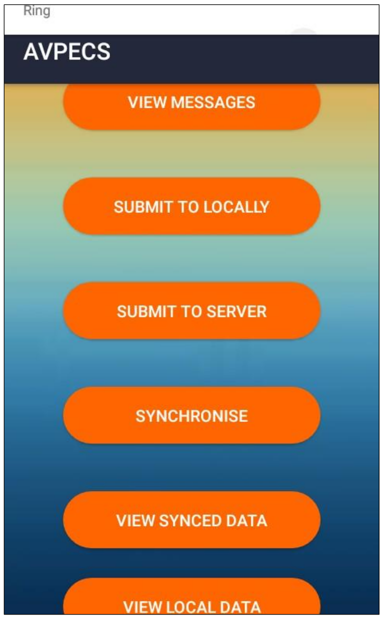

Figure 7: Mobile phone application to save data to local database and synchronize with computer

4.11.5. Program Flow Diagram for onboard continuous emission monitoring

For onboard emission monitoring, the program data flow diagram in Figure below was used. Detection devices collect data from vehicle exhaust tail pipes and gives it to the microcontroller, which then forwards data to the mobile phone through the GSM module. The process was repeated after every ten seconds.

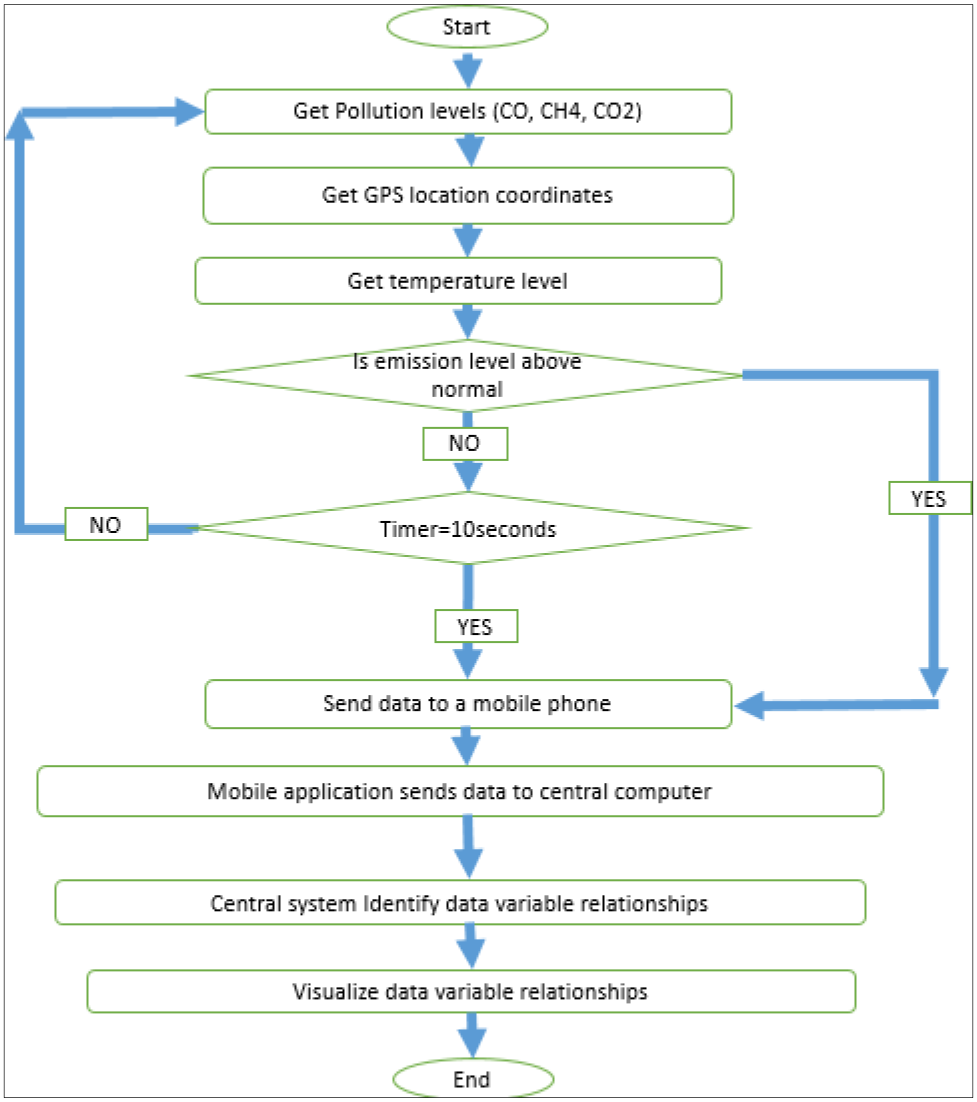

Figure 8: program flow diagram for onboard emission monitoring

5. Results

5.1.Data description for ambient air pollution monitoring

CO and CH_4 pollution levels were measured in Chinhoyi urban, at locations outlined in Figure 4. The total number of records gathered from all four locations is 2 617. Detailed data description is shown in Table 1

6.2.Data description

The table below describe the data collected for ambient air pollution monitoring. The average CO level obtained was 1.57ppm, 492ppm for CO_2, 21.08ppm for CH_4, and 29°C of ambient temperature. Maximum levels obtained are all toxic for all pollutants measured, 61ppm for CO, 2,116ppm for CO_2, 364.27ppm for methane.

	CO (ppm)	**CO_2**	**CH_4 (ppm)**	**Temp°C**
Count	2 617.00	2 617.00	2 617.00	2 617.00
Mean	1.57	492.02	21.08	29.33
Std	3.09	211.72	27.00	10.02
Min	0.00	0.00	1.63	9.70
25%	0.46	367.20	3.24	20.72
50%	0.99	423.00	6.45	27.33
75%	2.0	469.80	44.67	38.53
max	61.00	2 116.00	364.27	54.89

Table 1: Ambient air pollution data description

6.3.Methane

Average CH_4 level was 21.08ppm. However, the maximum CH_4 detected was 164.27ppm. Methane is considered dangerous when it exceeds 50 000ppm (Atia, 2004). Therefore, the Chinhoyi urban CH_4 levels are safe.

6.4.Carbon dioxide

It was noted by OSHA, (2010) and Bierwirth (2014) that CO_2 values in fresh air ranges from 300ppm to 400ppm. OSHA (2010) reported that permissible amount of CO_2 exposure for at least eight hours is 5,000ppm, with 10,000ppm having no effects, but can cause drowsiness and mild respiratory stimulation may occur for some people if CO_2 levels get to 15,000ppm. Average CO_2 levels for CHEMA was 891.456ppm, 378.884ppm for CCFCRobots, 495.404ppm for CHTMBusStop and 370.42ppm for CKERobots. Therefore, we can observe that the amount of CO_2 in some areas of Chinhoyi urban is not within the 300ppm to 400ppm range but it does not exceed the set thresholds which can pose danger to human life. However, CO_2 emissions contribute to climate change, specifically increasing global warming (Pachauri, 2014). It is so important to monitor carbon dioxide emissions because their adverse effects may take long time affecting people. Pachauri (2014) added that CH_4 also contributes to global warming.

6.5.Carbon monoxide

CO exposure contributes to annual deaths due to unintentional poisoning (Nielsen et al., 2011). Lawther (1975) reported that every year, 400 deaths are caused by accidental CO poisoning in the United States of America. According to Energy Safe Victoria (2014), the maximum threshold for CO exposure is 30ppm for eight hours. However, if the exposure is for a very short period of time, it may not have significant effects on human health. It was found by Energy Safe Victoria (2014) that 200ppm must not be exposed to humans for more than 15 minutes, 100ppm must not exceed 30 minutes and 60ppm must not exceed 60 minutes. With reference to Environmental Management Regulations (Atmospheric Pollution Control) (2009), maximum permissible CO levels is 90ppm for 15minutes. Average CO levels for CHEMA was 0.43787ppm, 0.56ppm for CCFCRobots, 3.27ppm for CHTMBusStop and 0.98ppm for CKERobots.levels. Since CO average values do not exceed dangerous levels, we can conclude that human life is not exposed to dangerous levels of CO. However, sometimes the amount of CO pollutants could exceed 30ppm for an unknown period of time. Therefore, time spent with high levels of CO pollutants needs to be monitored. We can observe from the data described in Table 2 above that the maximum CO level detected was 61ppm and this was detected on a high-way bus terminus from Chinhoyi Urban (CHEMA) to Harare. Although this may not last for long periods, experiencing such high CO emissions does not leave citizens safe because if the ambient air flow rate is low or if more than one car emits such amounts of CO gas, people in that location may be exposed to CO for more time than expected.

Therefore, it can be inferred that there is need for the monitoring of CO, CH_4, CO_2 as they pose danger to human life directly or indirectly. The above mentioned pollutants are related to one another as indicated by the correlation model in Table 3 below. CO_2 was found to be more related to temperature and location, therefore a regression model was built to predict CO_2quantities in the atmosphere given the location and temperature. This is so advantageous because people need to know the amount of pollutants in areas that they may wish to visit before visiting.

6.6.Vehicle density vs location as we approach CBD from Harare

The Figure 9 shows vehicle density variations against locations 1 to 4. Locations approach Chinhoyi urban from location 1 to 4. Location 1 is a highway location furthest from town CBD followed by location 2 which is Chinhoyi to Harare TM bus stop. Location 3 marks the first traffic lights in Chinhoyi town and Location 4 marks the last traffic lights in Chinhoyi urban along Harare – Karoyi highway. Figure 10 shows CO emission trend against Chinhoyi locations in the same order as shown in Figure 9.

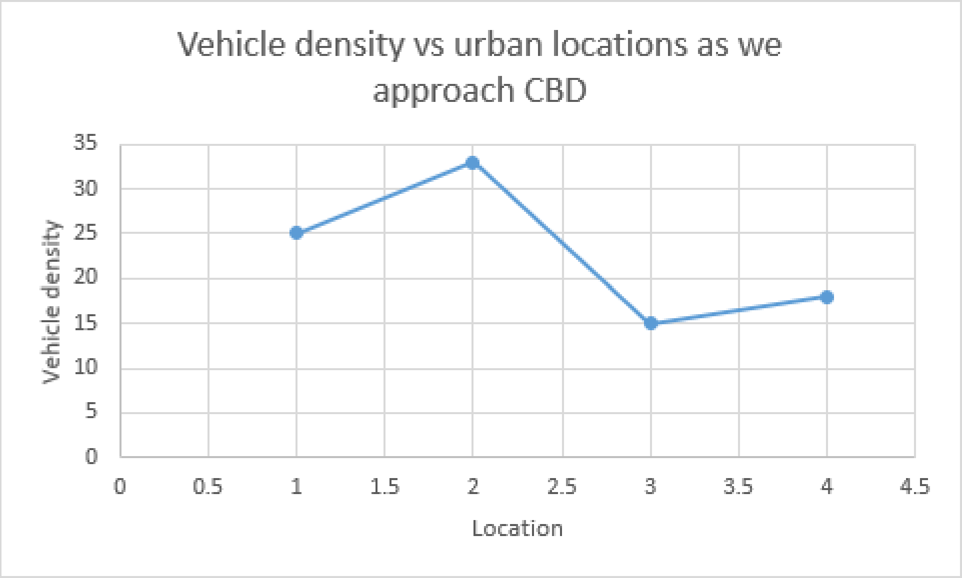

Figure 9: Vehicle density vs location 1 – 4, approaching Chinhoyi CBD.

6.7.Vehicle density vs location as we approach CBD from Harare

It can be clearly drawn from the similarity between the two graphs (Figure 9 and Figure 10) that locations with high vehicle density also have high CO concentrations. We can conclude that high levels (3.27ppm at CHEMA) of CO pollutants in areas with high vehicle density (33 vehicles at CHEMA) highly emanate from transport. It has also been observed that CHEMA had higher vehicle density as compared to location in Chinhoyi urban. However, CO concentration (0.44ppm) at Location 1 (CHEMA) is lower than CO concentrations at locations in Chinhoyi town (0.56ppm and 0.98ppm at Location 3 (CCFCRobots) and Location 4 (CKERobots) respectively). This is attributed to the driving mode of vehicles in highway driving cycle and urban driving cycle.

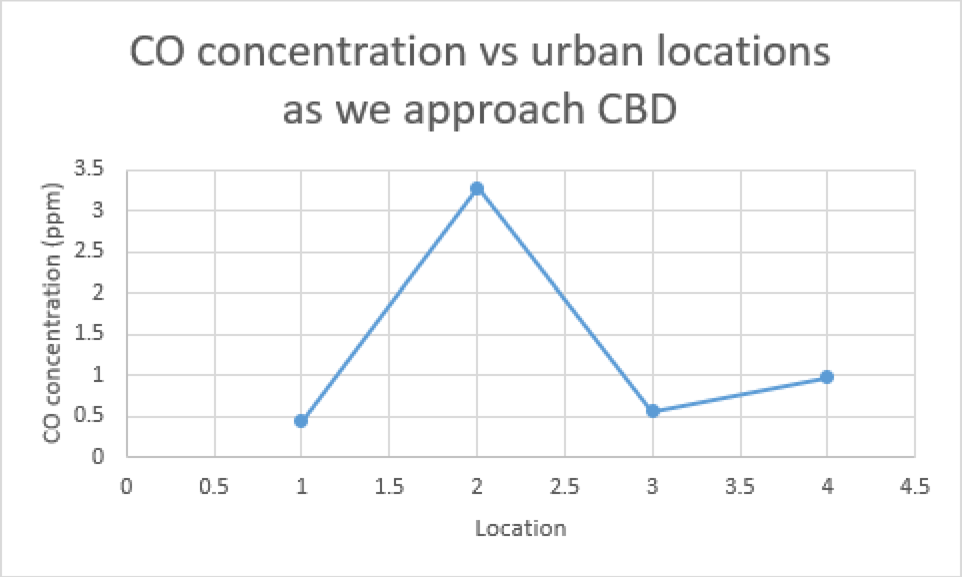

Figure 10: CO concentration vs Chinhoyi urban locations (1-4)

When we plot a graph of vehicle density against CO emissions (Figure 11), we can observe that as vehicle density increased from 15 to 18, CO concentration also increased from 0.56ppm to 0.98ppm respectively. However, when vehicle density increased to 25, CO concentration lowered down to 0.44ppm. This is due to the driving cycle at the location with such vehicle density.

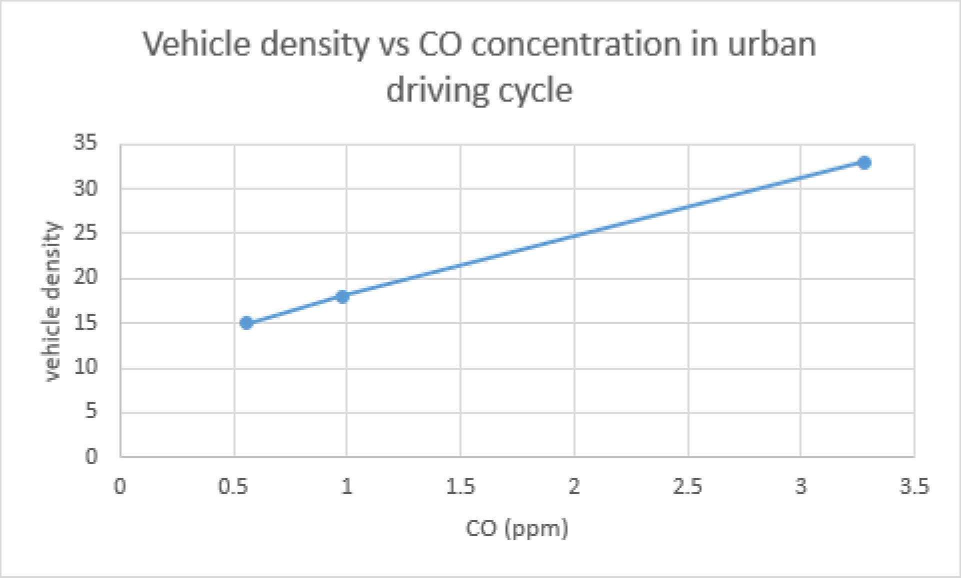

Figure 11: Vehicle density vs CO concentration in urban driving cycle

When we plot a graph of vehicle density against CO emissions (Figure 12), we can observe that as vehicle density increased from 15 to 18, CO concentration also increased from 0.56ppm to 0.98ppm respectively. However, when vehicle density increased to 25, CO concentration lowered down to 0.44ppm. This is due to the driving cycle at the location with such vehicle density.

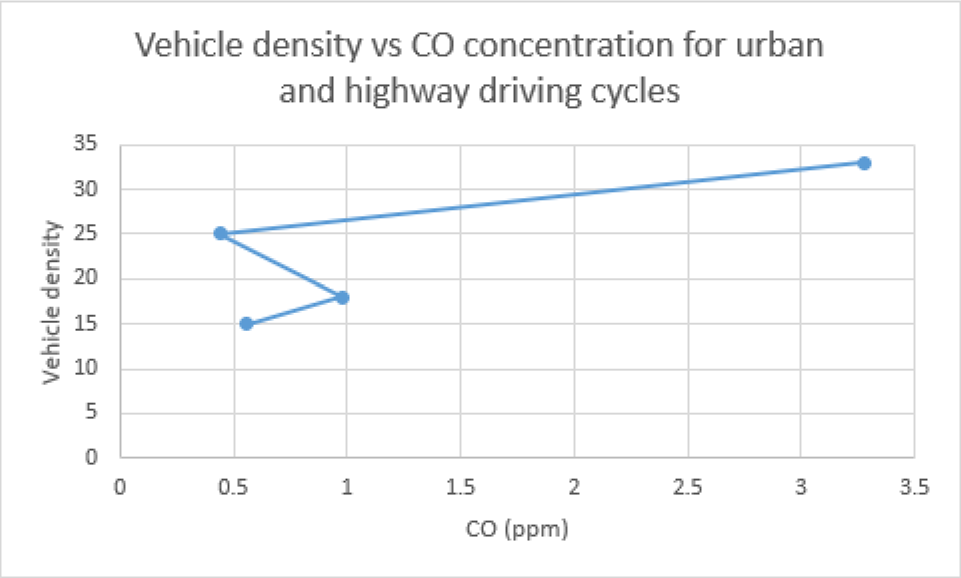

Figure 12: Effect of vehicle density on CO concentration in urban and highway driving cycles

6.8.Vehicle density vs CO concentration in urban driving cycle

Figure 13 shows CO vs vehicle density for urban driving cycle, eliminating highway driving cycle. We can observe a trend of increasing CO concentration as vehicle density increased. Therefore, vehicle driving mode also affect CO concentrations as depicted by Figure 12 and 13.

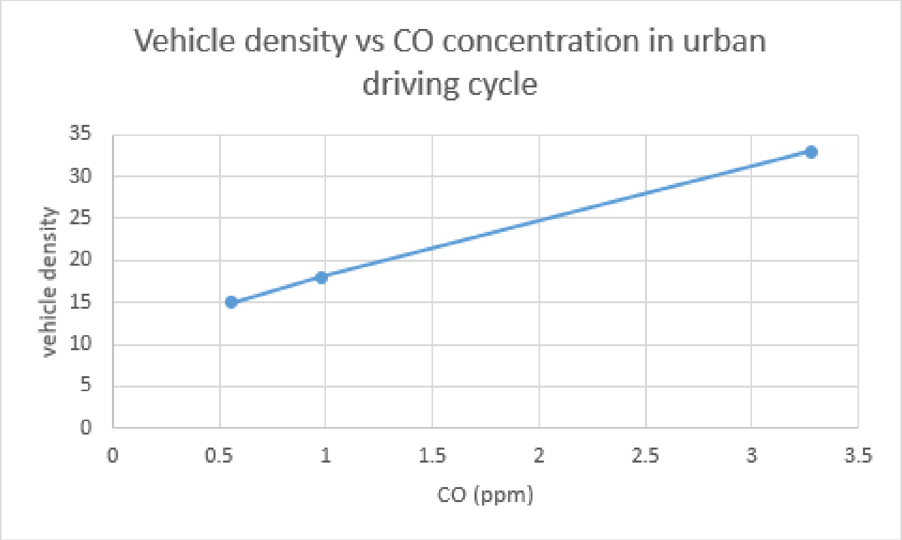

Figure 13: Effect of vehicle density on CO concentration in urban driving cycle

6.9. CH_4 concentration as we approach Chinhoyi urban

It is clearly outlined in Figure 14 that CH_4 might not actually be coming from vehicles. This is because the graph in Figure 14 is not in any related to vehicle density, but is increasing as the locations gets closer to Chinhoyi town CBD. A location furthest from town (location 1) had the minimum CH_4 concentration (2.57ppm), and as we move closer to town CBD (5.94ppm, 7.52ppm and 57.34ppm at location 2, 3, and 4 (Chinhoyi town CBD) respectively), CH_4 concentrations increased significantly. This clearly shows that, there could be another source of CH_4 besides vehicles.

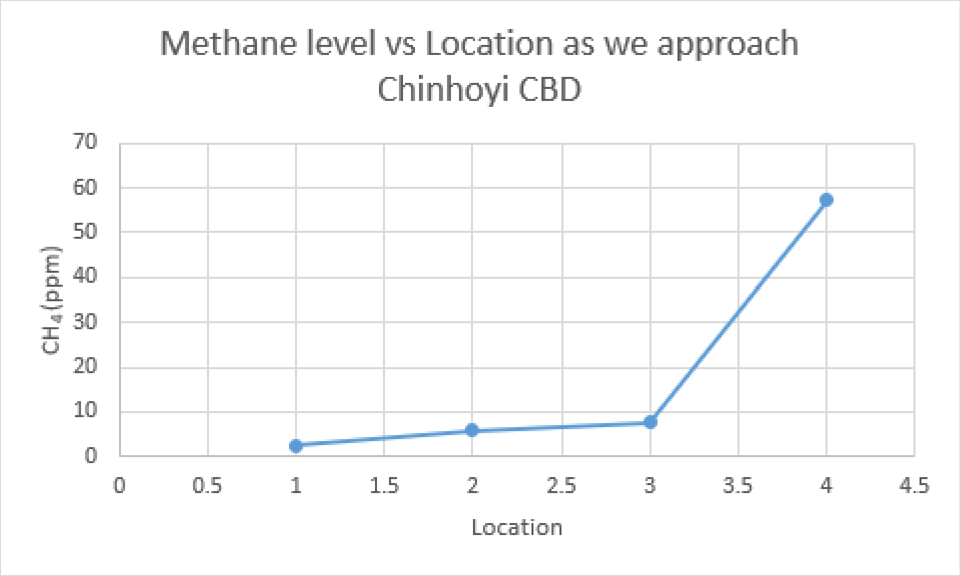

Figure 14: CH4 emission trend as we approach town

CO was found to be emanating chiefly from motor vehicles. The concentration of CH_4 was not related to the vehicle density and its concentration increases as we approach Chinhoyi town along Harare-Karoyi highway.

6.10. Data description for onboard emission monitoring

The table below describe the data collected for onboard emission monitoring. The average CO level obtained was 78ppm, 882ppm for CO_2, 1094ppm for CH_4, and 36°C of ambient temperature. Maximum levels obtained are all toxic for all pollutants measured, 988ppm for CO, 1,711ppm for CO_2, 57,618ppm for methane.

	CO (ppm)	**CO_2 (ppm)**	**CH_4 (ppm)**	**Temp°C**
Count	322.00	322.00	322.00	322.00
Mean	78.39	882.32	1 094.74	36.35
Std	174.39	422.57	5 482.06	9.59
Min	0.51	356.40	0.01	11.74
25%	4.80	518.40	29.22	30.63

50%	7.12	685.80	39.33	37.71
75%	28.92	1 331.10	51.81	41.15
Max	988.69	1 711.80	57 618.60	54.63

Table 2: Onboard emission data description.

Onboard emission monitoring was done and a sum of 322 records was collected from three vehicles. The maximum concentration of CO observed was 988.69ppm which is above the stated emission limit (90ppm for at most 15minutes) for Zimbabwe (Environmental Management Regulations (Atmospheric Pollution Control), 2009). The average CO emission level (78.39) is not above the set limit. Nissan Sylphy, which had no converter was found to emit more CO pollutants (279.97ppm) as compared to Toyota Alex2001 and Toyota Runx (58.57ppm and 20.91ppm respectively). The CO emission levels from vehicles with catalytic converter exist within Zimbabwean emission regulations. The maximum CO_2 concentration recorded (1 711.80ppm) was below 15 000ppm which can cause drowsiness and mild respiratory stimulation (OSHA, 2010; Bierwirth, 2014). Maximum CH_4 recorded was 57 618.60ppm and this is above 50 00ppm which is considered hazardous. However, the average CH_4 concentration is as low as 1 094.74ppm. All these pollutant concentrations were obtained at temperatures below 55℃ and such pollutants are classified as cold start pollutants.

7. Limitations of the study

The research made use of mobile network in transmitting data messages using GSM module and sometimes the network connectivity was not available. The researcher ended up using Econet and NetOne's network connectivity interchangeably, depending on the network that was available. On another note, for data transmission to be successful, the researcher needed some money to buy messaging data bundles, which was a challenge managed by asking for help from workmates and colleagues who helped willingly.

8. Recommendations

Researchers recommend that this research can be advanced by allowing the public to access pollution monitoring data from the central server on their mobile phones. This allows people to know where to know highly polluted areas and avoid passing through such places. This reduces exposure to toxic gases in some areas. Additionally, motorists may also require to have access to the data collected from their vehicles and saved on the central server. This allows motorists to know if their vehicles require service. On another note, future research may directly look into vehicle service status by gathering data from vehicle sensors including oxygen sensors already installed by vehicle manufacturers.

9. Conclusion

We may conclude that a significant contributing factor to Chinhoyi's high CO pollution levels is transportation. Furthermore, the amount of pollution is influenced by the manner in which automobiles travel in both urban and highway driving cycles. Vehicle emissions are low when traveling on highways since the engines would have reached light-off temperature. Additionally, automobiles release harmful emissions into the atmosphere, although these emissions only persist a short while, resulting in low ambient pollution levels that do not endanger human health.

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