A Cloud-Linked Ambient Air Quality Monitoring Apparatus for Gaseous Pollutants in Urban Areas

Eunalili Maye Culpa, Jes Ian Mendoza, Jasper Gabriel Ramirez,
Aldrine Lennart Yap, Elline Fabian, and Philip Virgil Astillo*
Department of Computer Engineering, University of San Carlos, Philippines, 6000
emculpa@gmail.com, jimendoza02@yahoo.com, jaspgabrielramirez@gmail.com
lennartnat@live.com, elfabian.usc@gmail.com, pvbastillo@usc.edu.ph

Received: October 11, 2020; Accepted: February 2, 2021; Published: February 28, 2021

Abstract

The quantity of motor vehicles in the Philippines is continuously increasing with a substantial number, which consequently worsen its traffic condition, especially in many metropolitan cities. In proportion to the rising road congestion level, the quality of air in these areas is persistently degrading due to vehicle emissions. Individuals who live near the roadway or even those passengers that got stuck in the middle of road traffic have high chances of getting a plethora of diseases due to the gaseous pollutants emitted by vehicles. In order for drivers, passengers, and pedestrians to carry-out the appropriate preventive measures, it is important for them to get near to real-time information about the actual measure of the quality of ambient air outside. This paper presents the development of an air quality monitoring and information system that provide details of the level of target gaseous pollutants in a particular area where sensors are deployed. A low-powered wireless sensor device equipped with gas sensors that measures the CO, NO_x, and C_6H_6 concentrations in ambient air is developed.The device is also equipped with a GSM module to transmit valuable information to a cloud server. In addition, a web application is also developed to tabulate and visualize data in real-time as well as present the air quality index and short-term exposure limit warning. Moreover, it is demonstrated that the monitoring device's readings are comparable to a particular commercialized exhaust gas analyzer.

Keywords: Smart urban area, sensors, air quality monitoring, cloud computing

1 Introduction

Air quality is a vital criterion for the overall quality of the environment. It gets polluted most significantly by the combustion of fuels[23]. Vehicular sources have been found to emit the largest portions of carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs). All of these are major pollutants that can adversely affect the human health and ecosystem[14]. CO is a colorless, orderless, and tasteless gas which is commonly a result of incomplete combustion. It competes with oxygen when inhaled and would lead to oxygen deficiency. Short and long-term exposure to NO_x can cause lung function injury and respiratory infections[2]. Benzene is an aromatic hydrocarbon VOC which is also a product of vehicular exhaust emissions. Exposure to benzene through inhalation is risky and has been found to cause cancer to humans[4].

A study in [24] revealed that CO concentration is higher in urban areas, especially during rush hours, which is associated by heavy vehicle traffic. The study strongly suggested that vehicular emissions

Journal of Internet Services and Information Security (JISIS), volume: 11, number: 1 (February 2021), pp. 64-79
DOI:*10.22667/JISIS.2021.02.28.064*

*Corresponding author: Department of Computer Engineering, University of San Carlos, Talamban, Cebu City, Cebu, Philippines, 6000, Tel: +63-947-640-9675.

greatly contribute to CO levels in the environment. In contrast, a considerable amount of nitrogen oxides are detected even outside the metropolitan areas. Meanwhile, exposure to benzene is significantly proportionate to the amount of time people spend in traffic jams or during car refueling[9]. These indicate that people who are often stuck in the middle of a traffic congestion, especially in urban areas, have high chances of getting infected with the aforementioned plethora of diseases.

Manila Philippines has a traffic congestion of 71% , which is ranked second among 416 cities across 57 countries[22]. Considerable contributors to the traffic congestion of the country are the public utility vehicles (PUV) such as jeepneys and buses. Almost all of these PUVs have an open door-window design that allows air, including pollutants, to freely flow inside. This is an alarming condition considering that many Filipinos, regardless of age, gender, and socio-economic status, take such mode of transportation everyday. For this reason, monitoring the level of pollutant gases is imperative as it would be the first step in controlling and preventing their adverse effects to human health. Meanwhile, wireless telecommunication networks substantially offered greater opportunities for people to share and access valuable information at any time and anywhere [10, 21]. Hence, this technology is also the perfect platform for wireless remote sensing devices to be linked with the cloud applications in order to provide their sensed data to the consumers in real-time. Accordingly, this paper focuses on developing a monitoring apparatus that is capable of providing a real-time concentration of gaseous pollutants in urban areas while considering the available telco-network technology of the selected city or particular location in the country. In this case, the area of study is limited to Cebu City, Philippines. The main objectives of this paper are summarized as follows:

- Develop a lost-cost device that can measure pollutants concentration in ambient air limited to CO, C_6H_6, and NO_x.
- Classify the safety of the measured gas concentrations in accordance to standards.
- Develop a web application capable of serving and mapping multiple sensor nodes deployed in different locations
- Transmit data to the web application through GSM and display them along with useful information in near-real-time.

The remainder of this paper is organized as follows. Section 2 surveys related literature, followed by the adopted methodologies in Section 3. Results and analysis is discussed in Section 4. Finally conclude this paper in Section 5.

2 Related Work

Air pollution is one primary contributor to human health problems in many metropolitan cities, especially those areas where vehicles are apparently congested. There are several proposed systems that monitor the air pollution level in an outdoor environment. Pal et al. [18] and Francis et al. [6] designed a pollution monitoring system with a sensor that is attached near the exhaust pipe of a car. The data collected by the sensor node are wirelessly transferred to a mobile phone through wireless connection, and subsequently, push data to the server for future processing. The designed system faced several challenges such as sensor malfunction due heat emission from the exhaust pipe, and Wi-Fi disconnection resulting in the delay of data posting to the server. Parmar et al. [19] developed a prototype monitoring device with low-cost components to measure the concentration of CO, CO_2, SO_2, and NO_2. The device also reports through Wi-Fi connection the acquired reading to a Raspberry-pi that serves as a local server. Gupta et al. [8] also proposed a device that measures temperature, humidity, CO, LPG, and other gas pollutants in the air using Raspberry-Pi as a gateway. Pushpam et al. [20] incorporate neural network algorithms to predict the PM level of their target gas pollutant from time series data that were collected by an IoT device. The proposed system also suggests routes to the users for them not to pass areas with high levels of air pollution. Kalajdjieski et al. [12] proposed a collaborative IoT-based architecture that composed of static and mobile sensor nodes not only to monitor the presence and level of air pollutants in an area but also helps in validating the operational integrity of each node. When a mobile sensor overlaps on the covered area of a static node, an error will be raised when differential reading of the two nodes is beyond a predefined threshold. The same approach was implemented in the work Kaivo et al. [11] to determine air pollution level in the city of Uppsala, Sweden. Zhang et al. [25] also adopted both static and mobile sensing approach, and applied machine learning algorithms to analyze a full spectrum of air quality. These aforementioned studies technically helped achieve a green environment through the adoption of various technologies. However, to the best of our knowledge, our approach is novel relative to others in a way that physiological factors, such as average breathing of a person as well as their (e.g. Filipino) height, are considered in the monitoring of air pollution. This approach could provide us with more realistic information with respect to the danger that these pollutants give to human health.

3 Proposed Approach

3.1 System Concept

Figure 1 shows the conceptual framework of the system. Air is sampled to the system using a fan unto the sensors which measure the concentrations of the gases and transmit their analog voltage outputs to the microcontroller unit. An Arduino Mega 2560 microcontroller unit (MCU) was used for data processing and controlling the whole device. The MCU then converts and calculates the received signal into their appropriate units of measurement for outputting. The outputs are then sent to the cloud via GSM which are then available for viewing through the web application. Furthermore, an RGB LED lights up in red or green to indicate whenever a gas concentration (GC) is above its safety threshold T_r, respectively. Additionally, all data were logged to a micro SD card as comma-separated value (.csv) file as an offline backup storage.

3.2 Air Sampling

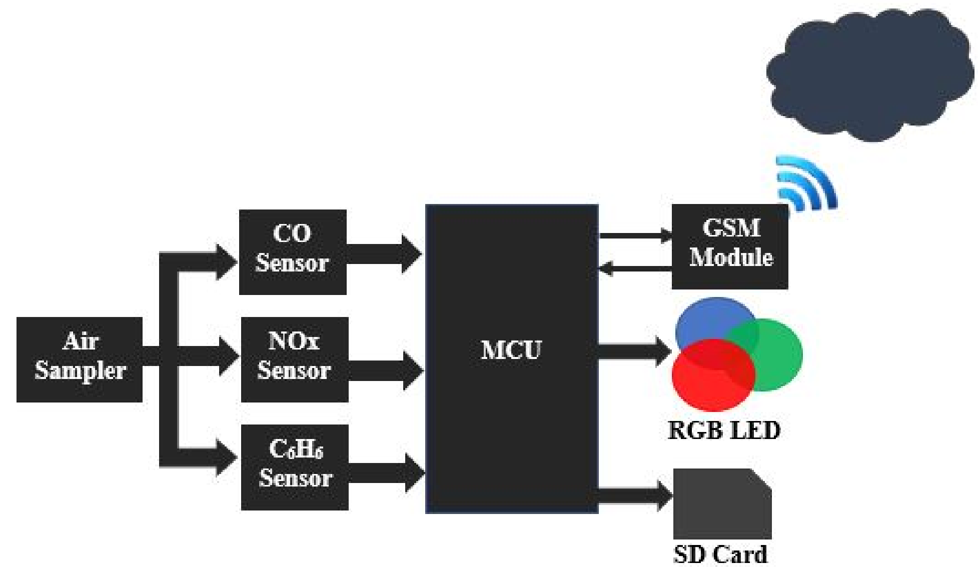
The device evaluates the concentration of pollutants in the air that a person breathes on the side of the road. The sampling occurred under a typical daily routine at a pre-established location[7].

3.2.1 Foundation of Sampling Analysis

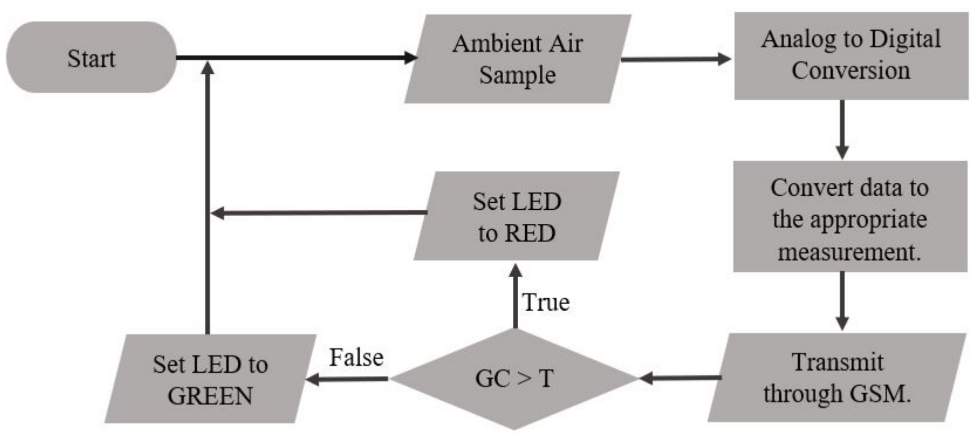
The method of air sampling was set to analyze an estimated volume of air inhaled by an average-weight person per minute. The amount of air inspired per minute is normally about 6L and its derivation is shown in equation 1[3].

$$Airintake = \frac{500\,ml}{1\,breath} * \frac{12\,breathes}{1\,minute} = \frac{6\,liters}{minute} \tag{1}$$

As an average person breathes 6 liters of air per minute, the device gathers a sample of air on a 6 liters per minute basis to simulate and sample the volume of air a person breathes within a minute. Since having 6-liters per minute flow is too weak to pull enough air with concentrated levels of pollutants, the device's air flow was made faster using a fan. The sample period was fixed to 1 minute for the purpose of having output of mg/m^3 per minute.



(a) Overview of monitoring device



(b) System Flowchart

Figure 1: Conceptual framework and Operation flow

3.2.2 Sampling Method

The air sampling device is designed in a free-flowing method as shown in figure 2 The inlet and outlet sides measure 17 cm by 17 cm, while the length measures 30.35 cm long. Air is pulled into an aluminum pipe in a specific range of flow rate with the help of a fan. The fan pushed the air into the tube where the gas sensors instantaneously measure the concentrations of the pollutant gases. Air flowed out of the chamber with help of another smaller fan.

Sampling Analysis The gathered sample volume can be calculated using equation 2. Within a sampling period of 1 minute, the MCU read the values from the sensors every second accumulating to 60 readings. Reaching the last second, the microcontroller then computes the average concentration levels of each pollutant. With a resulting density (mg/m^3) of the pollutant, the weight of pollutants in a 0.0006 m^3 volume can be computed to be able to acquire the X weight (mg) of pollutants a person possibly

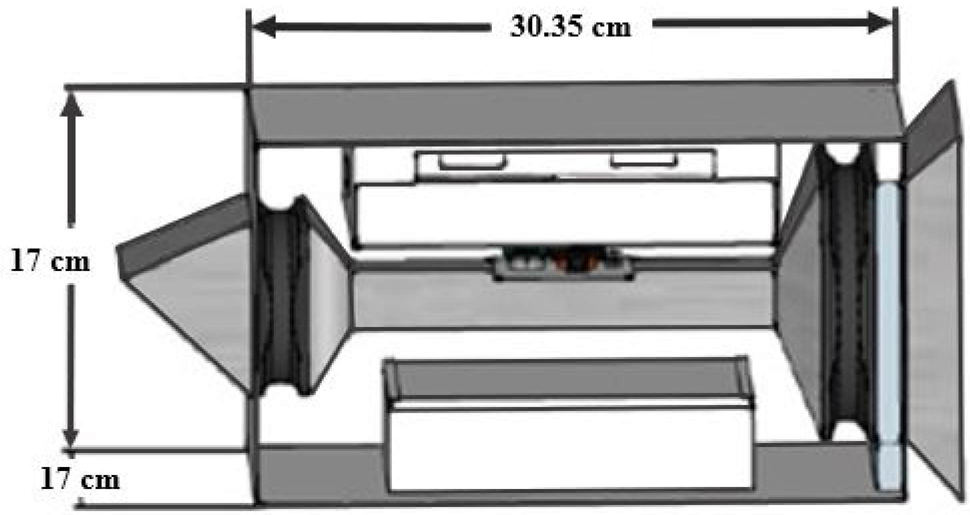


Figure 2: Free-flowing design of air sampling device

breathes on the same minute with proportion expressed in $N\,mg : M\,m^3 = X\,mg : 0.006\,m^3$.

$$V_{air} = FlowRate * \frac{P_{ave}}{P_{std}} * \frac{T_{std}}{T_{ave}} * t \tag{2}$$

Particle Filtration The device tolerated solid particulates which were accumulated as the fan pulled from ambient air. The smallest opening the air passed through which the sampling fan's inlet and outlet were considered. Accordingly, air passed through an aluminum steel strainer before entering the device.

Since air was sampled frequently, the device had to handle the cleaning of the dust filter itself. To do this, a vibration motor was attached onto the aluminum steel trainer to stimulate a pulsating pattern to the filter and dust it off. The vibration module was activated periodically after every sampling cycle.

The effect of the filter to the flow of the air was tested by using a digital anemometer which could measure the wind velocity. Measuring with or without the filter, the anemometer returned 0.13 m/s which indicated that the installed filter had no effect on the airflow.

Gas Sensing An array of three commercially available metal oxide semiconductor gas sensors with different sensitivities were used to detect and measure the gas concentrations. The MQ-3, MQ-7, and MQ-135 gas sensors were used to measure C_6H_6, CO, and NO_x, respectively. The MOS type of gas sensors employ a tin dioxide (SnO_2) metal oxide crystal as the sensitive layer such that when it gets sufficient heating from its heater voltage V_H pin, gas gets adsorbed[5]. Figure 3 shows a MOS gas sensor's typical measuring circuit. As the sensor detects a higher concentration of the gas, resistance R_L which is connected in series with the sensor increases, thus increasing the load voltage across R_L. Output voltages from the gas sensors are connected to the MCU analog input to get the 10-bit ADC readout which would then be converted to its voltage output equivalent, V_{out}.

V_{out} was then used to computer R_s which is the resistance from the sensing element of the sensor that changes depending on the gas concentration using the expression $R_s = (5\,Volt - V_{out}) * (V_{out})^{-1}$. The value of R_s was then used to calibrate the sensor as R_0 which is the value of R_s in clean air. Further calculations were done by solving for x using the equation of a line for the log-log graph expressed as $log\,y = mlog\,x + b$. The acquired value would be of log base 10, therefore the value x was raised to

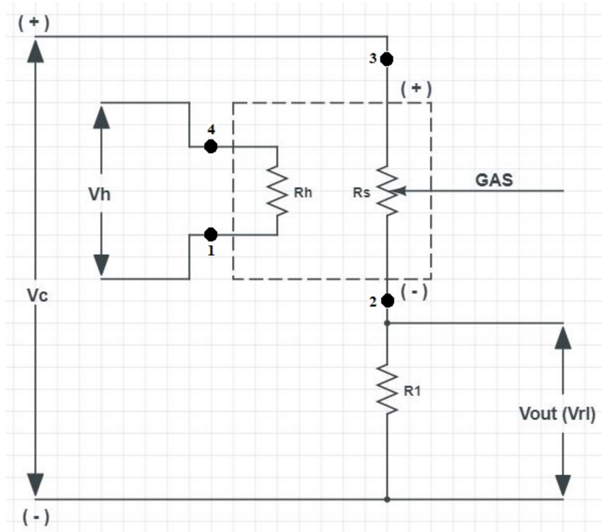


Figure 3: Gas sensor measuring circuit

Table 1: Gas Molar Masses

Gas	Molar Mass
Carbon Monoxide, CO	28.01
Benzene, C_6H_6	78.11
Nitrogen Oxides, NO_x	46.0055

the power of 10, i.e., $ppm = x_{10}$, to get the actual ppm value as calculated, constituting the final step in extracting the ppm concentrations from sensors. The calculated ppm values were then converted into mg/m^3 using the equation derived in the next section.

Gas Measurement Unit A very dilute solution is expressed in parts per million (ppm). The ppm unit, however, is dimensionless[15], and it would be hard for the average individual to perceive and understand the gas measurement under such a unit. In order for the gas concentrations known and understandable to the public, the values were converted to mg/m^3 as classified under the International System of Units. Table 1 shows the gases to be measured and their corresponding molar masses. The molar masses were used in the equation to convert the ppm reading to mg/m^3. Equation 3 is used in obtaining the ppm value at Standard Ambient Temperature and Pressure[17]. Transforming and manipulating equation 3, the final equation for computing the mg/m^3 is presented in equation 4.

$$ppm_{SATP} = \frac{(\frac{mg}{m^3}) * (\frac{24.45\,L}{mol})}{molar\,mass} \tag{3}$$

where:

ppm_{SATP} = ppm value in standard ambient temperature and pressure (SATP)
$molarmass$ = weights/mass of the gas
$24.45L/mol$ = molar volume at SATP

$$\frac{mg}{m^3} = \frac{ppm_{rv} * molar\,mass}{(\frac{24.45\,L}{mol}) * (\frac{760\,mmHg}{P}) * (\frac{T}{298\,K})} \tag{4}$$

Table 2: Short-term Exposure Limites

Gas	STEL (mg/m^3)
Carbon Monoxide, CO	10.01
Benzene, C_6H_6	7.8
Nitrogen Oxides, NO_x	1.9

Table 3: Air Quality Index

AQI	Category
0 to 50	Good
51 to 100	Moderate
101 to 150	Unhealthy for Sensitive Groups
151 to 200	Unhealthy
201 to 300	Very Unhealthy
301 to 500	Hazardous

where:

mg/m^3 = desired output
ppm_{rv} = readout value
P = ambient pressure
T = variable ambient temperature

Safety Classification Short-term exposure limits (STEL) are the acceptable average exposure values of the gases within a short span of 15 minutes[1]. The STELs for the target gases are shown in Table 2. Whenever a measured gas reached its STEL, the RGB LED on the device lit up as an indicator of the hazard. On the other hand, the LED stays green when no gas reaches its STEL. The STEL was likewise displayed in the web application when it reaches its STEL through a line threshold in the graph.

The Air Quality Index (AQI) is an indicator of air quality based on hazardous air pollutants. The different AQI levels are represented by certain colors and are associated with levels of health concerns are illustrated in Table 3. Additionally, Table 4 shows the different CO average mg/m^3 levels with their corresponding Air Quality Index values. Measurements of CO for 1 hour averaged and the AQI was calculated using equation 5. Subsequently, the obtained AQI is displayed in the web application along with its corresponding health advisory.

$$I_p = \frac{I_{high} - I_{low}}{C_{high} - C_{low}} * (C - C_{low}) + I_{low} \tag{5}$$

where:

I_p = AQI for pollutant P
C = Pollutant Concentration
C_{low} = Concentration breakpoint <= C
C_{high} = Concentration breakpoint >= C
I_{low} = Index breakpoint corresponding to C_{low}
I_{high} = Index breakpoint corresponding to C_{high}

Table 4: Air Quality Index Ranges for CO

AQI	CO (mg/m^3)
0 to 50	0 - 5.0
51 to 100	5.1 - 10.7
101 to 150	10.8 - 14.2
151 to 200	14.3 - 17.6
201 to 300	17.7 - 34.8
301 to 500	34.9 - 57.4

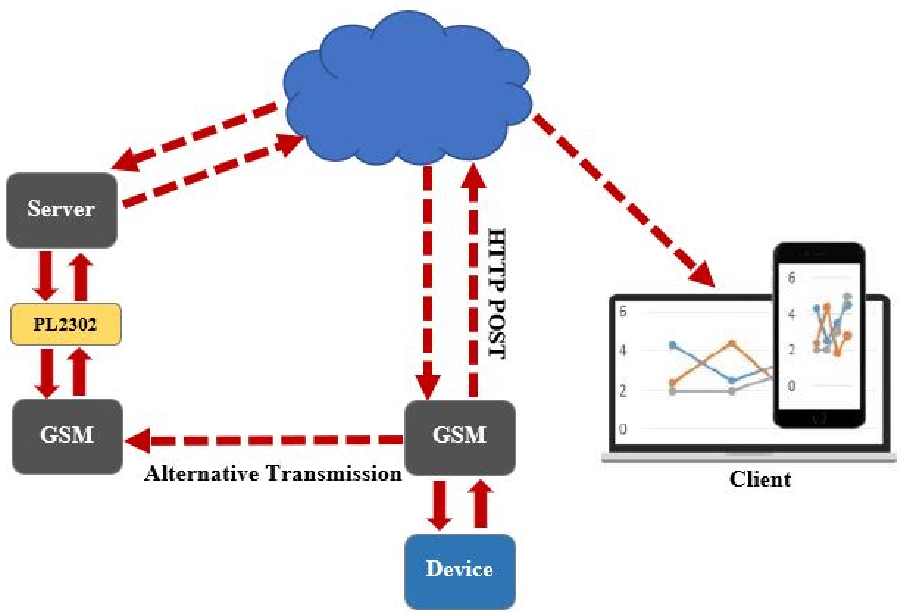


Figure 4: Data transmission routes

Cloud Computing The device immediately sent the measured CO, NO_x, C_6H_6, pressure, humidity, and temperature levels to the cloud while deployed at a remote area. It established connection to the internet via GPRS and requested to send data to the web server via HTTP POST employing device-to-cloud connectivity model[13]. Upon failure, the system utilized the second mode of transmission. The GSM module employed SMS to send a text message to another GSM module which was connected using a PL2302 USB to Serial TTL module to a server which sent the received serial data to the web server via HTTP POST through the RESTful API developed to fetch incoming data. Once the web server deployed in the cloud receives POST data, it then communicates with the clients in order to update their views and display the new data received in a near-real-time fashion. The routes for data transmission are illustrated in figure 4.

The web application is responsible for handling all the data. It was developed using Node.js in its Express framework to handle server-side processes and the classic Bootstrap front-end framework for designing the user interface. All data were stored and queried to and from the NoSQL database, MongoDB. All received data were visualized and plotted near-real-time through Socket.io. A screenshot of the user interface of the web app's dashboard for a single location in figure 5. It also shows the visualization of each of the pollutant concentrations through the graph.

Figure 5: Web app dashboard interface with graph display

At the part of the dashboard are the current AQI value and its details, the corresponding AQI health advisory for the public, and the current ambient temperature, relative humidity, and barometric pressure. Users are able to choose to display the data in a graph or a table. The STEL warning is depicted through the graph such that the data points in the time series graph changes its color into red when it exceeds its respective threshold. The individual AQIs are also deployed along with a small histogram to show its previous values.

Users can also visit the dashboard for a particular location wherein a device is currently deployed at. Accordingly, deployed devices can also be viewed through a map. The devices are marked with a circle which is colored depending on its current AQI as shown in figure 6.

Research Environment This paper focused on estimating human breathing exposure to gaseous pollutants in traffic areas and this was situated on the side of the road as shown in figure 7. The testing was conducted at selected a road in front of an academic institution where traffic conditions in a day are varying. The device is placed in such a way it stood as tall as an average human height of Filipinos which is about 157 cm or $5^{\prime}1\ 1/2^{"}$ [16]. The device gathers data for two 3-hour periods in two different days. The first 3-hour period was operated during a moderate traffic hour in the morning from 8:26 AM to 11:26 AM, which is known to have bad traffic conditions. On the other hand, the second data was operated during dawn, from 4:04 AM to 7:04 AM, with less traffic where only a minute quantity of vehicles had passed by. The device sampled air for one minute in every 5-minute sampling cycle. The data gathered enabled for the comparison of the levels of the gaseous pollutants between the times of varying traffic conditions to reveal how the level of traffic and other air-polluting exercises can affect them.

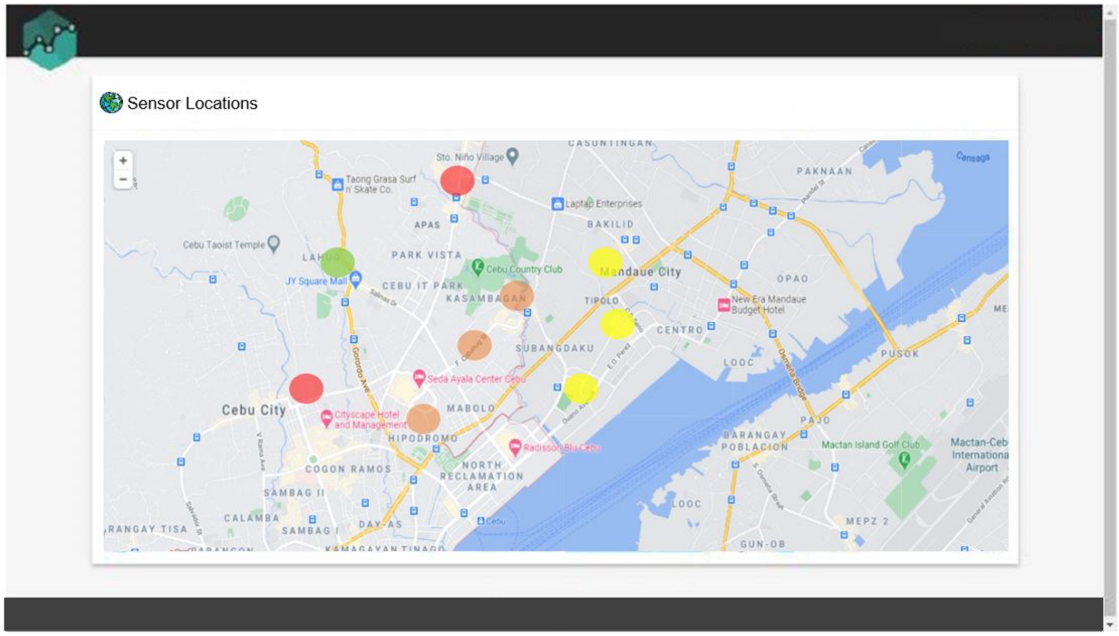


Figure 6: Map of device around urban city

Figure 7: Experimental Setup

4 Data Presentation, Interpretation and Analysis

4.1 Sampling at Dawn on Moderate Traffic Hours

The following data presented in figure 8 and 9 show that levels of CO, NO_x, C_6H_6 during dawn and at the morning at moderate traffic hours, respectively. A low concentration of the pollutants measured by sensors in the street at dawn, from 4:04 AM to 7:04 AM as presented in figure 8. However, at the final part of the 3-hour experimentation, carbon monixide, nitrogen oxides, and C_6H_6 concentrations rose from

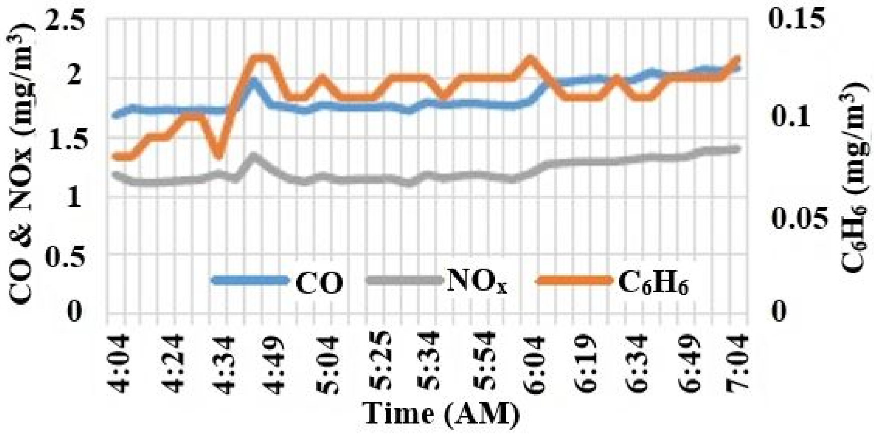


Figure 8: Gas concentration during dawn

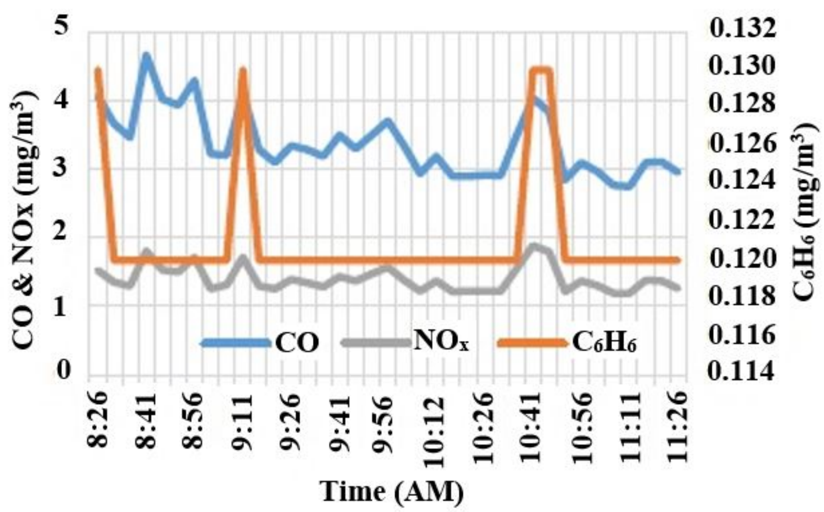


Figure 9: Gas concentration in the morning with moderate traffic

1.68 to 2.08 mg/m^3, 1.18 to 1.4 mg/m^3, and 0.08 to 1.13 mg/m^3, respectively, As time transitioned towards morning, the pollutant levels rose given that the number of vehicles on the road started to increase. From the gathered results, it can be determined that when the number of vehicles increases, pollutant concentration rises as well since motor vehicles are a great source of urban air pollution.

Meanwhile, during moderate traffic from 8:26 AM to 11:26 AM, a fluctuating concentrations of CO, NO_x, and C_6H_6 levels were recorded as shown in figure 9. The spikes were taken note of, observing a similar pattern. It was caused by vehicles loading and unloading passengers close to the monitoring device. This implies that the device is sensitive in detecting the change of pollutant levels. Moreover, the levels of pollutants during moderate traffic is relatively higher as compared to that during dawn.

Comparing the two graphs, it can be declared that the levels of pollutants at dawn were significantly lower compared to the levels in the morning when traffic runs. The main factor considered to have

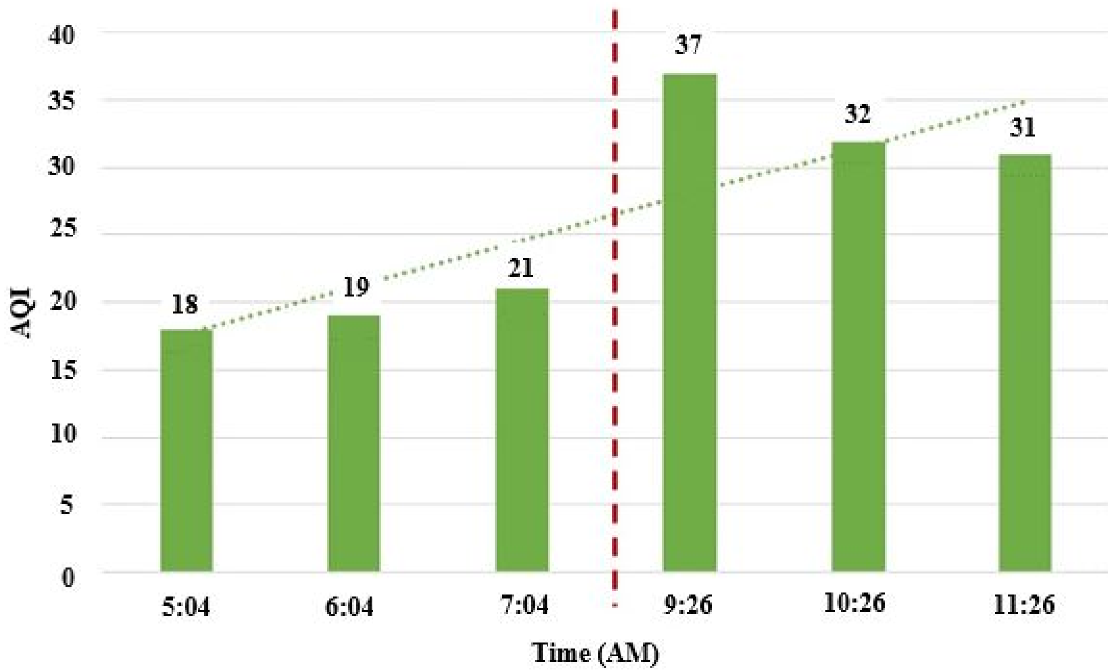


Figure 10: Air Quality Indexes for the 3-hour periods

affected the difference of the gathered data was the number of vehicles in the street. With the countable vehicles passing by at dawn, the pollutants dispersed in the air making the pollutants less concentrated in ambient air. As for ambient air in a busy street, pollutants come from a number of vehicles which makes them fairly concentrated and it becomes possible to detect them in higher levels.

4.2 Air Quality Index

As the device was monitoring air quality during the two 3-hour periods, the Air Quality Indexes were calculated at an hourly rate. Figure 10 shows the AQIs for the two sampling periods. In both periods, the quality of air is considered GOOD according to the Air Quality Index shown in Table 3. Meanwhile, the AQIs during dawn was significantly lower compared to the index values in the morning. The trend line shows an upward trend which indicates how air quality slowly worsened from dawn to noon.

4.3 Prototype's Reading vs Private Emission Testing Center's (PETC) Gas Analyzer

To verify the device's gas measurements, the readings were compared with a PETC's gas analyzer's readings. The PETC's device first measured the emissions of a gasoline-fueled four-stroke motorcycle. As shown in figure 11, the gas analyzer measures CO in percentage which is equivalent to ppm/10000. Subsequently, the prototype was then used to measure the emission form the same vehicle for 10 repetitions as presented in Table 5. Accordingly, we can see our device's CO readings are comparable with the PETC gas analyzer. On the other hand, the reading for C_6H_6, which is one out of the many hydrocarbons (HC), are relatively lower compared to the gas analyzer's HC value.

Figure 11: PETC's measurement using Authocheck^{TM} Exhaust Gas Analyzer

Table 5: CO and C_6H6 reading from prototype

Trial No.	Prototype Output		Converted Values	
	CO (ppm)	C_6H_6	%CO	≈ %CO
1	142.3804	3.5135435	0.014238	0.01
2	119.9314	6.0554030	0.011993	0.01
3	103.4026	6.0554030	0.010340	0.01
4	92.38906	7.2492620	0.009239	0.01
5	92.67964	4.8598709	0.009268	0.01
6	127.5193	7.6197387	0.012752	0.01
7	215.0539	8.7039443	0.021505	0.02
8	104.3263	9.4327319	0.010433	0.01
9	164.0309	9.3493692	0.016403	0.02
10	123.2833	9.8356163	0.012328	0.01

5 Conclusion

The device developed was capable of measuring CO, C6H6, and NOx concentrations in ambient air in which its CO reading was verified through the comparison with the PETC gas analyzer's reading. The data were successfully transmitted to the web through HTTP POST requests using the GSM module, yet produced some significant delays when using the GPRS connection due to the unreliability of the connection and the network provider itself.

Graphing and tabulation of data in the web application's view was done in a near-real-time fashion with the use of web sockets which resulted in imperceptible delays upon reception of data through the built REST API. The Air Quality Index was also computed for and was displayed and updated in the web application every hour. Moreover, the web application has the capability of deploying multiple sensor nodes deployed at different locations and serving them at once, only requiring a node's respective serial number for a successful request to be granted.

The gathered monitoring data in the university's Portal proved an upward trend in the pollutants' concentrations in the transition from dawn to early morning and showed irregular spikes when faced with traffic and other air-polluting activities. Generally, the gathered data presented how the air quality in the target area was good during the monitoring periods based on the Air Quality Index for carbon monoxide.

For the future work, we plan to add a particular feature in the system where it can suggest to the drivers an alternative route towards their destination. Since an elevated concentration of gaseous pollutants can be associated with high level of road vehicle congestion, this feature can not only help drivers from getting caught with the traffic but also reduces the number of vehicles that will contribute air pollution to the particular area. Indirectly, it helps prevent air pollution level of an already congested road from increasing further. Additionally, we plan to incorporate data security techniques to protect the reported information from exploitation by malicious individuals in misleading the public. We also wish to study how the system can be transformed to be ready for the fifth generation (5G) network.

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Author Biography

Eunalili Maye Culpa received the B.S degree in Computer Engineering from the University of San Carlos, Philippines in 2017. She is currently working at Kyocera Document Solutions Development, Philippines as a software developer. Her interests include artificial intelligence and cloud computing.

Jes Ian Mendoza received the B.S. degree in Computer Engineering from the University of San Carlos, Philippines, in 2017. He is currently working at Accenture, Inc., Philippines as a software developer. His interests include artificial intelligence and cloud computing.

Jasper Gabriel Ramirez received the B.S. degree in Computer Engineering from the University of San Carlos, Philippines, in 2017. He is currently working at TO Simplus, Inc., Philippines as software developer. His interests include artificial intelligence and cloud computing.

Aldrine Lennart Yap received the B.S. degree in Computer Engineering from the University of San Carlos, Philippines, in 2017. He is currently working at Rakuten, Inc., Japan as a software developer. His interests include artificial intelligence and cloud computing.

Elline Fabian received the B.S. and M.Eng degrees in Computer Engineering from the University of San Carlos, Philippines, in 1999 and 2019, respectively. She is currently a lecturer in the Department of Computer Engineering in the said university. Her research interests include IoT applications and image processing.

Philip Virgil Astillo received a B.S and M.Eng degrees in Computer Engineering from the University of San Carlos, Philippines, in 2009 and 2011 respectively. He is currently a on-study leave lecturer in the Department of Computer Engineering in the said university while pursuing his Ph.D degree in Information Security at Soonchunhyang University, South Korea. From 2014 to 2015, he was a Research Assistant with the Phil-LiDAR Project under the Agricultural Mapping Program. From 2015 to 2016, he was a Research Assistant with the Sensor Laboratory, Clemson University, Clemson, SC, USA. His research interests include embedded systems design and development, artificial intelligence, federated deep learning, IoT application and security, and intrusion detection system.