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The Real World Performance Evaluation between Integrated Intelligent Pollutants Prototype and Physical Monitoring Device

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ABSTRACT

The presence of air pollutants in enclosed spaces such as buildings and vehicle cabins can have serious health consequences and therefore it's essential to have a monitoring system that can alert users of the presence of harmful gases. This study reports on the second phase of the development of an indoor air quality (IAQ) monitoring device that is equipped with sensors to measure particulate matter (PM), carbon monoxide (CO), carbon dioxide (CO_2), temperature, humidity, and air velocity. The device was tested on a moving bus from Kuala Terengganu to Penang, Malaysia, to measure in-vehicle air quality. The data collected was displayed on a liquid crystal display (LCD) and stored on an SD card, and compared to commercial devices for validation. The results showed that the prototype performed well in measuring temperature, humidity, CO_2, and particulate matter, but did not detect CO gas. Further improvements in the technology and integration with cloud databases are needed to enhance the accuracy and reliability of air pollutant measurement in enclosed spaces.

1. Introduction

Indoor air quality (IAQ) has been a matter of concern as it relates to the health, comfort, and well-being of occupants in enclosed spaces, such as buildings and motor vehicle cabins. The sources contributing to IAQ include building materials, ventilation and air conditioning systems, heaters for buildings or vehicles in some regions, chemical-rich products, and various human activities. General IAQ guidelines [1] typically assess the concentrations of different pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), respirable particulates (PM), ozone (O_3), total volatile organic compounds (TVOCs), formaldehyde, and specific physical parameters such as air temperature, relative humidity, and air movement. The components of indoor air pollutants can lead to morbidity and mortality, underscoring the need for efficient and effective IAQ monitoring devices.

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Recent developments in IAQ monitoring devices focus on using low-cost sensor technology to make these devices more affordable. The specific characteristics of IAQ monitoring, which often depend on the intended environment, influence the selection of sensors for these devices. For instance, Gillooly *et al.,* [3] developed a device for monitoring temperature, relative humidity (RH), CO, CO_2, and $PM_{2.5}$, as well as nitrogen oxides (NO, NO_2) and noise levels inside a house. Similarly, Marques and Pitarma [4] developed an in-house IAQ monitoring device with sensors to detect ammonia (NH_3), propane (C_3H_8), butane (C_4H_{10}), methane (CH_4), hydrogen (H_2), and ethanol (C_2H_5OH), along with CO and NO_2 sensors. Yang *et al.,* [5] developed a device to monitor IAQ parameters such as temperature, RH, formaldehyde, VOCs, CO, and CO_2 in hospital buildings. Meanwhile, Benammar *et al.,* [6] developed a general IAQ monitoring device capable of measuring temperature, RH, CO, CO_2, NO_2, SO_2, chlorine (Cl_2), and ozone (O_3), testing the device in different indoor room sizes.

The advent of technologies such as the Internet of Things (IoT) and cloud computing in recent years has introduced new possibilities for real-time monitoring across various disciplines. Consequently, several studies have reported incorporating these technologies into IAQ monitoring systems [1-9]. The integration of these technologies has the potential to significantly enhance IAQ monitoring, as they allow for automatic data transmission, processing, analysis, and visualization. These features enable real-time monitoring and visualization of IAQ and provide alerts when pollutants are detected.

The development of IAQ devices for monitoring the microenvironment inside motor vehicle cabins has also been reported [8], [10-13], but such studies remain rare. Although people spend less time in vehicles than in buildings, emissions from interior components and pollutants from exhaust fumes can migrate into the cabin from outside. The concentration of contaminants in vehicle cabins may be higher, resulting in more immediate impacts than those outlined by the World Health Organization (WHO) and other governmental health bodies for building IAQ standards [13-15]. For instance, researchers have investigated CO_2 levels in various types of transport cabins in recent years, highlighting how elevated CO_2 levels can impair concentration and cause drowsiness, fatigue, and other discomforts while driving [16-21].

This research study proposes a device that integrates an IoT sensor network with a cloud computing-based web server and alert system for indoor air quality monitoring in various enclosed spaces, such as buildings and motor vehicle cabins. The development of this integrated intelligent pollutant and physical parameter monitoring device is divided into three phases: 1) sensor selection, 2) integration of sensors with a microcontroller and display/storage of physical data, and 3) connecting the device to a cloud server for online monitoring, visualization, and alerting. This paper reports the results of the second phase of the indoor air quality monitoring prototype's development, which involved testing the prototype on a bus traveling between Kuala Terengganu and Penang in Malaysia.

2. Methodology

2.1 Instrumentation System Architecture and Design

The overall system architecture and a visual representation of the current prototype can be found in Figure 1. The focus of the second phase was to develop a prototype equipped with sensors to measure temperature, humidity, air velocity, and the concentration of CO, CO_2, $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, and PM_{10}. This was achieved by interfacing the various sensors with a low-power PIC18F47Q43 microcontroller.

2.2 Real-Time Data Display and Storage Capabilities

The device's capability to display collected data on an LCD screen serves as a crucial feature for immediate environmental assessment. The data collected by the device was displayed on an LCD screen, providing real-time feedback on the monitored indoor air quality parameters. This visual display enabled immediate assessment of environmental conditions, making it easier for users to interpret data at a glance. The LCD was designed to show key metrics such as temperature, humidity, and concentrations of various pollutants (CO, CO_2, $PM_{1.0}$, $PM_{2.5}$, $PM_{4.0}$, and PM_{10}) simultaneously. The intuitive layout of the display allows users to quickly interpret the data, thereby promoting a proactive approach to managing indoor air quality.

In addition to real-time display, the collected data were also stored on an SD card. This feature allowed for extensive data logging over the duration of the test campaign, facilitating further analysis and review. The use of an SD card provided a convenient and reliable method for data storage, ensuring that all measurements could be archived for future reference and evaluation. Table 1 summarizes the details of the sensors used in this project, including specifications such as measurement range, accuracy, and response time. Each sensor was selected based on its suitability for monitoring specific IAQ parameters in the microenvironment of a motor vehicle cabin. For instance, sensors measuring particulate matter were chosen for their sensitivity to fine particles, while gas sensors were selected for their capability to detect low concentrations of harmful gases.

The integration of these sensors into the monitoring device allowed for a comprehensive assessment of indoor air quality, contributing to the validation of the prototype's performance against established commercial standards. The combination of real-time data display and robust data storage capabilities enhances the overall functionality and reliability of the IAQ monitoring system.

2.3 Methodology for Data Collection and Analysis

The primary objective of the test campaign was to validate the performance of the developed prototype by comparing its data quality to that of high-end commercial devices. The test involved mounting the prototype on a bus, which traveled for a total duration of 7 hours and 15 minutes, covering a distance of 428 km from Universiti Malaysia Terengganu (UMT) in Kuala Terengganu to the Royale Chulan Hotel in Penang. During the journey, the bus made two scheduled stops: the first stop lasted 15 minutes, while the second stop extended to 60 minutes. A total of 430 one-minute data samples were collected en route, providing continuous measurements of pollutants and physical parameters throughout the sampling periods. The route taken during the testing phase is illustrated in Figure 2. The device was placed side-by-side to assess performance of the in-vehicle air quality on a moving bus traveling from UMT to Penang. This extensive dataset offers valuable insights into air quality conditions along the entire route, supporting the comparative analysis between the prototype and commercial monitoring devices.

The data were compiled, processed and analyzed using Microsoft Excel. Throughout the journey, the bus's air conditioning system remained operational. To validate the prototype, the temperature, humidity, CO, and CO2 data captured by the prototype were compared with reference data obtained from the VelociCalc/Q-Trak 7575 handheld digital meter. In parallel, the particulate matter data were compared with reference measurements from the DustTrak DRX Aerosol Monitor 8533. Both reference instruments were thoroughly calibrated before the testing began to ensure accuracy. The DustTrak DRX Aerosol Monitor 8533, in particular, met all required performance and acceptance specifications. The calibration of the DustTrak DRX Aerosol Monitor 8533 was conducted according to ISO 12103-1 standards, both at the factory and regularly in the lab. For the Q-Trak 7575/VelociCalc, calibration was performed using a standard method, with accuracies traceable to the National Institute of Standards and Technology (NIST), within the scope of NIST's calibration services.

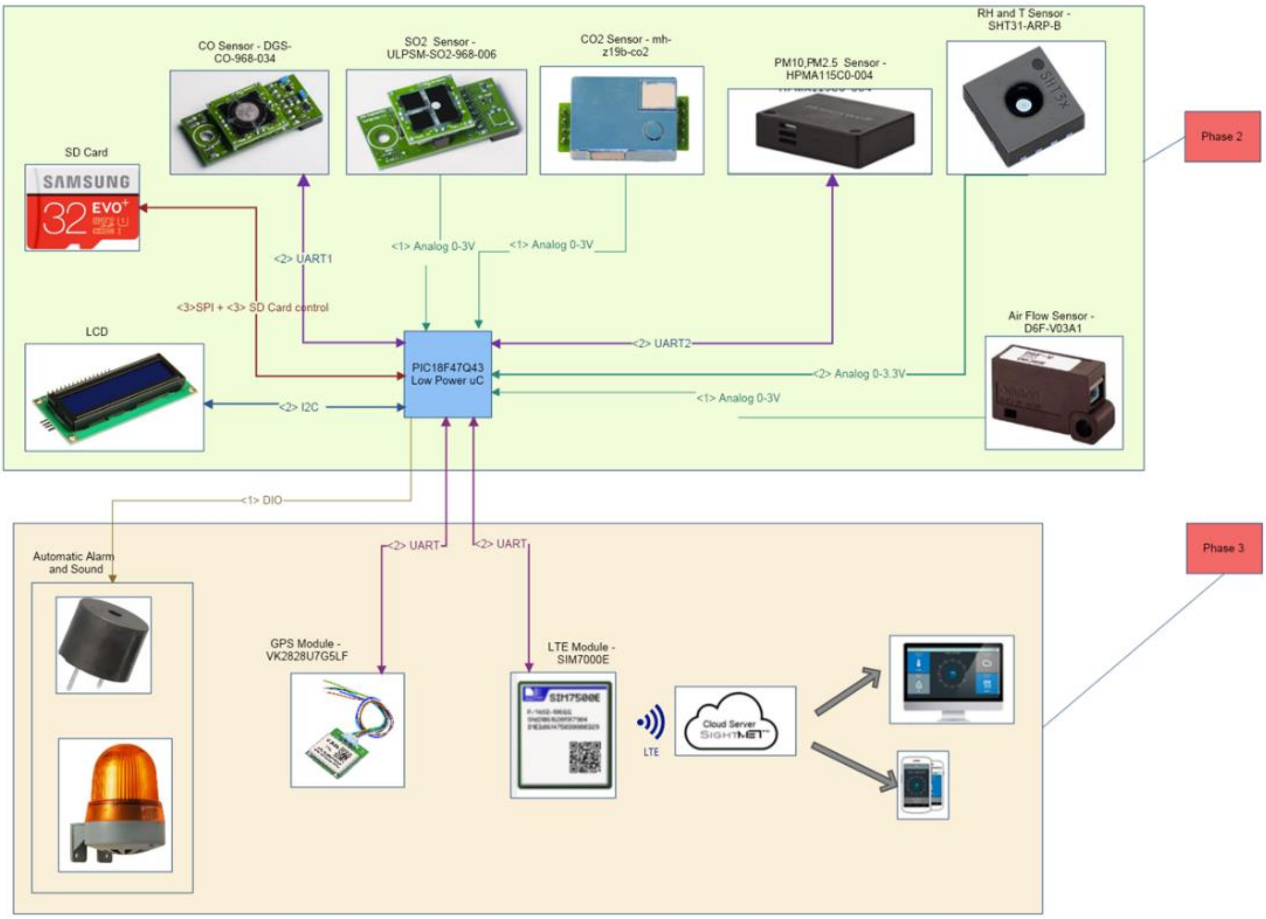

Fig. 1. System architecture design for an integrated intelligent monitoring device for pollutants and physical parameters

Table 1
Types and specification of the sensors used in the prototype

No.	Component	Model No.	Manufacturer	Range
1.	CO sensor	DGS-CO-968-034	Spec sensors	0 – 1000 ppm
2.	CO_2 sensor	MH-Z19b-CO2	Texas Instruments	0 – 5000 ppm
3.	SO_2 sensor	ULPSM-SO2-968-006	Spec Sensors	0 – 20 ppm
4.	Particulate Matter sensor	HPMA115C0	Honeywell	0 – 20 ppm
5.	Airflow sensor	6F-V03A1	Omron	0 – 3 m/s
6.	Temperature and humidity sensor	SHT31-ARP-B	Sensirion	-40 – 90 ^{o}C, 0 – 100 % RH

2.4 Method of Data Analysis

The Pearson correlation coefficient (r) is a widely used statistical method for measuring the linear correlation between two continuous variables. In this study, the correlation between the data from the prototype and the reference instruments was assessed using both the Pearson correlation coefficient and the Root Mean Square Error (RMSE). The Pearson correlation coefficient quantifies the strength and direction of the association between two variables measured on the same interval or ratio scale. It ranges from -1 to 1, where a value of 1 indicates a perfect positive correlation, -1 indicates a perfect negative correlation, and 0 signifies no correlation. The closer the value is to either -1 or 1, the stronger the linear relationship between the two variables. By applying the Pearson coefficient, we could evaluate how well the prototype's measurements aligned with those of the calibrated reference instruments. This analysis provides valuable insight into the performance and reliability of the prototype compared to established, high-quality reference devices.

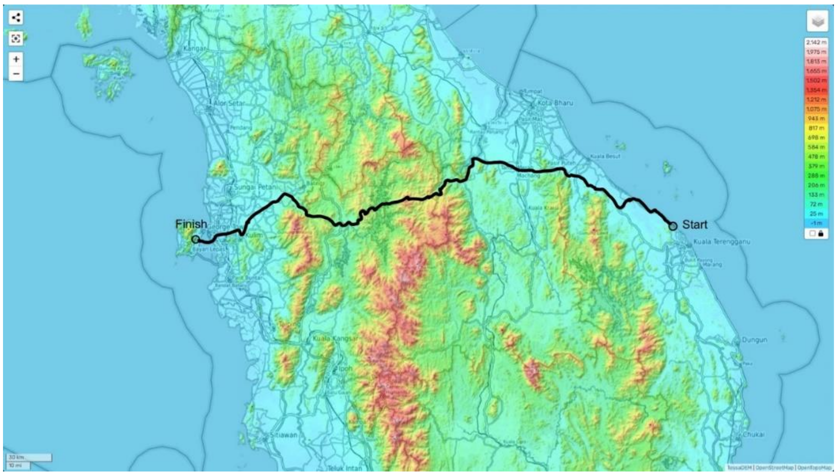

Fig. 2. Map of the sampling route covered by the bus from UMT to Royale Chulan Hotel, Penang

3. Results

Accurate temperature and humidity measurements are essential in environmental monitoring. To validate a new prototype sensor, this study compares its data with the widely trusted VelociCalc reference device. By analyzing the correlation between the measurements, we assess the prototype’s accuracy and potential reliability for real-world applications. In this study, we conduct a comparison between a newly developed prototype sensor and the widely trusted VelociCalc reference device for measuring temperature and humidity. By analyzing the correlation between the data from both instruments, we assess the prototype’s accuracy and its potential reliability in real-world environmental monitoring applications.

Overall, the prototype performed well in measuring temperature and humidity, showing strong correlations and low RMSE values. However, its performance in measuring particulate matter (PM_1, $PM_{2.5}$, PM_4, PM_{10}) and CO_2 was weaker, as reflected by the lower Pearson coefficients and higher RMSE values. These results suggest that while the prototype is effective in capturing temperature and humidity data, further optimization is needed for accurately monitoring particulate matter and CO_2 levels.

Table 2 summarizes the RMSE analysis for the various parameters assessed in this study. Table 2 provides an overview of the RMSE and Pearson correlation coefficient values for various parameters measured by the prototype, compared to reference instruments. The Pearson coefficient indicates the strength and direction of the linear relationship between the prototype’s measurements and the reference data, while the RMSE measures the average difference between the two sets of values, with lower RMSE values indicating better agreement.

The comparison between the prototype and VelociCalc reference data, as shown in Figure 3a and Figure 3b, reveals a strong correlation between the temperature and humidity measurements. The Pearson correlation coefficients were 0.86 for temperature and 0.82 for humidity, indicating a strong linear relationship between the two datasets. Additionally, the RMSE values were relatively low, at

0.14 °C for temperature and 0.26 % RH for humidity, suggesting a high level of agreement between the prototype and the VelociCalc reference device. These results demonstrate that the prototype performed well in capturing both temperature and humidity data. However, an interesting observation was made: temperature readings were consistently higher when the bus was stationary with the engine running, compared to when the bus was in motion. In contrast, the humidity data displayed a different pattern—higher values were recorded during the 15-minute stop and lower values during the 60-minute stop, compared to when the bus was in motion.

Table 2
RMSE analysis results from this study

Parameters	Pearson coefficient	RMSE
Temperature	0.86	0.14 °C
Humidity	0.82	0.26 %RH
PM_1	0.21	0.53 µg/m^3
$PM_{2.5}$	0.27	0.62 µg/m^3
PM_4	0.27	0.54 µg/m^3
PM_{10}	0.26	0.32 µg/m^3
CO_2	0.74	6.62 ppm

3.1 Temperature and Humidity

The Pearson correlation coefficient for temperature measurements is 0.86, reflecting a strong positive correlation between the prototype and the VelociCalc reference instrument. This high correlation suggests that the prototype closely mirrors the performance of the calibrated device in measuring temperature. Additionally, the RMSE of 0.14°C indicates only a minimal deviation between the two instruments, highlighting the prototype's precision and reliability in capturing temperature data. The low RMSE value confirms that the temperature readings from the prototype align very closely with those from the reference device, demonstrating high accuracy and consistency in real-world conditions. This level of precision is particularly important in environmental monitoring, where small deviations in temperature data can significantly impact the overall analysis. Figure 3(a) and 3(b) further illustrate this by comparing the time series and correlation plots between the two instruments, showing how closely the temperature readings match over time. Overall, the strong correlation and minimal error in temperature measurements validate the prototype's effectiveness in delivering reliable and accurate temperature data.

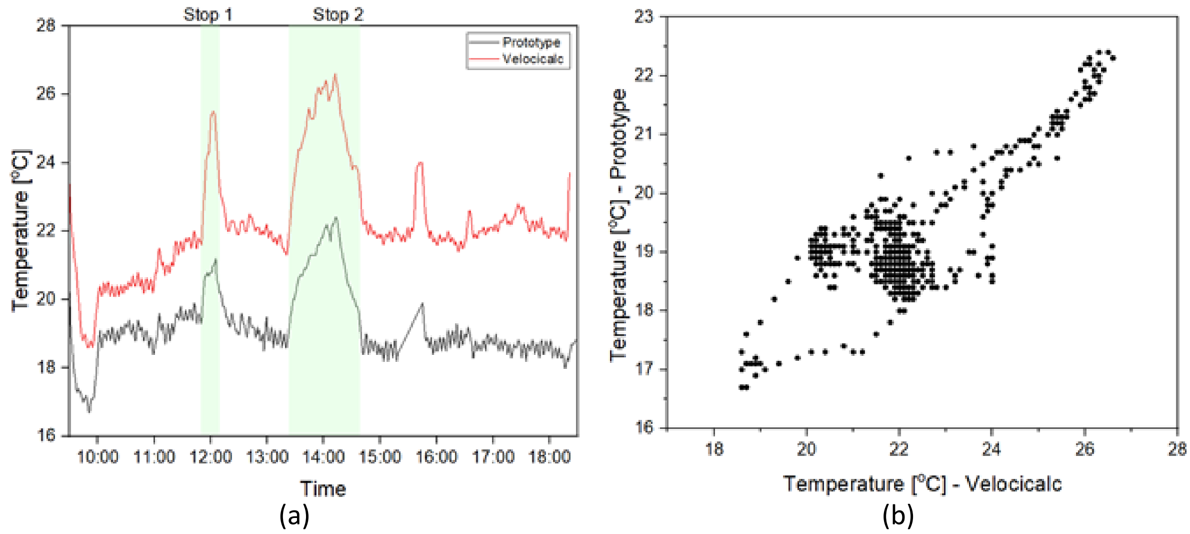

Fig. 3(a) and 3(b). Time series and scatter plot from the prototype and VelociCalc handheld meter for (a-b) temperature

3.2 Humidity

The Pearson correlation coefficient for humidity measurements was found to be 0.82, indicating a strong correlation between the prototype and the VelociCalc reference device. Although this correlation is slightly lower than that observed for temperature, it demonstrates that the prototype performs well in capturing humidity data, with only a marginal reduction in accuracy compared to the temperature readings. The RMSE of 0.26 %RH suggests a minor deviation in the humidity readings, reflecting some degree of measurement variance. However, this level of deviation is still relatively low, implying that the prototype's humidity readings are closely aligned with the reference values. While the RMSE indicates areas where the prototype may require further calibration or refinement, the overall strong correlation and low error values suggest that the prototype remains a reliable tool for humidity measurement in environmental monitoring. Figure 4(a) and 4(b) illustrates the time series and correlation plots comparison between instruments.

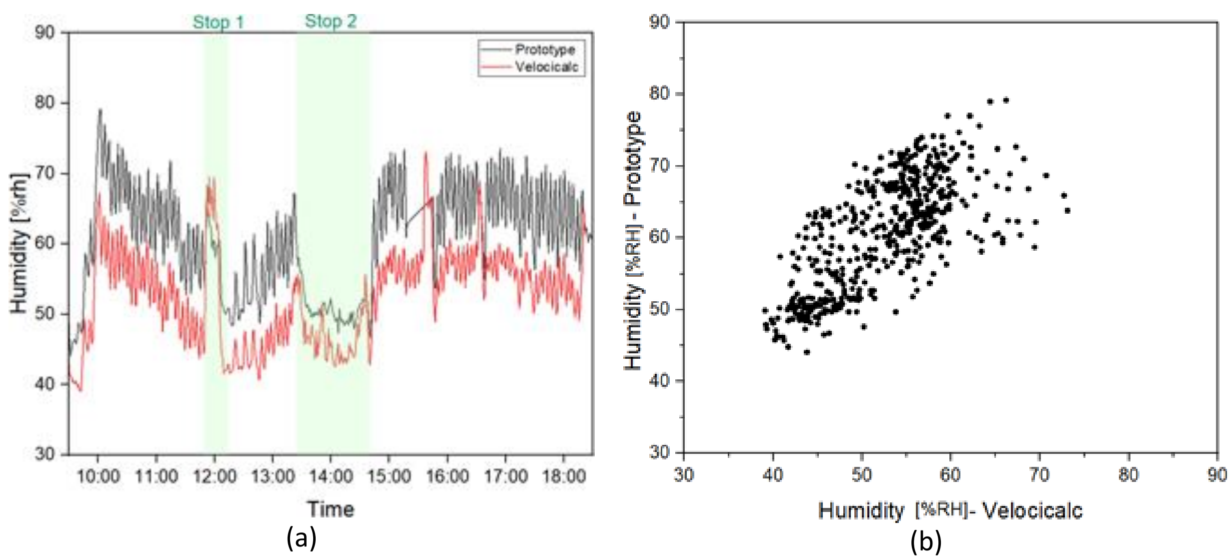

Fig. 4(a) and 4(b). Time series and scatter plot from the prototype and VelociCalc handheld meter for (a-b) humidity

3.3 CO_2

The comparison between the prototype's CO_2 emission data and the VelociCalc reference data, as illustrated in Figure 5, demonstrates a strong correlation, evidenced by a Pearson correlation coefficient of 0.74 and a RMSE of 6.62 ppm. These metrics suggest that the prototype generally performs well in tracking CO_2 levels. However, a significant observation is that the prototype exhibited a lag of up to 27% behind the VelociCalc measurements when CO_2 concentrations surpassed 1000 ppm. This discrepancy indicates a need for technical enhancements in the prototype to ensure accurate readings at elevated concentrations, which are critical since levels above 1000 ppm have been associated with health risks for sensitive populations, including children and individuals with respiratory issues.

Additionally, the data indicated that CO_2 concentrations inside the vehicle were lower when it was parked with the engine running compared to when the vehicle was in motion. This phenomenon may be attributed to reduced exhaust emissions from the engine while the vehicle is stationary. Understanding the factors that influence these variations—such as the duration of idling, the type of engine, and the efficiency of the vehicle's exhaust systems—could provide valuable insights into vehicle air quality.

Further research is necessary to explore the causes behind these observed patterns in CO_2 emissions and to enhance the prototype's ability to measure CO_2 accurately, especially in contexts where precise monitoring is essential for health and safety. This investigation could lead to improvements in vehicle air quality monitoring systems, ultimately contributing to better health outcomes for passengers exposed to potentially harmful CO_2 levels.

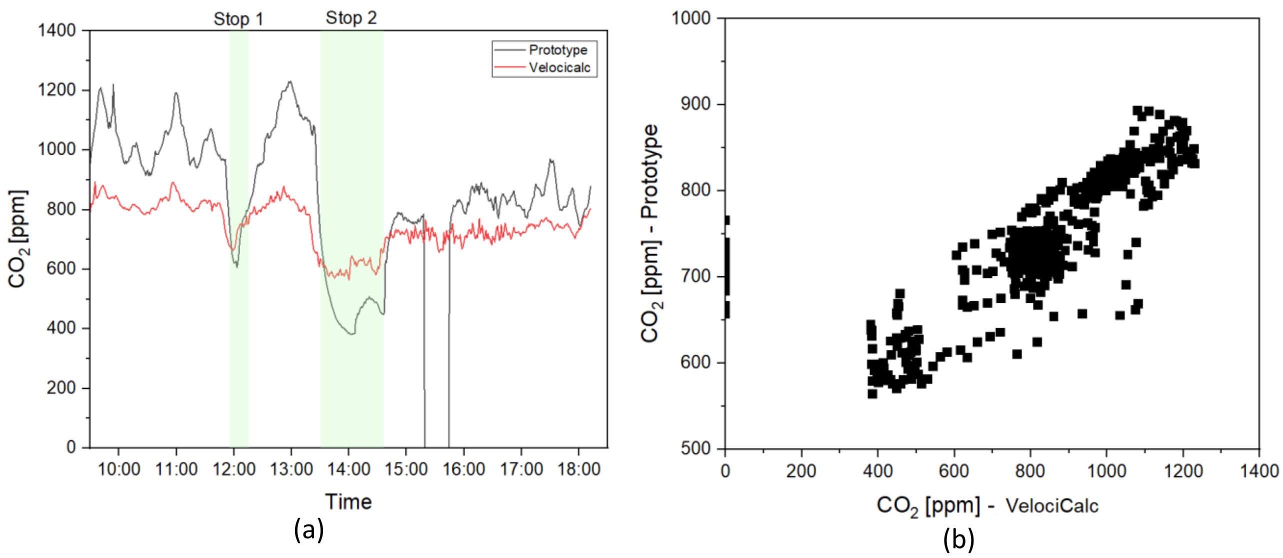

Fig. 5. Time series and scatter plot from the prototype and VelociCalc handheld meter for CO_2

3.4 Particulate Matter (PM_1, $PM_{2.5}$, PM_4, PM_{10})

The correlation coefficients for particulate matter measurements (PM_1, $PM_{2.5}$, PM_4, PM_{10}) are notably lower, ranging from 0.21 to 0.27. This indicates a weak linear relationship between the prototype and the reference device, suggesting that the prototype did not effectively track particulate matter levels compared to its performance in measuring temperature and humidity. The RMSE values for particulate matter measurements range from 0.32 to 0.62 µg/m³, reflecting moderate discrepancies between the prototype and the reference data, particularly for $PM_{2.5}$ and

PM_1. These elevated RMSE values indicate that the prototype requires further refinement to enhance its accuracy in detecting particulate matter.

As shown in Figure 4, the comparison between the prototype's particulate matter data and the DustTrak reference data highlights these discrepancies, with Pearson correlation coefficients of 0.21 for PM_1, 0.27 for $PM_{2.5}$, 0.27 for PM_4, and 0.26 for PM_{10}. Correspondingly, the RMSE values for these measurements are 0.53, 0.61, 0.54, and 0.32 mg/m³, respectively. During the first half of the journey, the prototype readings were consistently lower than those recorded by DustTrak. However, this discrepancy decreased in the second half of the journey. Notably, the DustTrak recorded significantly higher particulate matter levels, especially when the bus was stationary for 60 minutes, with readings exceeding 200 µg/m³, whereas the prototype recorded values around 90-150 µg/m³. Inaccurate readings from the prototype could pose health risks to passengers, as levels exceeding 35.5 µg/m³ for $PM_{2.5}$ and 155 µg/m³ for PM_{10} are classified as unhealthy for in-vehicle air quality according to [9].

To improve the accuracy of particulate matter readings from the prototype, further technical enhancements are necessary. This includes investigating the impact of environmental factors on the prototype's performance and implementing strategies such as adaptive filtering and machine learning algorithms to mitigate these influences and improve measurement accuracy. Lastly, the results from the prototype indicated no detection of carbon monoxide (CO). While the overall accuracy of the prototype is still under evaluation, the absence of CO detection is concerning, given that CO is a toxic gas that can pose serious threats to human health. The safe limit for CO exposure over a duration of 15 minutes is set at 100 ppm [15]. This lack of detection raises questions about the prototype's ability to monitor potentially hazardous conditions effectively, highlighting the need for further investigation and improvements in the sensor's design and functionality.

4. Conclusions

This study presents the second phase of developing an indoor air quality monitoring prototype tested along a bus route from the Universiti Malaysia Terengganu (UMT) campus to Penang. The prototype successfully measured temperature, humidity, carbon monoxide (CO), carbon dioxide (CO2), and particulate matter, with results indicating satisfactory performance, particularly in temperature and humidity measurements. However, improvements are needed for particulate matter sensors, as their accuracy and reliability were lower compared to reference devices.

Additionally, the current prototype does not measure volatile organic compounds (VOCs) and sulfur dioxide (SO2), which are essential for a comprehensive assessment of air quality. Future work will focus on integrating these sensors and connecting the device to a cloud database for real-time monitoring and remote data access. In summary, while the prototype shows promise for monitoring indoor air quality, further refinements and enhancements are necessary to improve its capabilities and contribute to better public health outcomes.

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