Investigating the Air Quality in Bus Stops Using IoT-Enabled Devices

Teo Hong Ray, Danish Uzair B. Abdul Hamid Khan Surattee and A. Muhammed Madhih

Abstract Air pollution is a global problem, with particulate matter being one of the major air pollutants. Small particulate matter smaller than 2.5 μ in diameter ($PM_{2.5}$), are the most harmful. Traffic emissions are a major source of particulate matter in urban cities. This issue is particularly pertinent for bus commuters, who spend extended periods of time exposed to traffic emissions during their daily commute waiting at bus stops. This study employed a mobile Internet of Things (IoT) device to detect $PM_{2.5}$ air quality at bus stops of various conditions. It was of interest in this study to investigate $PM_{2.5}$ air quality with regards to three parameters. Firstly, the position within bus stop. Secondly, the frequency of buses arriving and lastly, the amount of vehicular traffic including cars, motorcycles and lorries. The results of this investigation shows that there are marginal differences in $PM_{2.5}$ air quality between positions in a bus stop. Air quality further away from the road is found to be consistently though marginally better compared to the edge of the road. The variation of frequency of bus arrivals did not provide a strong correlation with the air quality contrary to previous literature. The amount of vehicular traffic also did not have a strong positive linear relationship with air quality contrary to expectations.

Keywords Internet of things · Air quality · Particulate matter · Bus stops · Public transport · Singapore

1 Introduction

Air pollution is a global problem as the world is becoming more modernized, with particulate matter being one of the major air pollutants [1]. Small particulate matter, such as those smaller than 2.5 μ in diameter ($PM_{2.5}$), is the most harmful as they cannot be naturally removed from the body once inhaled [1]. This results in adverse health effects from exposure, ranging from cardiovascular problems such as arteriosclerosis, stroke and myocardial infarction [2], to neurological disorders like white matter disease and exacerbating Alzheimer's and Parkinson's diseases [3], and

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even psychological distress [4]. Although Singapore is known as a ‘garden city’ and its air quality ($PM_{2.5}$ concentration of 19 $\mu g/m^3$) is significantly better than that of least developed countries (average $PM_{2.5}$ concentration of 49 $\mu g/m^3$) [5], this number is an average across the whole country and certain groups within the population might be exposed to higher $PM_{2.5}$ concentrations.

One such group would be bus commuters, who spend extended periods of time exposed to traffic emissions during their daily commute when waiting at bus stops. These traffic emissions are a major source of particulate matter in urban cities [6]. A study conducted in London found that a bus commuter’s total exposure to $PM_{2.5}$ is twice as much as that of a car commuter [7]. Another study in Buffalo, New York suggested that exposure to $PM_{2.5}$ inside a bus stop is 18% higher than exposure outside the bus stop [8]. In Singapore, a country where 46.7% of working people take a bus when commuting to work [9], this problem is one that can have far reaching effects.

In response to the hazards of air pollution, several cities have put in place Internet of Things (IoT) systems to monitor air quality. For example, in Chicago, sensors mounted on lampposts were deployed to measure several air pollutants. Chicago used this data to analyze and forecast air quality incidents [10]. Meanwhile, the city of Dublin uses sensors mounted on bikes in its bike share program to gather citywide air quality data [10]. However, the data gathered from these systems do not focus on specific microenvironments within the city. Thus, it is hard to analyze the causes of air pollution and the effects of potential interventions on air pollution at specific locations.

There have been limited studies conducted with regards to air pollution in bus stops in Singapore. One of these studies analyses the nature of air pollutants and the size of particulate matter in 5 crowded bus stops in Singapore [11]. However, these 5 crowded bus stops are not representative of bus stops in Singapore, and the findings may be unable to account for the $PM_{2.5}$ concentrations of bus stops at other locations.

Hence, this study will use IoT devices to collect and analyze data from many bus stops with varying characteristics in Singapore, in search of factors that would influence the $PM_{2.5}$ concentrations in bus stops. As there are many variables that might affect the $PM_{2.5}$ concentration, 3 parameters were targeted in this study: Position within bus stop, frequency of buses arriving and vehicular traffic including cars, motorcycles and lorries. The $PM_{2.5}$ concentration might vary depending on the position within the bus stop due to the distance away from pollutants, such as the bus exhaust or the road [12]. The frequency of buses arriving is a good gauge of the extent of the stop-start driving behavior of buses, which could heighten $PM_{2.5}$ concentrations [13]. It is also suggested that vehicular traffic emissions from vehicles travelling along the road contribute substantially to $PM_{2.5}$ concentrations in urban areas [14].

This valuable information can be used by the Land Transport Authority (LTA) of Singapore to predict which bus stops would be the most polluted. They would then be able to take on a targeted approach to improve areas such as the ventilation [15] or position [16] of bus stops predicted with high $PM_{2.5}$ concentrations. Ultimately, this research aims to show how IoT devices can be effectively used for environmental monitoring and research.

2 Hypothesis

$PM_{2.5}$ concentrations are higher at the back of the bus stops as it is closer to the bus exhaust, the primary source of pollution from a bus. The edge of the road, which is closer to passing vehicles, will contain higher $PM_{2.5}$ concentrations. The frequency of buses arriving and the volume of vehicular traffic have a positive correlation with the $PM_{2.5}$ concentration at bus stops.

3 Methods and Materials

To test this hypothesis, a field study was conducted using a mobile Air Quality detector (AirQ), which is an Internet of Things (IoT) device, along with the corresponding mobile AirQ smartphone app, jointly developed with Centre for Smart Systems at Singapore University of Technology and Design.

3.1 Mobile AirQ and Smartphone App

The mobile AirQ is a small (77.70 mm $\times$ 60.15 mm $\times$ 32.10 mm) and lightweight (118 g) device, owing partly to its modern 3d printed casing. It contains a Particulate Matter (PM) sensor (Plantower PMS7003) and a temperature and humidity sensor (Bosch BME280) wired to a development board (Linkit 7697), which is powered by a lithium-ion rechargeable battery (Fig. 1).

3D modelling using Fusion 360 also enables us to create compact structures that help to hold the components in place, preventing them from falling out of position when the mobile AirQ is moved about. This ensures the durability of the mobile AirQ. For example, the PM sensor is firmly held such that the air inlet and outlet is always exposed to surrounding air. Moreover, the design is easy to replicate at a low cost.

The Linkit 7697 board is designed for IoT applications, boasting low cost and low power consumption while providing inbuilt Wi-Fi and Bluetooth connectivity. During the course of this project, the mobile AirQ was found to have a battery life of 3 h. These characteristics make the mobile AirQ easily portable.

During data collection, the mobile AirQ device is first turned on and paired to a smartphone through Bluetooth within the mobile AirQ app. Data streams from the environmental sensor are then processed by the Linkit 7697 and sent via Bluetooth to be displayed on the app, which is updated every 5 s (Fig. 2).

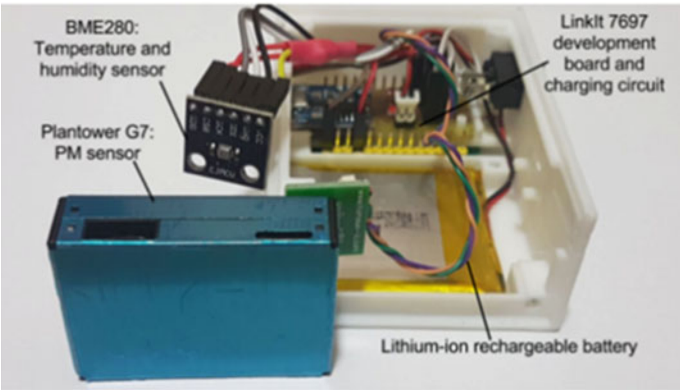


Fig. 1 Diagram showing the different components in the Mobile AirQ

Fig. 2 Diagram shows how data is received and displayed on the Mobile App

The data streams are also able to be exported as a csv file for ease of data analysis (Fig. 3).

The Mobile AirQ and AirQ app is user-friendly and intuitive to use. This enables the device and app to be used by people who wish to conduct environmental studies but lack the technical knowledge of complicated monitoring equipment.

Data collection

Table 1 shows how data were collected for the different variables under investigation.

A good variety of bus stops were chosen, with a good spread of variables such as the busyness of the adjacent road, land use of the surrounding area and size of bus stop (Table 2).

All measurements were taken within 7:30 to 10:00 during the morning peak hour on weekdays, from 15 December 2017 to 31 December 2017. The morning peak hour was chosen as there is a high number of commuters travelling, making it an important time period to study. This would also capture the highest exposure to $PM_{2.5}$ by commuters due to the relatively high traffic density at that time.

	A	B	C	D	E	F	G	H
1	Date	Time	PM 2.5	Temperat	Humidity	PM 10	Latitude	Longitude
2	9/11/2017	3:35:12	20	26.53	45.26	21	1.307104	103.9193
3	9/11/2017	3:35:17	19	26.52	45.27	20	1.307104	103.9193
4	9/11/2017	3:35:22	19	26.54	45.3	21	1.307104	103.9193
5	9/11/2017	3:35:27	20	26.51	45.31	22	1.307104	103.9193
6	9/11/2017	3:35:32	22	26.53	45.32	24	1.307104	103.9193
7	9/11/2017	3:35:37	22	26.52	45.2	23	1.307104	103.9193
8	9/11/2017	3:35:42	21	26.52	45.16	24	1.307104	103.9193
9	9/11/2017	3:35:47	21	26.5	45.23	25	1.307104	103.9193
10	9/11/2017	3:35:52	21	26.53	45.47	26	1.307104	103.9193
11	9/11/2017	3:35:57	20	26.55	45.87	26	1.307104	103.9193
12	9/11/2017	3:36:02	22	26.54	45.61	28	1.307104	103.9193
13	9/11/2017	3:36:08	22	26.53	45.31	27	1.307105	103.9193
14	9/11/2017	3:36:13	24	26.54	45.12	28	1.307105	103.9193
15	9/11/2017	3:36:18	26	26.56	45.16	29	1.307105	103.9193
16	9/11/2017	3:36:23	23	26.54	45.03	25	1.307105	103.9193
17	9/11/2017	3:37:46	25	26.76	48.79	27	1.307533	103.9193
18	9/11/2017	3:37:48	26	26.76	51.47	27	1.307533	103.9193
19	9/11/2017	3:37:51	25	26.78	50.27	25	1.307533	103.9193
20	9/11/2017	3:37:53	26	26.79	48.77	26	1.307533	103.9193
21	9/11/2017	3:37:56	23	26.81	47	25	1.307533	103.9193
22	9/11/2017	3:37:58	23	26.81	46.45	25	1.307533	103.9193
23	9/11/2017	3:38:01	24	26.82	46.12	26	1.307533	103.9193

output

Ready

Fig. 3 CSV file containing output data

Table 1 Methods of data collection for each variable studied

Factor analyzed	How data were collected
Position within bus stop	Two experiments were conducted. The first experiment involved 14 bus stops, where the $PM_{2.5}$ concentrations at the front, middle and back of the bus stop was measured (Fig. 4). The second experiment involved 6 bus stops, where the $PM_{2.5}$ concentrations at the edge of the road and far from the road was measured (Fig. 4)
Frequency of buses arriving	6 bus stops were studied in this experiment. The number of buses stopping at the bus stop was counted over 15 min, and the average rate of buses passing per minute was derived The ambient $PM_{2.5}$ concentration was also measured by standing 10 m away from the bus stop (Fig. 4), where the bus does not come to a stop and starts to move off, thus eliminating the stop-start effect
Vehicular traffic	14 bus stops were studied in this experiment. The number of other vehicles passing by the side of the road nearer to the bus stop was counted over 5 min, and the average rate of vehicles passing per minute was derived

Table 2 Bus stops chosen for investigation

Bus stop name	Bus stop location
Aft Sims Way	Near KPE
Blk 111	Rivervale Plaza
Blk 248A	Compassvale Primary School
Blk 2C	Near Geylang West CC
Chai Chee Ind Pk	Decathlon at Chai Chee
Dhoby Ghaut Stn	Plaza Singapura
Kallang MRT	Kallang MRT
Katong Shop Ctr	Katong Shopping Centre
Maranatha Hall	Before Tanjong Katong Secondary School
Opp Blk 2C	Near Kallang MRT
Opp Playground@ Big Splash	East Coast Park
OUE Bayfront	OUE Bayfront
Paya Lebar Stn	Paya Lebar MRT
Siglap Link	Behind Victoria School

The mobile AirQ was standardized to be placed at 1 m above the ground as that is the average height of one's head when seated within the bus stop. All $PM_{2.5}$ readings were averaged over 5 min to improve the accuracy of the data.

4 Results and Discussion

4.1 Position within Bus Stop

4.1.1 Front, Middle and Back

Comparison between the average $PM_{2.5}$ concentrations at the front (33.24 µg/cm^3), middle (31.35 µg/cm^3) and back (32.54 µg/cm^3) of the bus stops surveyed reveals a marginal variation of $PM_{2.5}$ concentrations between the different positions of the bus stop (Fig. 5) within 1.89 µg/cm^3. This is mainly due to the diffusion where the $PM_{2.5}$ particles spread across a span of not more than 3 meters in width (Fig. 4).

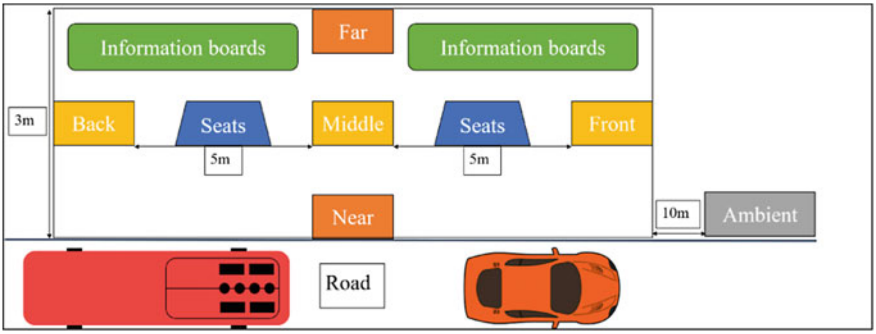
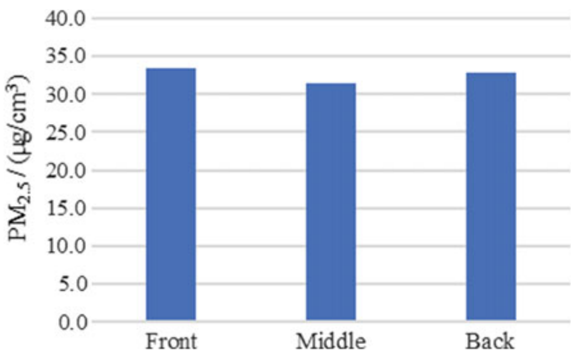


Fig. 4 Locations at the bus stop where data was collected

Fig. 5 The average $PM_{2.5}$ concentrations at the front, middle and back of a bus stop



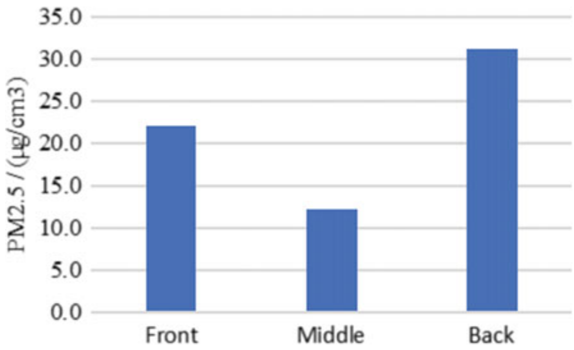


Fig. 6 The $PM_{2.5}$ concentrations at the front, middle and back of Dhoby Ghaut Stn

However, it is interesting to note the huge difference in $PM_{2.5}$ concentrations for Dhoby Ghaut Stn (Fig. 6), with the back being higher than the front by 9.22 $\mu g/cm^3$, and the front being higher than the middle by 9.70 $\mu g/cm^3$. This causes the standard deviation of the $PM_{2.5}$ concentrations at Dhoby Ghaut Stn to be more than 3 times higher than that at other bus stops. This could be due to the presence of an air-conditioned Mass Rapid Transit (MRT) station exit right behind the bus stop. The presence of air-conditioners could filter the polluted air from the road and release fresh air near the bus stop, causing anomalies in the data collection.

4.1.2 Edge Versus far from the Road

Comparison between the $PM_{2.5}$ concentrations at the edge of the road (average of 32.31 $\mu g/cm^3$) and far from the road (average of 30.82 $\mu g/cm^3$) reveal that the edge of the road has a consistently higher $PM_{2.5}$ concentration than far from the road (Fig. 7). Nevertheless, this difference of 1.49 $\mu g/cm^3$ is relatively minor, and it is suspected that this might be attributed to the short distance between the locations of the two readings of not more than 3 m, and the fact that $PM_{2.5}$ is suspended in the air longer than larger particles [17], allowing it to diffuse more profoundly.

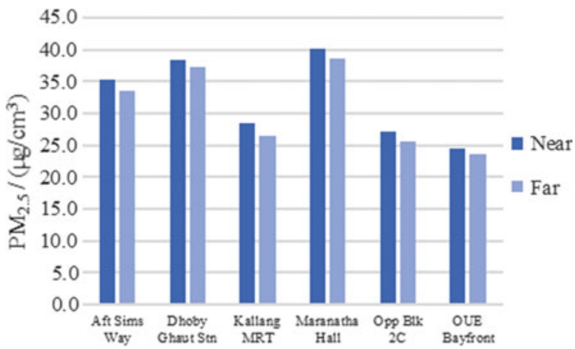


Fig. 7 The average $PM_{2.5}$ concentrations at the edge versus far away from the road

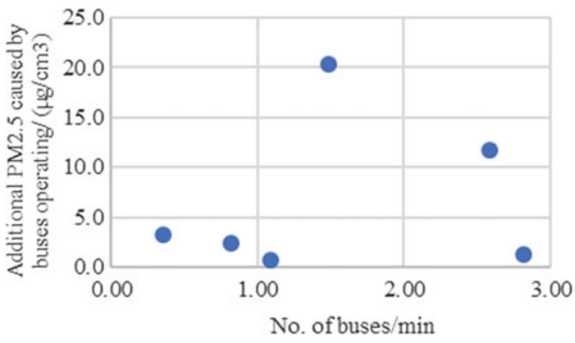


Fig. 8 Difference between the additional $PM_{2.5}$ caused by buses operating at the bus stop against frequency of buses arriving

4.2 Frequency of Buses Arriving

To analyze how the frequency of buses arriving affects the $PM_{2.5}$ concentration at bus stops, the average $PM_{2.5}$ concentration at bus stops was calculated by averaging, which is calculated by averaging the $PM_{2.5}$ readings from the front, middle and back of the bus stops. The additional $PM_{2.5}$ concentration was calculated by taking the difference between the average $PM_{2.5}$ concentration in the bus stop and the ambient $PM_{2.5}$ concentration. This is to control all other variables, such as the vehicular traffic or weather condition that could contribute to the $PM_{2.5}$ concentration of bus stops other than the stop-start effect of buses.

Results unexpectedly show that the frequency of buses arriving has an inconsistent effect on the $PM_{2.5}$ at bus stops (Fig. 8). This challenges what was proposed by Buonanno, Fuoco and Stabile in their paper [13], that the stop-start effect of buses would have a large impact on the $PM_{2.5}$ concentrations at bus stops. If found to be true, this is a significant discovery as it would mean that researchers have been wrongly identifying the extent of pollution in bus stops mainly based on the frequency of buses arriving.

However, these results are to be taken with a pinch of salt as the data collection for the ambient $PM_{2.5}$ was rather subjective, due to obstructions that prevent us from standardizing the location for data collection of the ambient $PM_{2.5}$. The additional $PM_{2.5}$ concentrations at OUE Bayfront and Dhoby Ghaut Station are exceptionally higher due to the ambient $PM_{2.5}$ concentrations there being lower than at the other bus stops. Thus, buses are seen to have a significant impact on $PM_{2.5}$ concentrations at such places only.

4.3 Vehicular Traffic

To analyze the effect of vehicular traffic on the $PM_{2.5}$ concentration at bus stops, the ambient $PM_{2.5}$ was used for comparison instead of the average $PM_{2.5}$ as the stop-start driving behavior of buses might unintentionally inflate the $PM_{2.5}$ concentration. Data

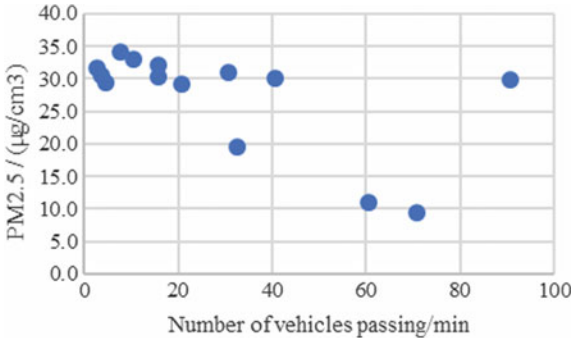


Fig. 9 Ambient $PM_{2.5}$ concentration against number of vehicles passing per minute

collected shows that the number of vehicles passing per minute is also unrelated to the ambient $PM_{2.5}$ concentration at bus stops (Fig. 9), unlike the predicted graph of a strong linear, positive correlation. This could be due to the strict regulations in Singapore, requiring all light petrol-driven vehicles, including cars, to be fitted with catalytic converters [18] that vastly reduce the amount of particulate matter and other air pollutants released from the exhaust of vehicles.

Something surprising was the two data points collected within the Central Business District (CBD) which had an exceptionally low ambient $PM_{2.5}$ (highlighted in Fig. 9). This could be due to the numerous presence of air-conditioned buildings in the region. As mentioned previously, air-conditioning could possibly filter the indoor air of polluting particles, assuming the units are properly maintained [19]. The clean air within these indoor locations can be released to the outside environment whenever the building doors are open, which is especially so during the morning peak hour, when many office workers are entering their worksites. As OUE Bayfront is located about 50 m from the sea, a morning sea breeze was felt during data collection that further disperses particulate matter, leading to lower $PM_{2.5}$ concentrations. From these two observations, wind might affect the $PM_{2.5}$ concentrations, making it an interesting area for further research.

5 Conclusion

This study is a proof of concept that IoT devices, which are less cumbersome than traditional monitoring equipment, can still be used for environmental monitoring and research. In addition, the results are exciting as some counterintuitive trends have been uncovered, which could change the way we think about urban air pollution and how we tackle it. Moving forward, it is hoped that this study can prompt further research using IoT devices that can validate these findings and explore other factors that might influence commuters' $PM_{2.5}$ exposure at bus stops, such as the presence of greenery or the effect of wind.

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