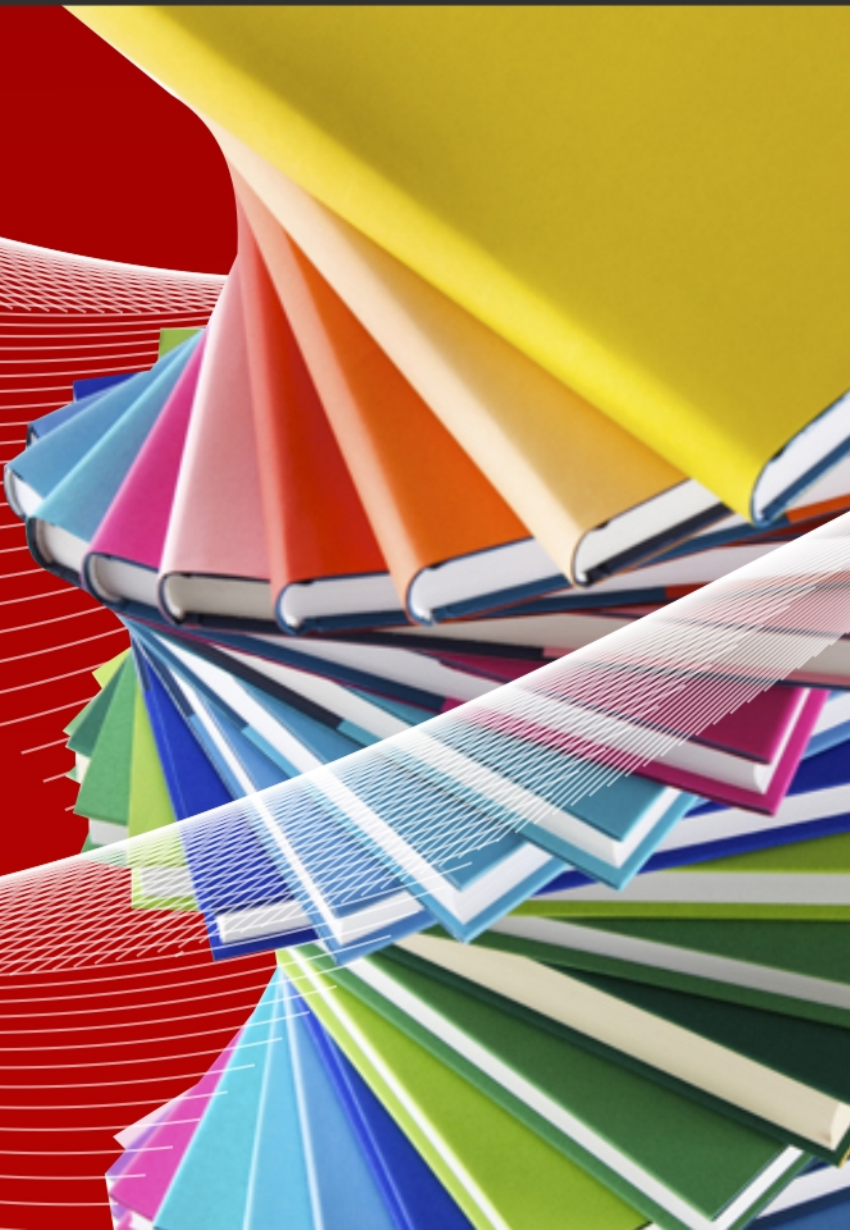
澳門大學
UNIVERSIDADE DE MACAU
UNIVERSITY OF MACAU

Outstanding Academic Papers by Students
學 生 優 秀 作 品



Exposure to Black Carbon and Fine Particulate Matter (PM2.5) in Three Different Locations in Macau

By

HUANG JINQUAN

Final Year Project Report submitted in partial fulfillment
of the requirement of the Degree of

Bachelor of Science in Civil Engineering

2017

Faculty of Science and Technology
University of Macau

DECLARATION

I declare that the project report here submitted is original except for the source materials explicitly acknowledged and that this report as a whole, or any part of this report has not been previously and concurrently submitted for any other degree or award at the University of Macau or other institutions.

I also acknowledge that I am aware of the Rules on Handling Student Academic Dishonesty and the Regulations of the Student Discipline of the University of Macau.

Signature : 黃錦權

Name : Huang Jin Quan

Student ID : DB325726

Date : 16/05/2017

APPROVAL FOR SUBMISSION

This project report entitled "**Exposure to Black Carbon and Fine Particulate Matter (PM2.5) In Three Different Locations in Macau**" was prepared by HUANG JINQUAN in partial fulfillment of the requirements for the degree of Bachelor of Science in Civil Engineering at the University of Macau.

Endorsed by,

Signature : ______________________

Supervisor : Prof. Yongjie Li

ACKNOWLEDGEMENTS

After a certain long time of working, the final year project finally comes to an end. I would like to express my appreciation and gratitude to my supervisor Dr. Yongjie Li who gave me a wonderful opportunity and lots of assistance and suggestions to complete this final year project. And a special thanks to a post-graduate student, Mr. Ben Liu, who helped me to finish the measurements and gave me guidance and encouragement in analyzing the data and writing the report. Besides, I was very grateful to my friends who fought side by side with me.

ABSTRACT

Air pollution becomes the leading environmental concern in Macau. For studying indoor or outdoor air quality, fine particulate matter (PM ≤ 2.5μm in aerodynamic diameter, also known as PM2.5) has become the focus in air quality research due to its effects on human health, environment, climate, and visibility. Black carbon (BC, soot) is one of the major components of PM2.5 that comes from incomplete combustion of biomass or fossil fuel. BC is a component that is responsible to absorb visible light primarily. Recent studies in Macau showed a lack of information about PM2.5 and BC but they are one of the important contributors to impact human health and global environment. The project aims to measure and compare the concentrations of BC and PM2.5 during different time in three locations in Macau. For the analysis, the ambient surroundings of the three locations is one of the most important factors to affect the BC and PM2.5 concentrations. We selected University of Macau, Guia Park and Sai Van Lake for the measurements, as these locations are popular outdoor jogging trials in the city. We used portable handheld real-time aerosol measurement devices to measure BC and PM2.5 concentrations. At the same time, we used a GPS device to combine with the BC and PM2.5 data in specific locations. In this paper, we would compare and comment on the current state of BC and PM2.5 emission status. We then estimated the exposure to BC and PM2.5 in these three locations and recommend the people to choose a better time and better place to do sports. Finally, we also hope to improve people's concerns about BC and PM2.5 for climate change and public health after reading this paper.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Particulate matter (PM), also known as particulate contaminants, is a mixture of very small particles and droplets suspended in air and mostly are hazardous (US EPA O., 2017). Ambient fine particulate matter (PM ≤ 2.5 μm in aerodynamic diameter, also known as PM2.5) is the leading environmental risk factor for human mortality globally (Wikipedia, 2017). Black carbon (BC, soot) is one of the major components of fine particulate matter (PM2.5). BC produced from both open burning (OB) and controlled combustion (CC) (Ni *et al.*, 2014). In Macau, primary combustion like vehicle emissions takes a big part of black carbon emission. It is an anthropogenic aerosol that significantly warms the atmosphere through absorption of solar radiation (Cheng *et al.*, 2006). In terms of a direct climate forcer, ranking alongside methane and just behind carbon dioxide (IPO, 2009), BC is believed to be a principal composition of global warming because its warming effect has been found to balance the net cooling effect of other anthropogenic aerosol constituents (Cheng *et al.*, 2006). China is currently facing severe air pollution in the transition phase of industrialization and urbanization (Xing *et al.*, 2016).

Macau (22.2 °N 113.6 °E, also spelled Macao) is a tiny city which locates on China's southern coast, and the economy of the city is largely based on tourism and gambling industry. With an estimated population of around 647,700 in an area of 30.5 km², it is the most densely populated region in the world (Wikipedia, 2017). As of September of 2016, the number of motor vehicles in Macau has increased to 0.25 million, resulting in one of the highest traffic densities all over the world (DSEC, 2016). Air pollution is now one of the leading environmental concerns and previous studies have indicated that vehicle emissions are the predominant local source of air pollution in Macau (Song *et al.*, 2014). Particulate matter (PM) is regarded as the principal air pollutant in Macau (Mok and Hoi, 2005). In recent years, air quality research has started to focus on fine particulate matter (PM2.5) due to its strong effects on human's health, environment, climate and visibility (Zhao *et al.*, 2011). However, there are few studies on personal exposure to BC and PM2.5 in Macau (Song *et al.*, 2014).

In this project, the measurements were carried out in Macau in August 2016. However, some collected data is non-usable because of the error generated by the devices or some human factors during the measurements. Data cleaning and preparation were performed to have the effective data ranging from Aug. 24 to Nov. 21. The main goals of this study were to monitor the exposure levels of BC and PM2.5 in the three different locations in Macau and assess if these levels are in the range that may cause adverse health concern. The three locations are popular outdoor jogging trials in the city. Specific objectives of the study included: (1) measuring levels of BC in three selected locations in Macau; (2) simultaneously measuring levels of PM2.5 in the same locations and comparing them with BC levels; (3) comparing BC and PM2.5 exposure levels between Macau and other cities; and (4) studying the spatial and temporal variations of BC and PM2.5 among the three locations. This project also hopes to help policy-makers promote development plans for controlling the number of Macau's future automobile market and current in-use fleet. On the other hand, we hope to inform the public about BC and PM2.5 emission status and give them some useful information by avoiding exposing to high concentrations of BC and PM2.5.

CHAPTER 2 LITEARTURE REVIEW

Nowadays, with fast urban development and modernization, air pollution is becoming worsen and its impacts on human's health has become an important research topic, especially in China. Air pollutants include gaseous pollutants and particulate matter (PM). The pathogenicity of PM is determined by their size, composition, origin, solubility and their ability to produce reactive oxygen (Xing *et al.*, 2016). It has been found that PMs with an aerodynamic diameter equal to or smaller than 10 μm would have a greater damage on human's health (Xing *et al.*, 2016). Studies have shown that short-term and long-term exposure to PM2.5 correlated with morbidity and research to provide evidence of the effects of exposure to airborne contaminants such as ultrafine particles (UFPs), nitrogen oxides, ozone, carbon monoxide, volatile organic compounds and sulfur dioxide on health, including respiratory diseases and lung cancer (Nyhan *et al.*, 2016). A report from the American Cancer Society concluded that the total mortality and mortality of cardiopulmonary and lung cancer increased by 4%, 6% and 8% per 10 $\mu g / m^3$ PM2.5 (particle aerodynamic diameter $\leq$ 2.5 μm, referred to as PM 2.5) increased, excluding other risk factors such as smoking, eating, drinking and occupation (Pope III *et al.*, 2002).

The World Health Organization (WHO) has reported that 92% of the world's urban population are now living in cities with toxic air (World Health Organization, 2016). Beijing, London, Paris, New Delhi and Mexico City are the cities that have drawn attention from the public with the high air pollution levels in 2016. Figure 2.1 shows the concentrations of PM2.5 around the globe in the year of 2014. WHO Library Cataloguing-in-Publication Data (2016) states that exposures are extremely high in the South-East Asian, Eastern Mediterranean and Western Pacific Regions. However, air pollution does not merely come from human emission or human activity, it can also be strongly affected by dust storms, such as the regions close to desert.

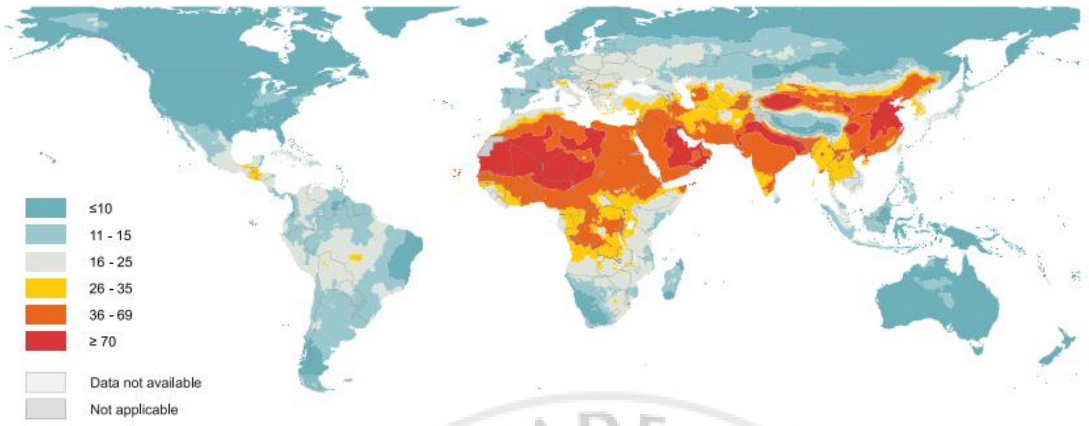


Figure 2.1 Global map of modelled annual median concentration of PM2.5 in year 2014, unit in µg/m³ (WHO, 2016)

Particulate carbon (total carbon, TC) can be broadly divided into three categories: organic carbon (OC), elemental carbon (EC) and inorganic carbon (IC), mainly in the form of carbonate (CC). The terms EC, Black Carbon (BC), soot, and light absorbing carbon (LAC) are used interchangeably in many literature and can be produced from any kinds of incomplete combustion of carbon-containing fuels (Karanasiou *et al.*, 2015). BC is a short-lived composition of PM2.5 and defined as the component of carbonaceous aerosol that absorbing light (Lei *et al.*, 2016). BC has both direct and indirect effects on climate change by heating the atmosphere and absorbing solar radiation (Lei *et al.*, 2016). This human emission fine particle ranks just second to CO_2 (carbon dioxide) as the most important climate change forcing. The link between BC and respiratory and cardiovascular diseases has also been found (Zhao *et al.*, 2011). Recent studies have shown that certain adverse health effects were more strongly associated with BC rather than PM2.5 because of BC can carry more potentially toxic compounds by its large surface. BC can also cause inflammation, penetrate into the deepest regions of the lung, and may deposit in secondary organs (Lei *et al.*, 2016).

Macau lies in the Pearl River Delta area and composed of the Macau Peninsula, Taipa Island and Coloane Island. The small coastal city locates on the western side of the Pearl River Delta in East Asia. Macau is warm and humid, with mean value of relative humidity (RH) of around 81% to 82%, and maximum RH is about 90 on average (Figure 2.2). With a typical subtropical and oceanic climate, Macau has an annual average temperature of 23.2°C (DSEC, 2015). The average wind speed is 3.5 m/s, with dominant easterly winds in summer and northerly and northwesterly winds in winter. In recent years, the vehicle number of Macau has grown rapidly because of the development of the economy, with an average annual increase of about 9.8% (Song *et al.*, 2014). The rapid growth of the vehicle number in Macau raises a certain concern for its adverse impacts on urban air quality and human health. Vehicle emissions will not only contribute to higher roadside pollutant concentration but also degrade ambient air quality. Motor vehicle density kept increasing in the past 3 years from 2013 to 2015 and nearly reached 600 vehicles/km in 2015 (Figure 2.3). Light-duty vehicles and motor vehicles account for about 97 % of the total vehicle population (DSEC, 2015). Motor vehicle emissions are considered to be the dominant local source of air pollutants in Macau since the region is not directly influenced by other local industrial emissions (Wang *et al.*, 2014). It has found that local emissions contributed at an estimation of least 35% to PM2.5 mass in Macau and higher BC concentrations were observed in the daytime and lower in the nighttime, which followed the diurnal variations of traffic flow (Song *et al.*, 2014). Moreover, "street canyon" effect will be resulted due to the interaction of the local wind field and surrounding tall buildings in the central business district which will extend the residence time of pollutants. Therefore, the accumulation of local air pollution may be amplified (Wang *et al.*, 2014).

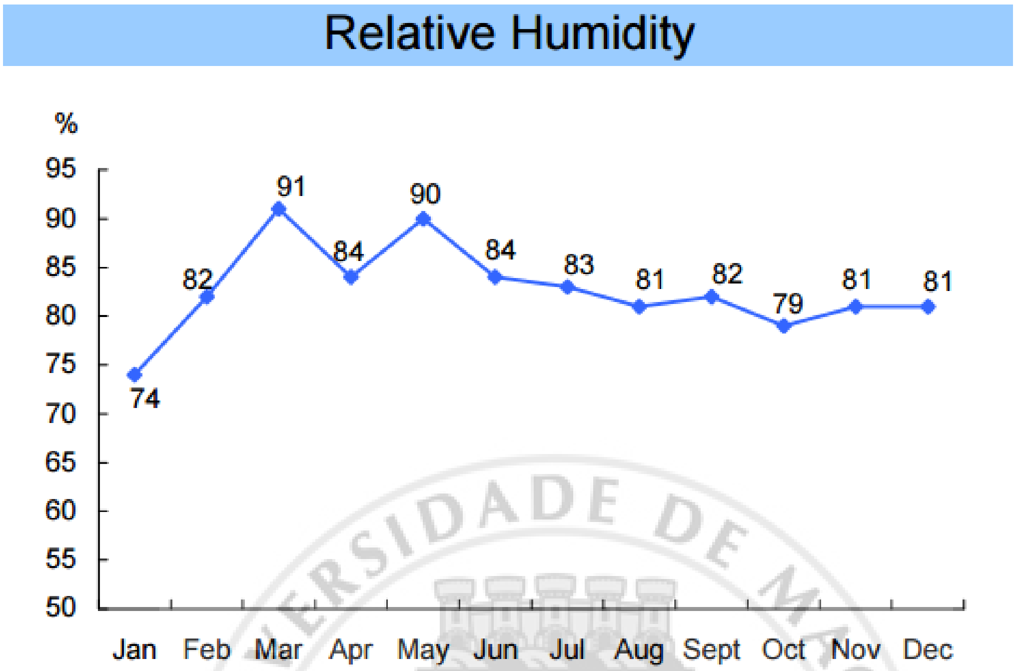


Figure 2.2 Relative humudity of Macau in 2015 (DSEC, 2015)

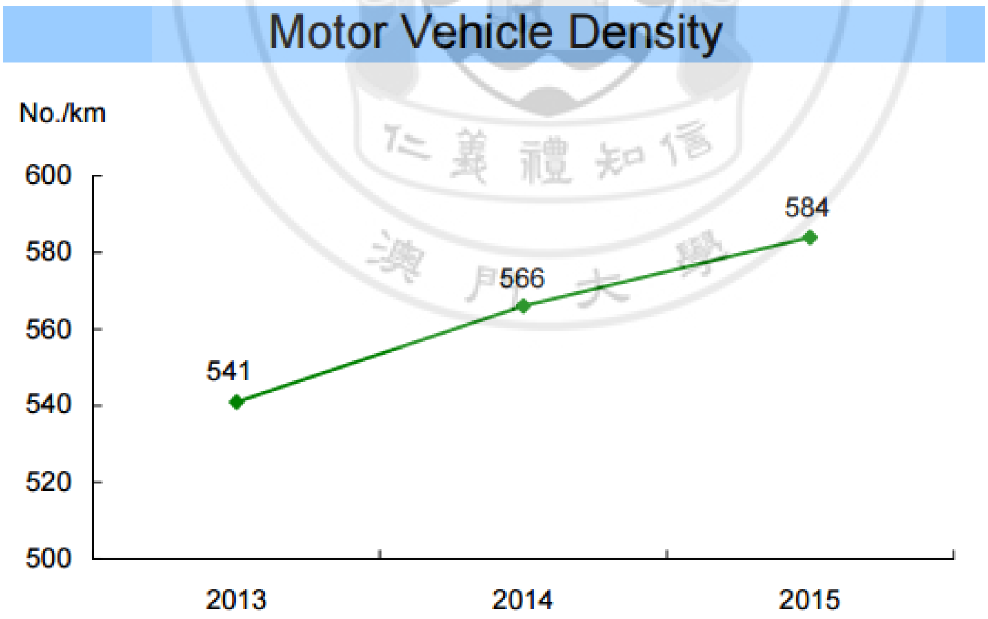


Figure 2.3 Moto vehicle density in Macau from 2013 to 2015 (DSEC, 2015)

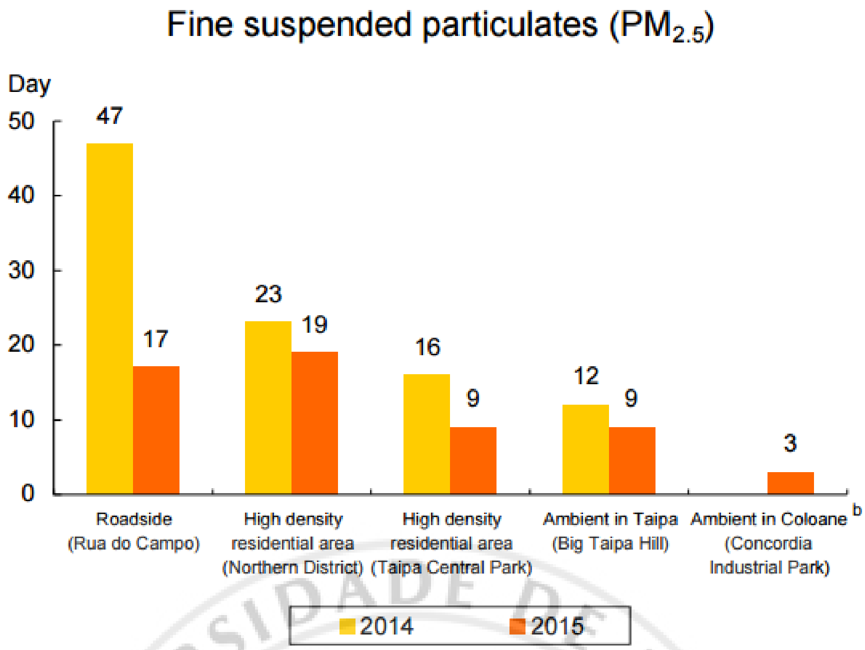


Figure 2.4 Days of high concentration of PM2.5 in Macau in 2014 and 2015 (DSEC, 2015)

PM2.5 is a serious problem in Macau. Figure 2.4 shows the days of high concentration of PM2.5 in different districts of Macau in 2014 and 2015. Obviously, the days in 2015 is less than in 2014, which may imply that there are some measures to reduce the PM2.5 emission. Besides, roadside is the most polluted location, followed by high residential area (northern district). This observation is easily understandable, because roadside is affected by the emission source from plenty of vehicles in street and northern district in Macau has larger population and higher density of traffic than Taipa Central Park. Other remote places in Macau had rather less days especially in the ambient in Coloane.

BC is widely viewed as an indicator of diesel engine vehicle emissions in dense traffic areas. All taxis and most vehicles are equipped with diesel engines while motorcycles and passenger cars mostly use gasoline engines in Macau (Song *et al.*, 2014). On-road emission measurements is one of the methods that can provide real-world emission status of in-use vehicles (Wang *et al.*, 2014). There are some on-road emission measurement methods including remote sensing, chasing car measurement and on-board measurement. With the development of portable emissions measurement system (PEMS) recently, researchers around the world have measured the on-board emission characteristics of motor vehicles under the driving conditions in real world (Wang *et al.*, 2014).

In Shanghai Xuhui District, China, a study (Li *et al.*, 2015) on a commuter's exposure to BC in five different traffic modes (taxi, bus, subway, cycling and walking) was conducted by using the same AE51 BC monitors during six non-rainy working days in August 2014. Two AE51 monitors were applied to conduct the measurements in pairs at the same time. For each monitoring, one volunteer always traveled by bike, and the other volunteer used another transportation way as a comparison. This study discusses the spatial and temporal distributions of peak and off-peak BC concentrations. Figure 2.5 showed the resulting maps. R3 is the center of Xuhui District. At peak hours, the BC concentration on the route was significantly higher than the off-peak hours. Because of the variation of traffic flow and street topology on routes, there are obviously differences in peak and off-peak BC exposure levels. BC exposure levels at the intersections were usually higher than other locations because of the low speed of vehicles and traffic congestions which would discharge more BC from incomplete combustion fuels. From R2 to R3, peak points increased due to the traffic congestion and street canyon effect. There were mainly composed of residential buildings at the end of R3, BC concentrations was in a lower level due to lower traffic flow than other parts in this route. Result of this study also showed BC concentration was influencing by the distance to the traffic and the street topology.

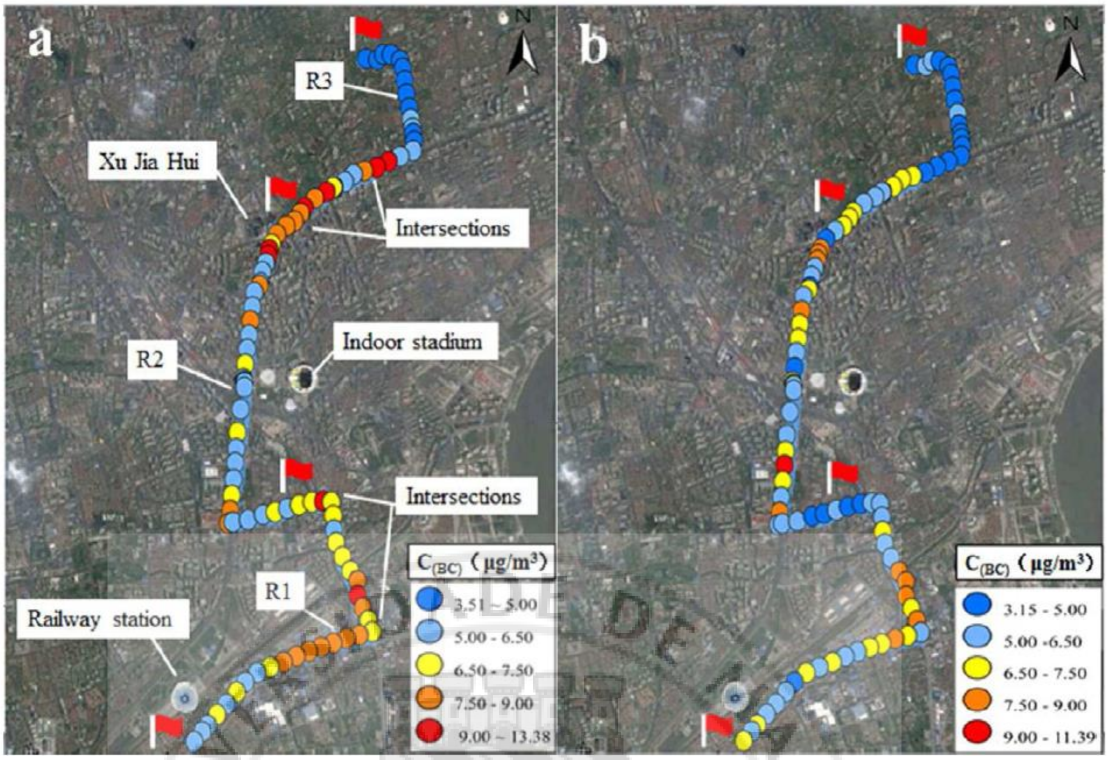


Figure 2.5 (a) Spatial and temporal distribution of BC concentrations in peak hours on three roads; (b) spatial and temporal distribution of BC concentrations in off-peak hours on three roads (Li *et al.*, 2015)

Another study (Kaur *et al.*, 2007) mentioned the concentrations of air pollutants are often particularly high in the traffic microenvironment or commuting. In general, most of the individuals may suffer a significant daily pollutant exposure when they travel a regular journey of some distance between one's home and place of work on a regular basis, even though it is no more than 6 to 8 % of their daily time. Respiratory rate is a key factor of human exposure and health risk assessment (Wang *et al.*, 2009). As Lei (2016) stated, transportation should be considered as one of the high air pollutant exposure microenvironments, especially in the high vehicle-density regions. WHO (2016) recommended a standard daily average PM2.5 concentration of 25 μg / m^3. Its recipients include Canada and Australia. The three interim targets are 75 μg / m^3 for China, India and Mexico, 50 μg / m3 for the European Union and Thailand, and 37.5 μg / m^3 for US, Japan and Singapore.

In addition to personal exposure, the amount of inhaled pollutants will vary significantly depending on the rate of inhalation, duration in a particular microenvironment, and other biological factors such as age and body weight (Lei *et al.*, 2016). The efficiency of inhalation of aerosols during inhalation is assumed to be 100%. The inhalation dose is determined based on three factors: the concentration of contaminants in the air, the time spent by people in the environment and the amount of air that people breathe during exposing (*Research Note: # 94-11*). Inhalation dose is calculated by the following equation 2.2:

$$D = \sum_{i=1}^{n} \{Et \cdot IR\ \ activity \cdot T\}\, i \tag{2.1}$$

where *D* represents the average inhalation dose, μg; *Et* is the average PM2.5 or BC concentration in the i^th microenvironment, μg/m^3; *IR* is the inhalation rate in i^th microenvironment, m^3/h; and *T* is the duration that people are exposed to i^th microenvironment during a journey, h (Lei *et al.*, 2016). The inhalation rate for different activities was referenced from Adams (1993), summary as in the following Table 2.1, the originally resources is available in APPDENDIX A.

Table 2.1 Mean hourly inhalation rate (*IR*, m^3/h) by group and activity for laboratory protocols

Activity	Young Children	Children	Adult Females	Adult Males
Lying	0.37	0.45	0.43	0.54
Sitting	0.39	0.44	0.46	0.56
Standing	0.41	0.51	0.50	0.64
Walking (2.5 mph)	DNP	0.93	1.22	1.45
Running (Jogging) (4.5 mph)	DNP	2.23	2.87	3.44
Running (5 mph)	DNP	DNP	3.05	3.51

*Young children (male and female), 3-5.9 year olds; Children (male and female), 6 -12.9 year olds; Adult Females, adolescent, young to middle-aged and older adult females; Adult Males, adolescent, young to middle-aged and older adult males; DNP, group did not perform this protocol.

CHAPTER 3 METHODOLOGY

3.1 Measurement Principles and Devices

A device based on the principle of light absorption are used to measure the concentration of BC. BC is a positive radiative agent that strongly absorbs light, thus contributing to climate change and is extensively investigated in atmospheric research. The aerosol light absorption is one of the most uncertain situations in which the aerosol affects directly and indirectly in the climate. Aethalometers are instruments used to determine BC concentrations. The Aethalometer is one of the optical instruments based on filters, which is most used to determine the content of light absorbing carbon (LAC). Other instruments based on the similar principle include the Particle Soot Absorption Photometer (PSAP). Theoretically, it is based on properties of light absorption by carbonated aerosols. In another word, they measure the attenuation of light transmitted through particles that are continuously collected on a filter. PM is collected in Aethalometers by using a quartz fiber filter. The change in light absorption is measured in the filter at several different wavelengths (Amaral et al., 2015).

The real-time, pocket-sized Black Carbon aerosol monitor, microAeth® AE51 (Figure 3.1.1, Magee Scientific Inc.,Berkeley, Calif.) was used to measure aerosol BC in real time together with the TSI DustTrak II Aerosol Monitor 8530 (Figure 3.1.2) to measure PM2.5 in real time in this project. A portable global positioning system (GPS) device, UniStrong Dora G120 (Figure 3.1.3), was used to get the GPS information during our walking in sites. . In order to measure the BC concentration in the ambient atmosphere in real-time, AE51 was placed in the backpack and its sampling inlet was mounted to the opening air through a long plastic tube. AE51 is light and convenient to provide high temporal resolution measurement of BC concentration (Wang et al., 2016). Real-time analysis by measuring the change in absorption of transmitted light due to continuous collection of aerosol deposit on filter. AE51 needs at least 15min warming up every time before monitoring. The filter stripe should be changed according to the lifetime (continuously measuring for 12 hours or 2 days' measurements in this case). The inflow rate is 50 mL/min and time resolution is 60 s for the measurement. DustTrak II Aerosol Monitor 8530 is a desktop battery-operated, data-logging, light-scattering laser photometer that provides real-time aerosol quality readings. It uses a sheath air system to isolate the aerosols in the optical chamber to keep the optical components clean to improve reliability and low maintenance. It is suitable for clean office environments and outdoor applications such as harsh industrial sites, construction and environmental sites (TSI, 2017). DustTrak II Aerosol Monitor 8530 needs zeroing every time before monitoring, of which the PM2.5 impactor should be cleaned and then added 1 drop of oil every time before taking measurements. In this measurement, the inflow rate is 3 L/min and the time resolution is 10 s.

Figure 3.1.1 The microAeth® AE51 for BC measurement

Figure 3.1.2 The DustTrak II Aerosol Monitor 8530 for PM2.5 Measurement

Figure 3.1.3 The GPS device UniStrong Dora G120

Overall, BC and PM2.5 concentrations were measured by using both real time personal air sampling instruments. The equipment was put into a backpack in case of the vibration will impact the accuracy of the data, and switched on before each measurement. At the same time AE51 is placed into a small bag to minimize the outside vibration while walking (Figure 3.1.4). All testing equipment, including PM2.5 sampler, BC monitor and GPS tracking device will be synchronized at the beginning of each measurement.

Figure 3.1.4 The backpack with AE51 and DustTrak II Aerosol Monitor 8530 inside

3.2 Measurement Sites

The Tower/Background (BG) (Figure 3.2.1) with height about 25 meters is located in front of the building E31 in University of Macau. Since there's no major emission sources located in the measurement site's surroundings, measurements at the top floor of the Tower in UM are expected to have "background" atmospheric properties, which are determined mostly by the of air masses transported from upwind (Cheng *et al.*, 2006). Therefore, we chose this place as our background data collection station.

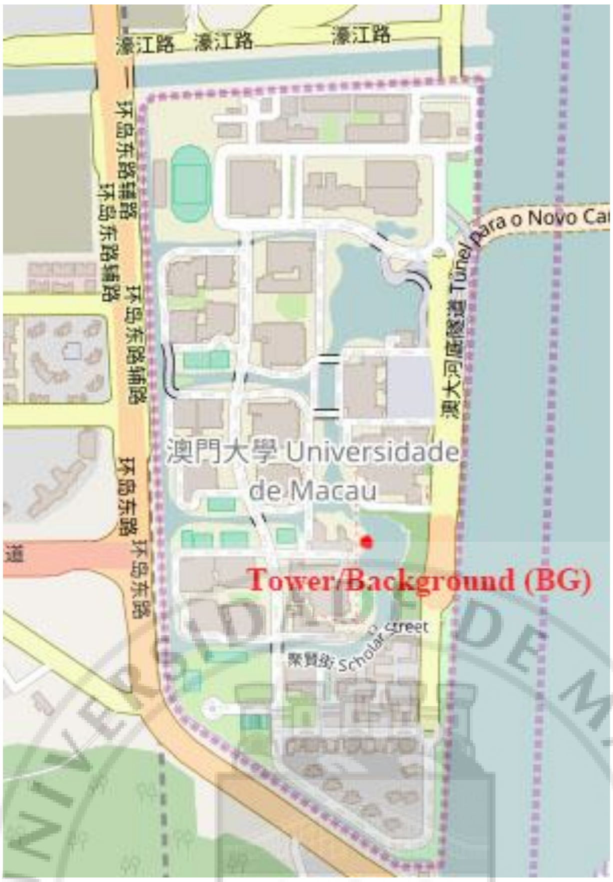


Figure 3.2.1 The location of the Tower in the University of Macau

We have selected three different locations (Figure 3.2.2) in Macau for our measurements. We want to provided comparable data, so the geographic locations, surroundings and ambient environments of these three places are very different but they have some similarities such as people like running or doing exercises there. For the geographic location of the ①University of Macau (UM), it is located on Hengqin Island which is far away from the center of Macau. It is in the east of a river wherever southwest by a mountain. Guia Hill is the tallest mountain in Macau. The whole health walking track in ②Guia Park (GP) is located on 52 meters above sea level, about 1700 meters in length. This measurement site is located in the center of Macau Peninsula but in high terrain. The third place is ③Sai Van Lake (SV). It is one of two artificial lakes in Macau. It locates at the southern tip of Macau Peninsula. To the north of SV there' s a small Colina da Penha. Southern is a main traffic road with high traffic density and eastern is a construction site.

Figure 3.2.2 Locations of three monitoring sites

3.3 Measurement

In this project, the first testing measurements were conducted on 1st December 2015. These tests collected the first batch of indoor monitoring data of BC. Several outdoor trials of measurements were repeated in several places in the following months to further acquaint with the operation and function of this highly sensitive device. The combination of the above instruments, as well as a GPS receiver, has presented a clear blueprint to quantify human exposure to PM2.5.

The measurement aims at exam the human exposure to PM2.5 and BC through the adjustability and optimized methods to improve the pertinence and effectiveness of data monitoring. The selected monitoring time period was based on daily traffic peak hours and off-peak hours. Several trials have been conducted at UM campus along with a previously designed route from February to August of 2016, followed by the final measurements undertaken at different places in Macau as below in Table 3.1.1.

Table 3.3.1 Measurement arrangement for the project in three locations of Macau

Location	**UM Campus(UM)**	**Guia Park(GP)**	**Sai Van Lake(SV)**	**Background(BG)/ Tower**
Strarting from	24.08.2016	19.09.2016	05.11.2016	05.09.2016
End on	03.09.2016	03.11.2016	21.11.2016	24.10.2016

For the schedule of background measurement (Table 3.3.2):

- 06:00:00, start warming up the AE51 and zeroing the DustTrak II Aerosol Monitor 8530, then measuring till 06:45:30 such that the background data is collected at from 06:15:00 to 06:45:00.
- 20:00:00, start warming up the AE51 and zeroing the DustTrak II Aerosol Monitor 8530, then measuring till 20:45:30 such that the background data is collected at from 20:15:00 to 20:45:00.

Table 3.3.2 Schedule of background measurements

Morning Loop	06:00:00 to 06:45:00
Night Loop	20:00:00 to 20:45:00

For the schedule of regular measurement in UM (Table 3.3.3):

- 2+2 loops (twice in the morning and in the evening, respectively), each loop is about 46 minutes.
- Repeating every day to obtain at least 7-days' effective data, including both weekdays and weekends.

Table 3.3.3 Schedule of regular measurements for UM

Loop 1	07:32:00 to 08:18:00
Loop 2	08:18:00 to 09:04:00
Loop 3	21:32:00 to 22:18:00
Loop 4	22:18:00 to 23:04:00

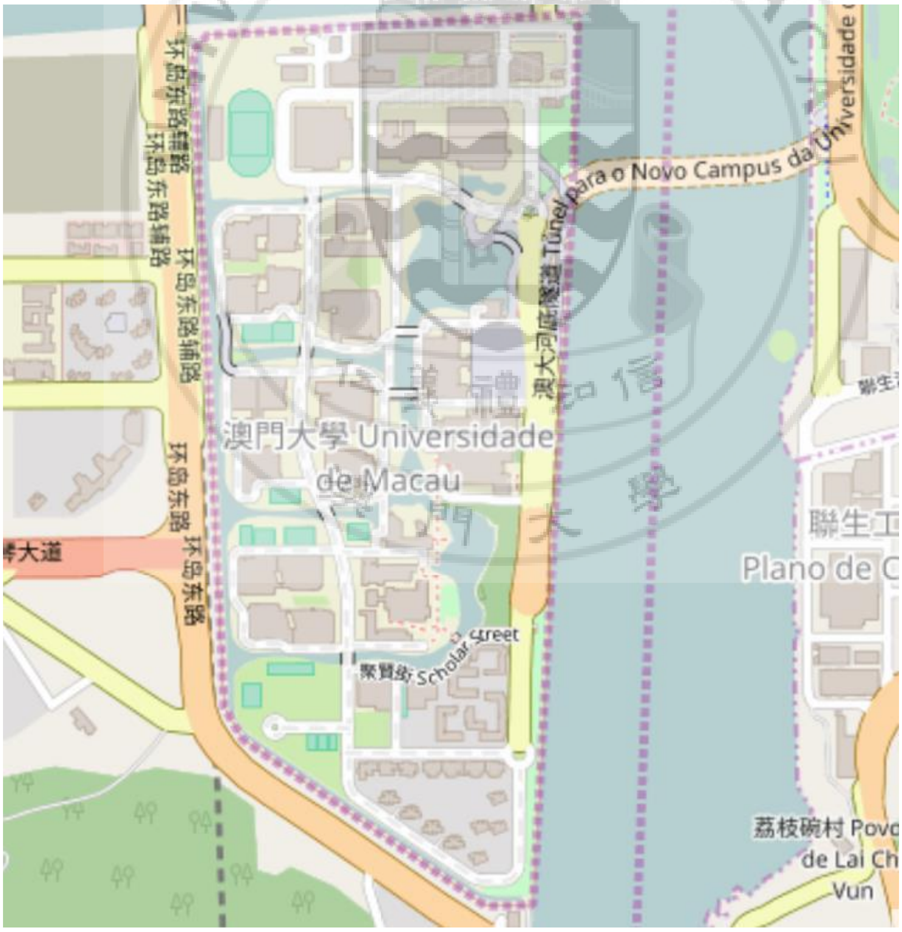


Figure 3.3.1 Monitoring site of UM

For the schedule of regular measurement in GP (Table 3.3.4):

- 3+3 loops (3 times in the morning and in the evening, respectively), each loop is about 22 minutes.
- Repeating every day to obtain at least 7-days' effective data, including both weekdays and weekends.

Table 3.3.4 Schedule of regular measurements for GP

Loop 1	07:40:00 - 08:02:00
Loop 2	08:02:00 - 08:25:00
Loop 3	08:25:00 - 08:47:00
Loop 4	21:40:00 - 22:02:00
Loop 5	22:02:00 - 22:25:00
Loop 6	22:25:00 - 22:47:00

Figure 3.3.2 Monitoring site of GP

For the schedule of regular measurement in SV (Table 3.3.5):

- 2+2 loops (twice in the morning and in the evening, respectively), each loop is about 28.5 minutes.
- Repeating every day to obtain at least 7-days' data (including both weekdays and weekends).

Table 3.3.5 Schedule of regular measurements for SV

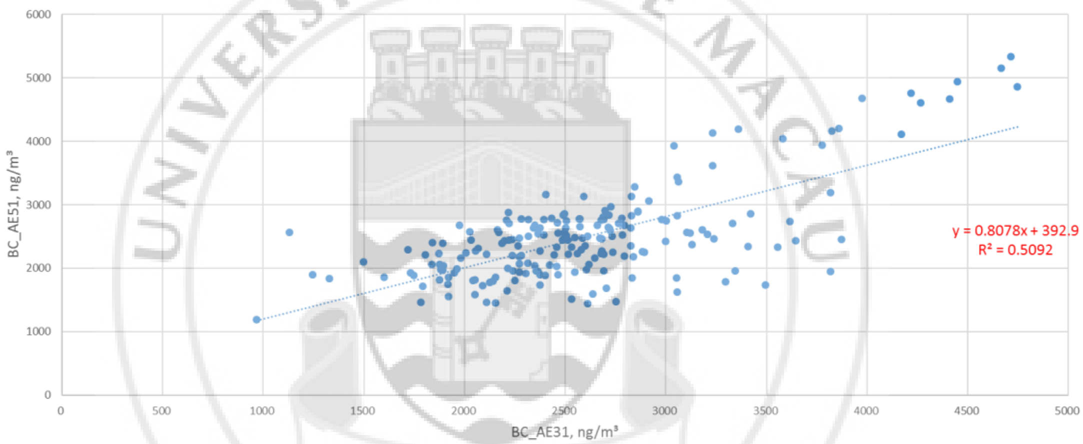
Loop 1	07:30:00 to 07:58:30
Loop 2	07:59:00 to 08:27:30
Loop 3	21:30:00 to 21:58:30
Loop 4	21:59:00 to 22:27:30

Figure 3.3.3 Monitoring site of SV

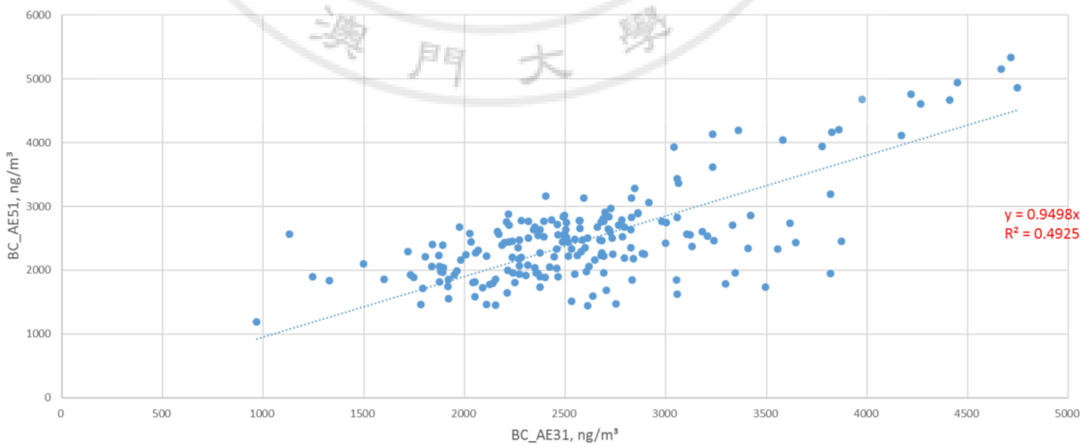
CHAPTER 4 RESULTS AND DISCUSSION

4.1 Correction Factor (CF)

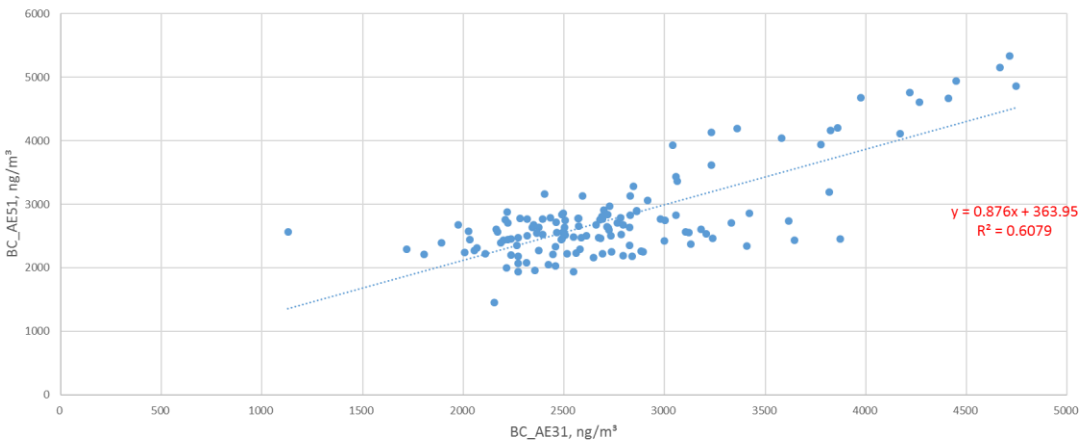
During the measurement, parallel simple tests (Figure 4.1.1 and Figure 4.1.2) have been conducted in November 2016 at the supersite in HKUST to testify the reliability and verify the adjustment coefficient of the instruments (AE51 and DustTrak II Aerosol Monitor 8530) used in this project. We used two different measurement devices both for PM2.5 and BC to collect a series of data, then find out what was the relation between them.



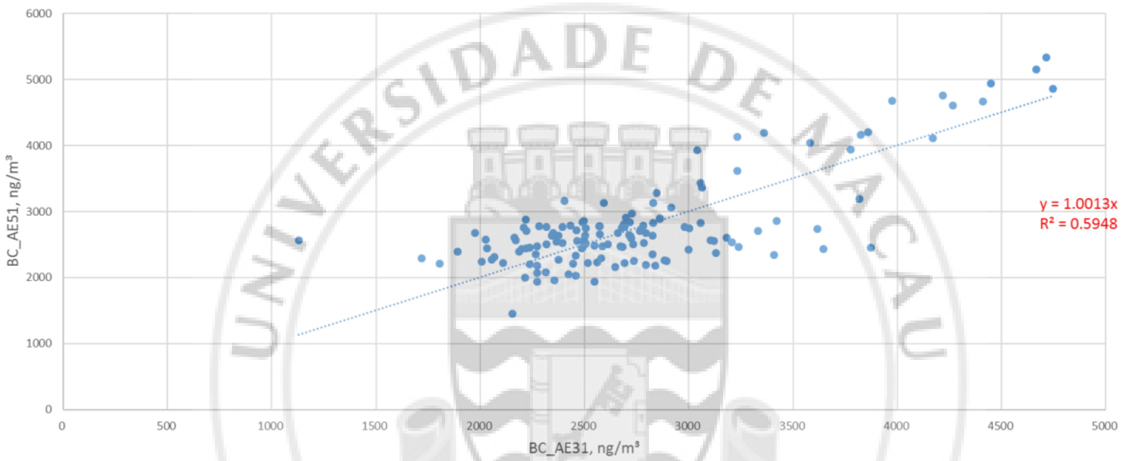
(a)



(b)



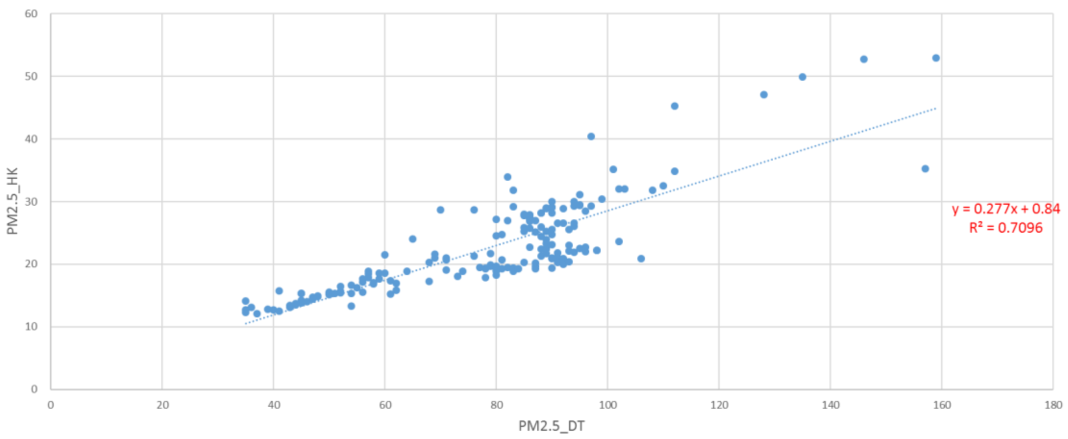
(c)



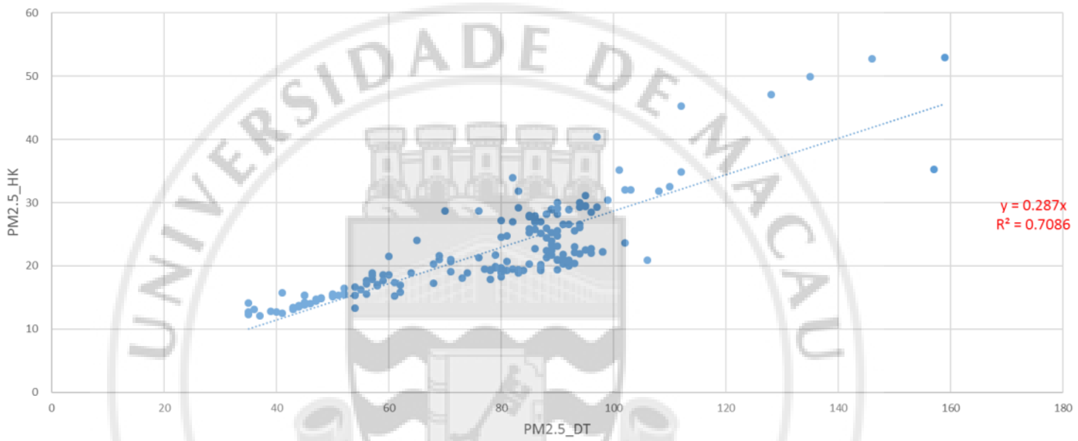
(d)

Figure 4.1.1 Data Correction for BC; (a) and (b) were plotted with data obtained when RH higher than 90%, (c) and (d) were plotted with data obtained when RH lower than 90%

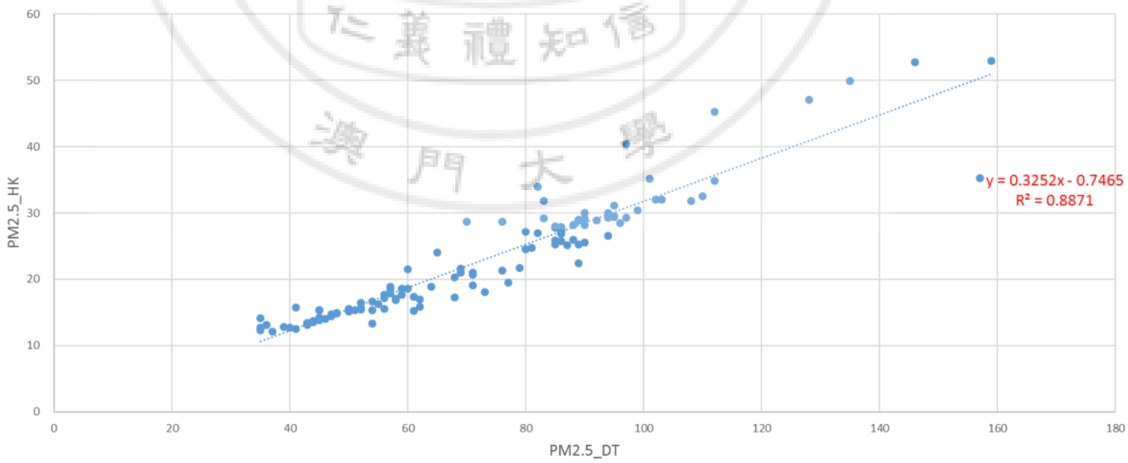
From Figure 4.1.2 (a) and (b), they were plotted with data obtained when RH higher than 90%, the index of the trend line are 0.8078 and 0.9498, respectively. From (a), it had the intercept, but the intercept is very large and unreasonable. And because RH is very high in Macau. Therefore, the correction factor for BC which was measured by AE51 should be 0.9498 from (b). In this case, the correction factor could be 1 because the relative error is very small. In another word, the data of BC concentration collected by AE51 was reliable and did not need to adjust.


PM2.5_HK
PM2.5_DT
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
y = 0.277x + 0.84
R² = 0.7096

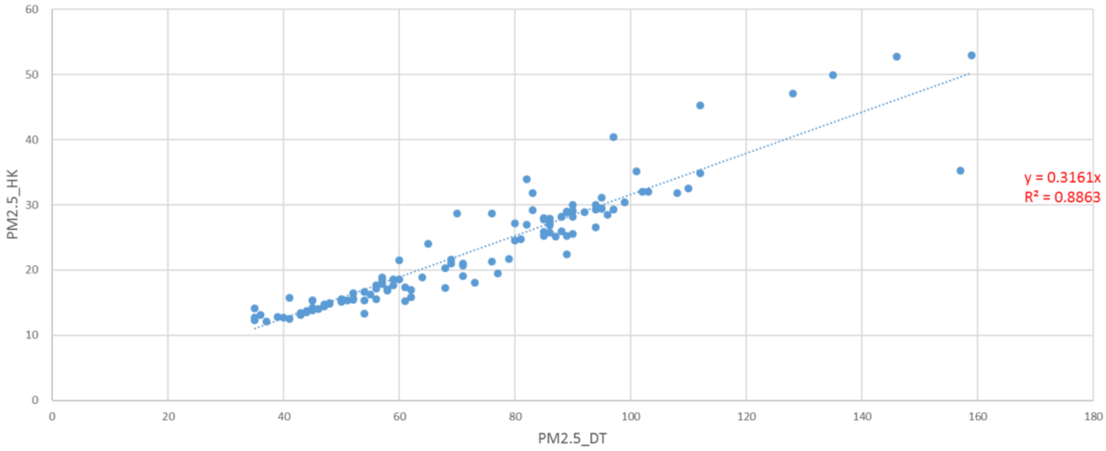
(a)


PM2.5_HK
PM2.5_DT
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
y = 0.287x
R² = 0.7086

(b)


PM2.5_HK
PM2.5_DT
0
10
20
30
40
50
60
0
20
40
60
80
100
120
140
160
180
y = 0.3252x - 0.7465
R² = 0.8871

(c)



(d)

Figure 4.1.2 Data Correction for PM2.5; (a) and (b) were plotted with data obtained when RH higher than 90%, (c) and (d) were plotted with data obtained when RH lower than 90%

From Figure 4.1.1 (a) and (b), were plotted with data obtained when RH higher than 90%, the index of the trend line were 0.277 and 0.287, respectively. From (a), it had the intercept, but the intercept was very small and could be neglected. Moreover, RH in Macau is very high. Therefore, the correction factor for PM2.5 which was measured by DustTrak II Aerosol Monitor 8530 would be 0.29 from (b) rather than the index in (a). And this factor will be used to time the PM2.5 raw data in order to get the refined data.

4.2 BC Data Cleaning

BC data cleaning is an important step before analyzing the data. In order to deal with the occurrence of abnormal BC data, some criteria has been set up based on the monitoring environment. The lower limit of BC concentration is 0.4μg/m³, which was the triple value of standard deviation when measured by AE51 together with a high density polyethylene (HDPE) filter. It is a filter with high density polyethylene, through the filter, the value of BC concentration should be equal to zero but not exactly in this test. From the value that collected by AE51 with HDPE filter, the triple value of standard deviation was used to define as the lower limit. And the upper limit is 21.0 μg/m³, which was the peak value when measured in the bus stop. Because in this project, the measurement value should not be higher than the value when measured in bus stop. Besides, the ratio of BC and PM2.5 should be less than 45%, which is referenced from published paper (Begum *et al.*, 2012). To sum up, they have been listed as the following three points:

(1) Lower limit: 0.4 μg/m³

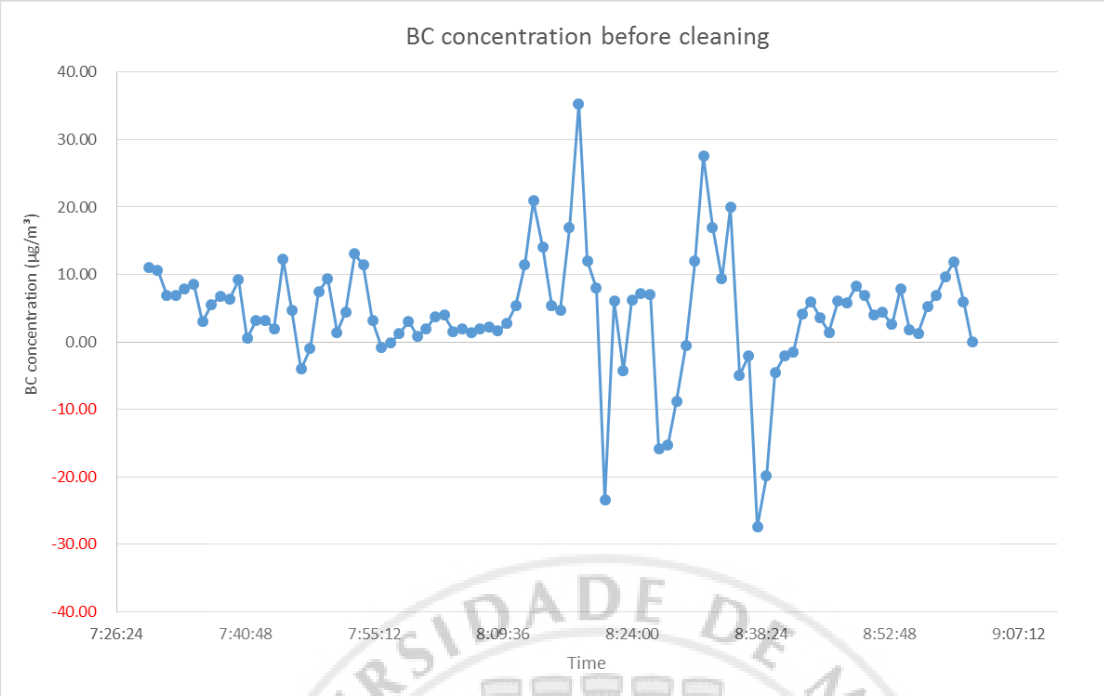
(2) Upper limit: 21.0 μg/m³

(3) BC/PM2.5: ratio less than 45%

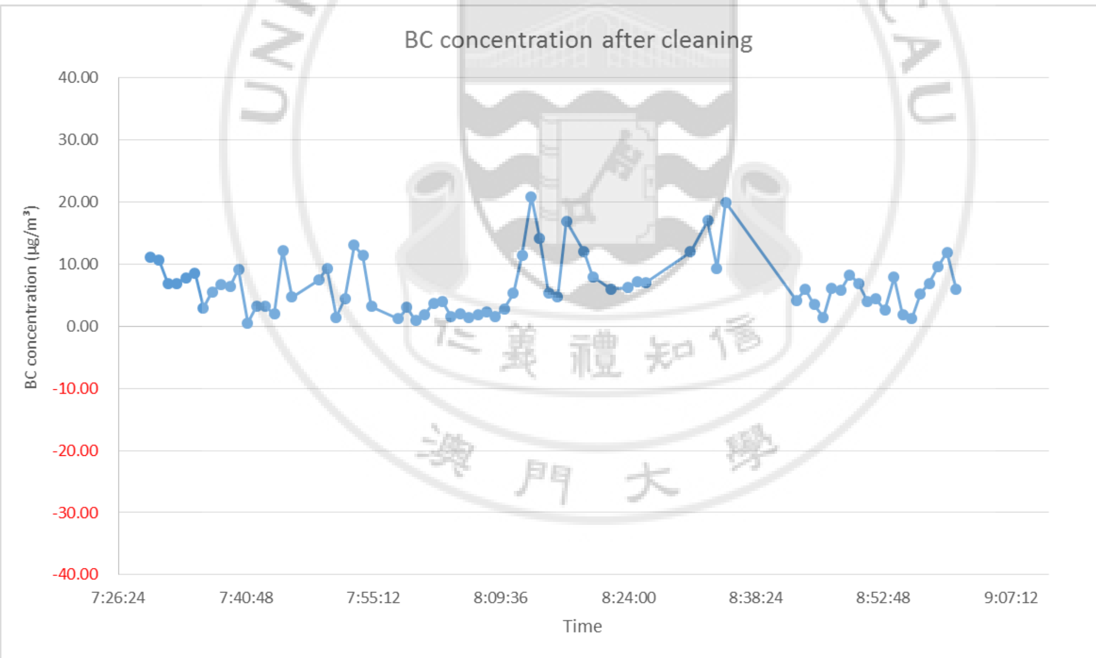
After cleaning the BC data, from the cleaning result in Table 4.2.1, the number of data has reduced by 5.89% which was acceptable at all. The ineffective data will be removed and left as blank. Then the effective data will be used to do the statistics and analysis.

Table 4.2.1 Results of BC data cleaning

	UM	**GP**	**SV**	**BG**
Raw Data Number	1240	1600	1068	3258
Effective Data Number	1060	1573	992	3119
Reduced Number	180	27	76	139
Reduced Percentage	14.52%	1.69%	7.12%	4.27%
Overall Reduced Percentage	5.89%			



(a)



(b)

Figure 4.2.1 BC concentration data comparison (a) before and (b) after cleaning

Figure 4.2.1 (a) and (b) demonstrated the outcome of the previous introduced BC data cleaning method. The figures were plot with the data in the same day and the same period (morning loops of 24 Aug. 2016) in UM. After cleaning, no more negative and over value data appeared in Figure 4.2.1 (b). The overall outcome of this cleaning method was feasible even some amount of the data has been removed, however, the final result was more impressive and reliable in the end.

4.3 Overall Statistical Analysis

After cleaning the BC data and correcting the PM2.5 data with CF, data analysis can be performed. The overall statistics briefing was shown in Table 4.3.1 which demonstrated the minimum, maximum, median and average concentration of BC and PM2.5. Note that "SD" and "CV" refer as standard deviation and coefficient of variance, respectively. Several points of important information were shown in the following:

(1) BC ranged from 0.4 to 19.54 μg/m^3, PM2.5 ranged from 2.9 to 97.44 μg/m^3, BC/PM2.5 ratio ranged from 1.60% to 44.93%.

(2) GP had the least dynamic BC concentration in terms of lowest CV value. SV had the least dynamic PM2.5 concentration in terms of lowest CV value.

(3) The highest BC concentration was monitored in SV, and PM2.5 in UM. Generally speaking, the BC and PM2.5 concentrations monitored in GP were relatively lower than other two measurement sites.

Table 4.3.1 Overall statistics briefing of different measurement sites (Unit for BC and PM2.5: μg/m³)

Statistics	**UM**			**GP**			**SV**			**BG**		
	BC	PM2.5	BC/PM2.5	BC	PM2.5	BC/PM2.5	BC	PM2.5	BC/PM2.5	BC	PM2.5	BC/PM2.5
Min	0.40	2.90	1.80%	0.41	8.70	1.64%	0.41	5.22	1.60%	0.40	2.90	1.87%
Max	13.04	97.44	44.76%	13.84	63.51	43.82%	19.54	58.29	43.18%	7.70	46.11	44.93%
Median	2.48	23.78	11.42%	2.38	19.72	11.50%	2.81	28.13	10.63%	1.68	17.98	10.19%
Average	3.20	27.19	14.36%	2.75	23.69	12.38%	3.47	28.57	12.64%	2.03	19.34	11.80%
SD	2.34	19.75	0.09	1.64	12.79	0.06	2.55	11.91	0.08	1.25	10.21	0.07
CV	0.73	0.73	0.63	0.60	0.54	0.48	0.74	0.42	0.60	0.61	0.53	0.58

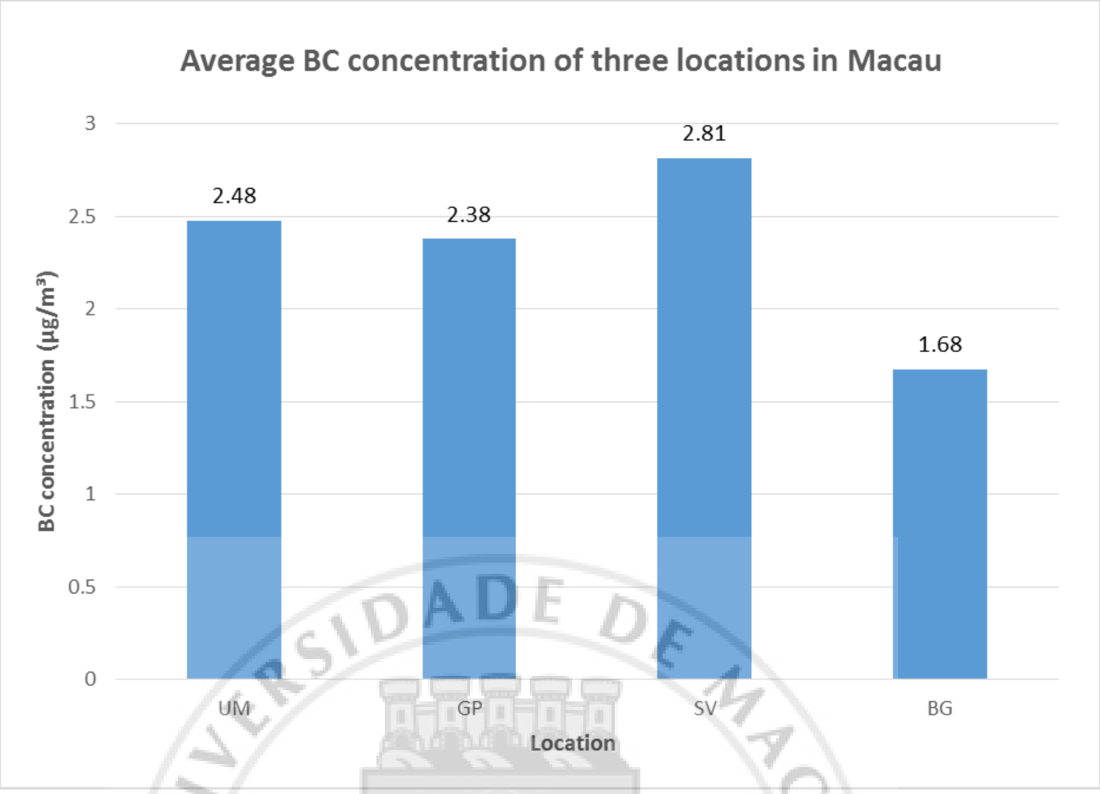


Figure 4.3.1 Average BC concentration of three measurement sites in Macau

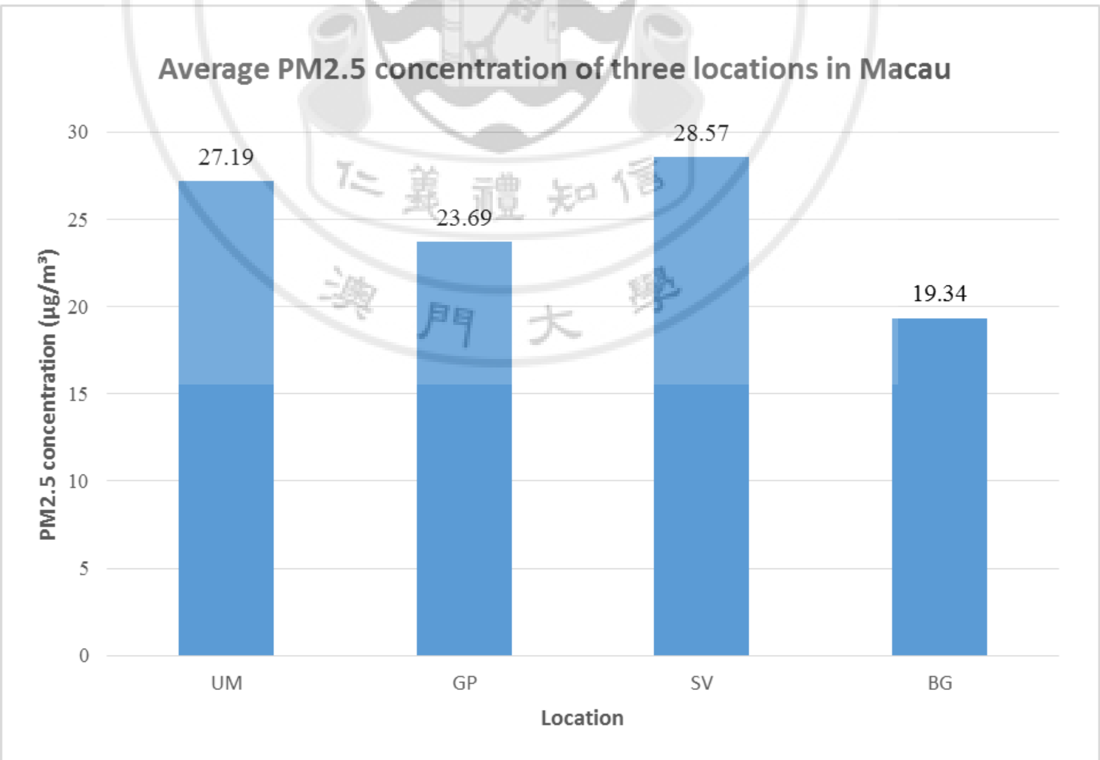


Figure 4.3.2 Average PM2.5 concentration of three measurement sites in Macau

From Figure 4.3.1 and Figure 4.3.2, they demonstrated the average BC and average PM2.5 in different measurement sites in Macau. The result showed both the maximum average BC and PM2.5 were in SV. Besides, both the minimum average BC and PM2.5 were in GP (except BG) and UM was in between. Since the traffic flow around SV was the maximum among these three sites which will lead the concentration of PM2.5 and BC to increase. To further analysis the result, it is because of the geographical location of SV. The northern of SV is a small mountain which will cause the pollutant rest in SV for longer time and hard to diffuse. What's more, there was a construction site located on its eastern side. For the reasons that the concentration of BC and PM2.5 were much higher than other sites and such result make sense.

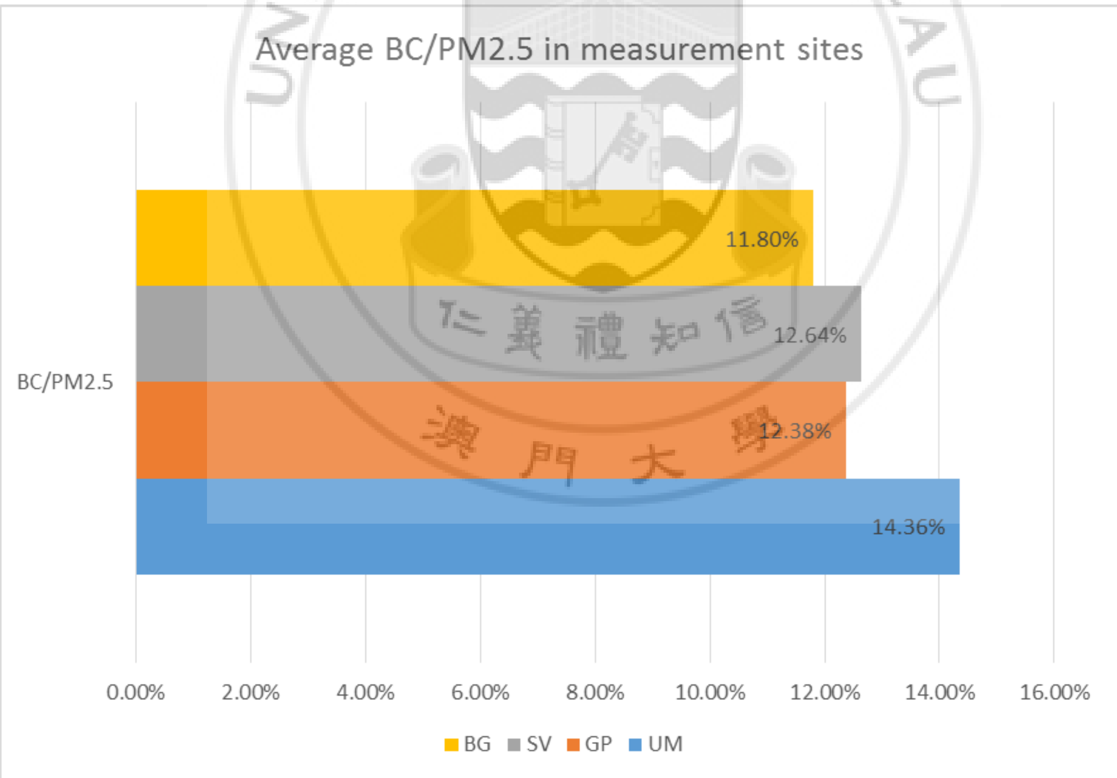


Figure 4.3.3 Average BC/PM2.5 of three measurement sites in Macau

Figure 4.3.3 showed the average BC/PM2.5 of three measurement locations in this project. The result presented UM had the largest BC/PM2.5, even though SV had the highest average BC concentration. Except BG, GP had the smallest BC/PM2.5 but it did not refer GP has largest PM2.5 concentration but the smallest BC concentration. Furthermore, SV did not has the largest BC/PM2.5 even if it had both the largest average BC and PM2.5 concentration. Nevertheless, SV should be considered as a high BC and PM2.5 exposure microenvironments among them which will be discussed in Section 4.6.

To further explain the highest concentration of BC and PM2.5 in SV among the three sites, it was because of high density of traffic flow around SV. Besides, there was a construction site which was a factor of PM2.5 emission source. Afterwards, the small hill and residential buildings located to the north of SV may act like street canyon effect to affect the diffusion or dilution effect of air pollutants. GP located in the center of Macau Peninsula with high density of population and traffic flow but thanks to its high terrain of about 52 meters and surrounded by a lot of trees to block the external pollutants. That is why it had lowest BC and PM2.5 concentration among the three sites.

4.4 Morning and Night Loops Comparison

In order to compare the difference between morning and night condition of the three measurement sites in Macau, Table 4.4.1 showed a statistical comparison result. Generally, it can be concluded that GP was with the lowest BC and PM2.5 concentration both in morning and night loops compared with other two sites even though its PM2.5 was a bit higher in morning. Rather than that, there are some other conclusions showed in the following:

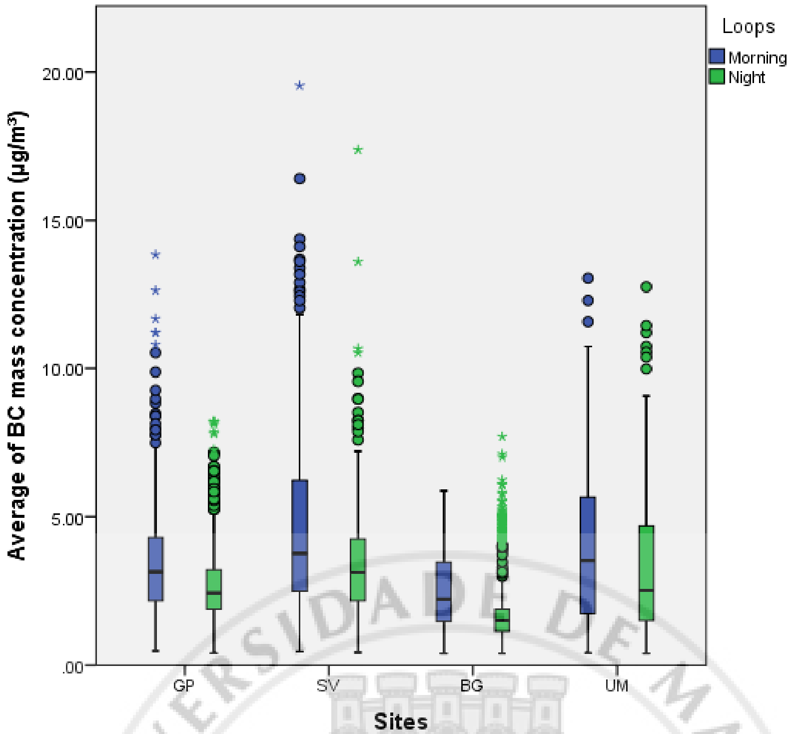
(1) Both BC and PM2.5 had higher concentration in the morning loops than in night loops, but the opposite for PM2.5 of UM.

(2) The variance of BC and PM2.5 seems not to be traceable among different locations nor between morning and night loops

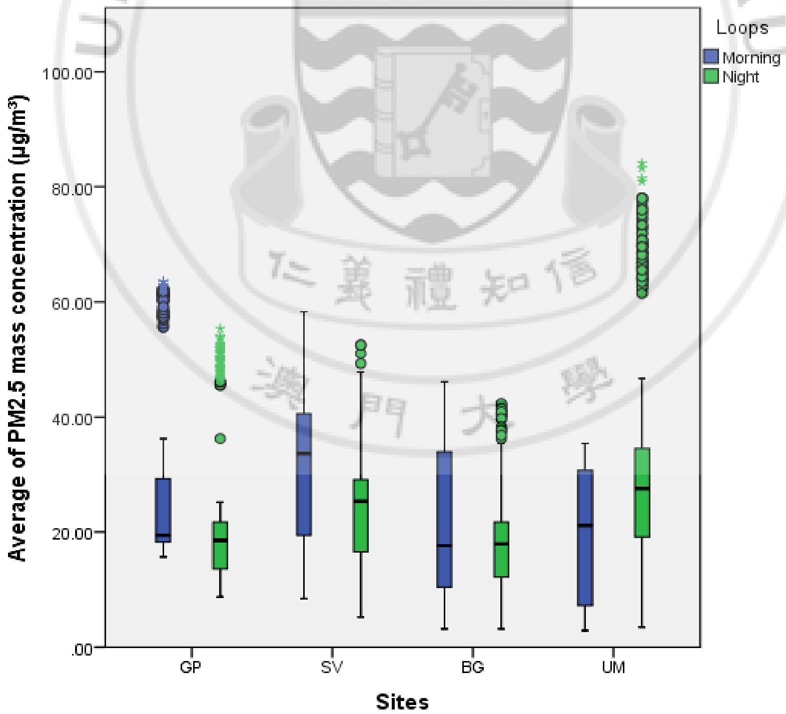
(3) BC/PM2.5 ratio obtained in the BG was much less dynamic than during roadside measurements in terms of the ratio range. The ratio was relatively stable between morning and night loops in terms of the average value, however, the results of UM measurements obviously depicted a lower ratio during night loops than in the morning. It could be attributed to the dynamic change of traffic flow in the campus.

Table 4.4.1 Statistics between morning and night loops (Unit for BC and PM2.5: μg/m³)

Location		Min		Max		Average		SD		CV	
		Morning	**Night**	**Morning**	**Night**	**Morning**	**Night**	**Morning**	**Night**	**Morning**	**Night**
UM	BC	0.42	0.40	13.04	12.75	3.91	3.26	2.59	0.06	0.66	0.02
	PM2.5	2.90	3.48	35.38	84.10	19.50	31.54	10.89	21.41	0.56	0.68
	BC/PM2.5	1.86%	2.01%	44.76%	43.82%	22.32%	11.87%	0.10	0.06	0.45	0.51
GP	BC	0.48	0.41	13.84	8.22	3.51	2.81	1.91	1.43	0.54	0.51
	PM2.5	15.66	8.70	63.51	55.39	26.02	20.86	14.00	11.57	0.54	0.55
	BC/PM2.5	2.49%	1.64%	43.82%	40.20%	14.58%	14.40%	0.07	0.05	0.47	0.34
SV	BC	0.46	0.43	19.54	17.38	4.82	3.47	3.33	1.99	0.69	0.57
	PM2.5	8.41	5.22	58.29	52.49	31.84	24.07	12.96	9.25	0.41	0.38
	BC/PM2.5	1.60%	1.71%	43.18%	42.66%	15.40%	15.45%	0.08	0.08	0.55	0.49
BG	BC	0.40	0.40	5.88	7.70	2.44	1.73	1.27	1.10	0.52	0.64
	PM2.5	3.19	3.19	46.11	42.34	21.29	17.38	11.93	7.65	0.56	0.44
	BC/PM2.5	3.04%	1.87%	36.79%	42.21%	12.36%	11.84%	0.04	0.09	0.31	0.74



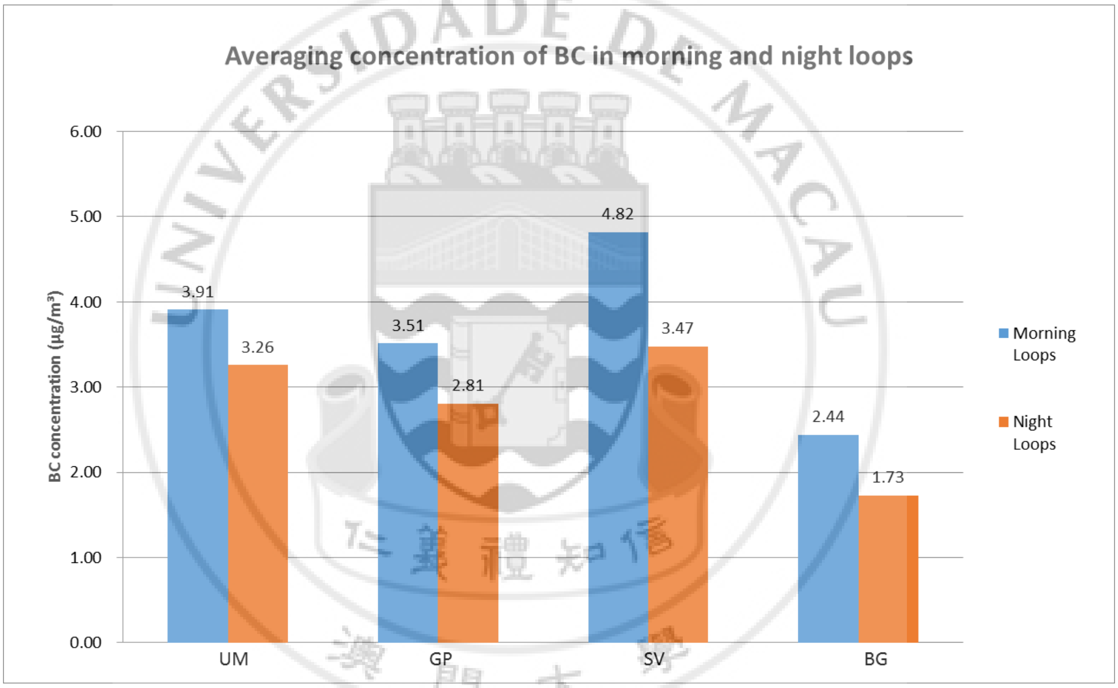
(a)



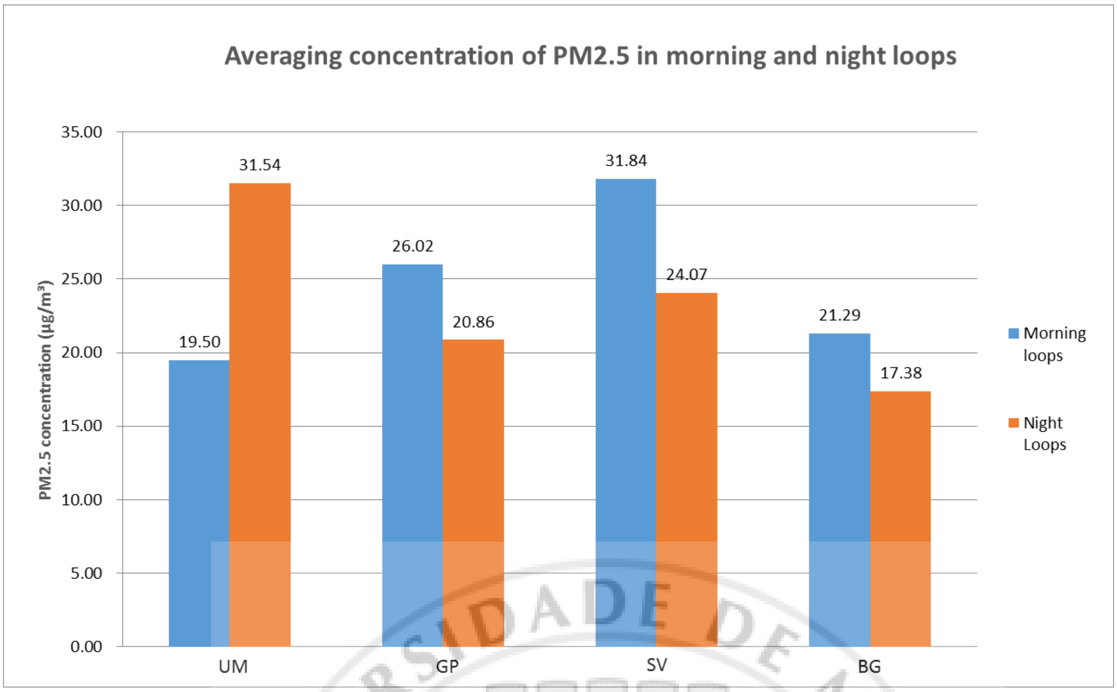
(b)

Figure 4.4.1 Box-Whisker plots for comparison of averaging concentration of (a) BC and (b) PM2.5 measured in different sites in morning and night loops measurements.

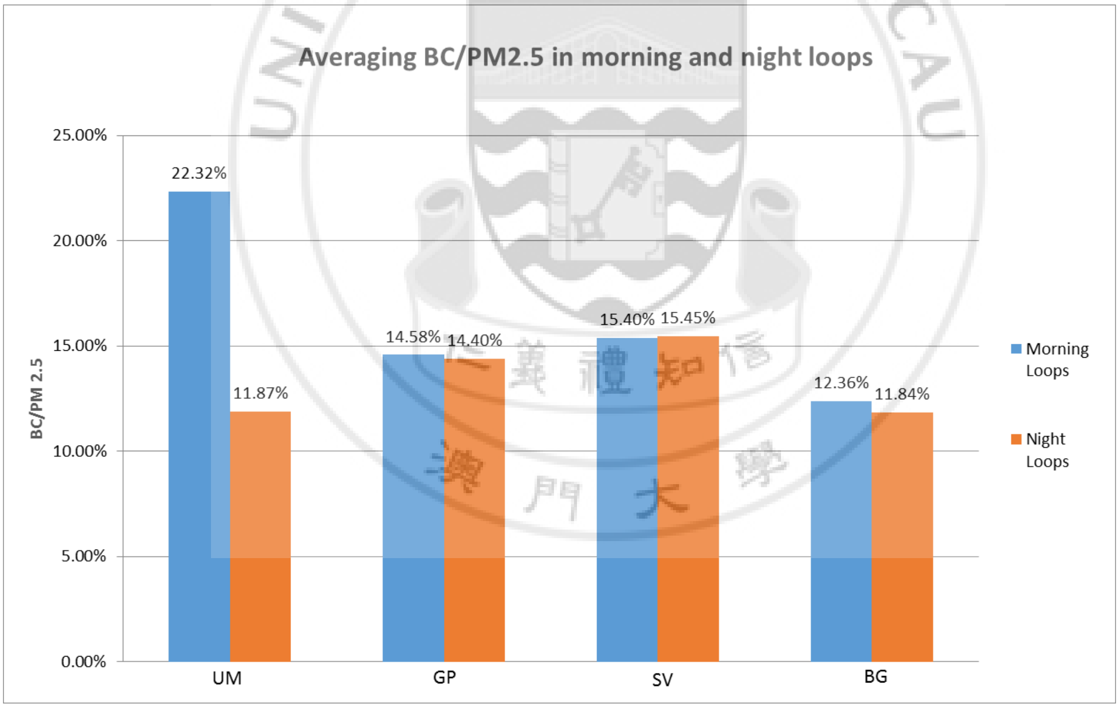
In Figure 4.4.1 (a) and (b), the box showed the interquartile range, the line in the box showed the median. The whiskers represent the upper 25% (Q3) and lower 25% (Q1) (excluding outliers). The "○" and "*" symbol represents mild outliers and extreme outliers, respectively. The result showed the median BC and PM2.5 concentration in the morning loops were always higher than at night, except the PM2.5 of UM. In (a), the variations of BC and PM2.5 in GP were the smallest than any others. At the same time GP had the smallest median concentration of BC and PM2.5.



(a)



(b)



(c)

Figure 4.4.2 Comparison of average concentration of (a) BC, (b) PM2.5 and (c) BC/PM2.5 in morning and night loops

Figure 4.4.2 (a), (b) and (c) showed the overall average concentration of BC, PM2.5 and BC/PM2.5 between morning and night loops. The result presented that it always had higher average BC and PM2.5 concentration in the morning loops than in the night loops except the PM2.5 of UM. The high concentration of PM2.5 in the night loops of UM was a bit abnormal but could be explained by the fireworks burning show from Zhuhai Chimelong Ocean Kingdom at 20:30 every evening. The fireworks can generate a large amount of pollutants. According to Table 3.1.1 in Chapter 3, the schedule of regular measurements for UM was starting from 21:32 which was one hour after the beginning of fireworks show. It is supposed that the diffusion of PM2.5 took some time to UM and led to this result.

4.5 Geographic Information Plots and Variance on Locations

In order to further investigate the spatial BC and PM2.5 concentration difference in the same route, geographic information plots have been plotted and shown in the following Figure 4.5.1 to 4.5.6. They were plot by the average concentration of BC and PM2.5 data together with GPS data. The statistical summary was shown in Table 4.5.1.

Table 4.5.1 Statistics among different locations (Unit for BC and PM2.5: μg/m³)

Location	Direction	BC_Avg		PM2.5_Avg		BC/PM2.5_Avg	
		Morning	Night	Morning	Night	Morning	Night
UM	A	4.4	3.4	20.1	33.6	24.06%	12.42%
	B	4.6	3.7	23.2	31.8	23.10%	12.82%
	C	3.4	3.1	18.4	30.5	20.26%	11.19%
	D	3.4	2.8	17.5	29.2	21.76%	10.87%
	BG	1.6	2.9	16.2	43.1	10.76%	6.99%
GP	A	3.1	2.6	25.7	21.1	13.21%	12.78%
	B	4.0	2.9	26.0	20.6	16.54%	15.07%
	C	2.9	3.4	27.2	21.2	11.42%	16.75%
	BG	2.0	1.8	26.2	22.5	7.33%	8.21%
SV	A	4.4	3.2	31.3	22.7	14.68%	15.06%
	B	4.9	3.6	31.7	25.2	15.01%	15.33%
	C	5.8	3.9	33.3	25.0	17.76%	16.55%
	BG	2.6	2.0	34.2	25.4	7.22%	7.98%

From the geographic information plots and Table 4.5.1, it was much easier to find out the high and low concentration points in each location. There were some conclusion after analyzing:

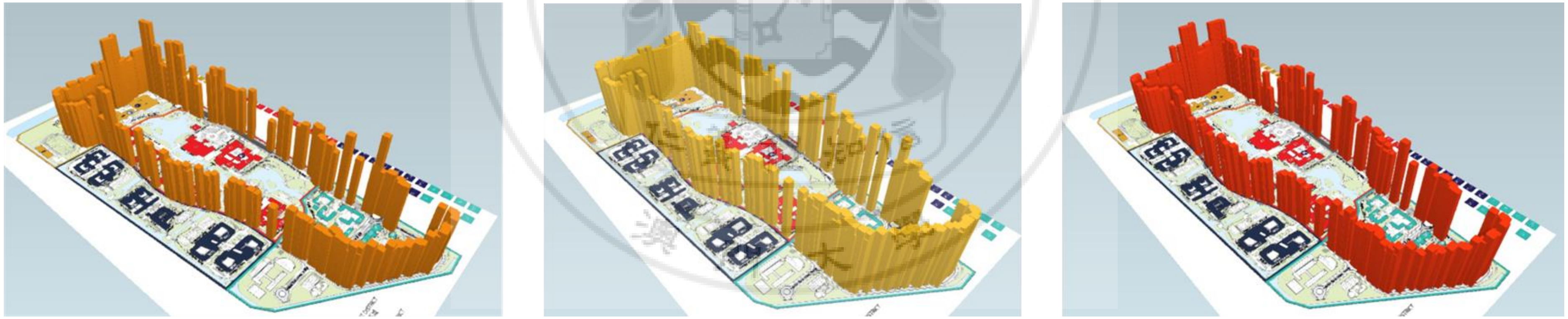
(1) In Figure 4.5.1 and 4.5.2 of UM, point C was close to the main road side, in general, the BC or PM2.5 concentration should be higher along this point. However, point A reflected the maximum concentration relatively. It could be explained by a bus terminal located on point A. For point B, the concentration was relatively high, it was because there were some engineering project along the roadside from time to time. Point D was the lowest concentration because around point D there was residential area. Moreover, a small mountain with lots of trees was at its back

(2) Along the route of GP, even though point B had a bit higher BC concentration, but overall its variance in the geographic information plots was smaller than other two sites.

(3) Figure 4.5.5 and 4.5.6 demonstrated both BC and PM2.5 at point C were the highest in SV. Because there was a construction site together with high traffic flow. During the monitoring, a strong smell of dusk could be smell out when passed by point C. Along the route of SV, it almost had high concentration of BC and PM 2.5 due to its high traffic flow. And its variance in the geographic information plots was very high by compared with UM and GP which could attribute to the change of traffic volume.

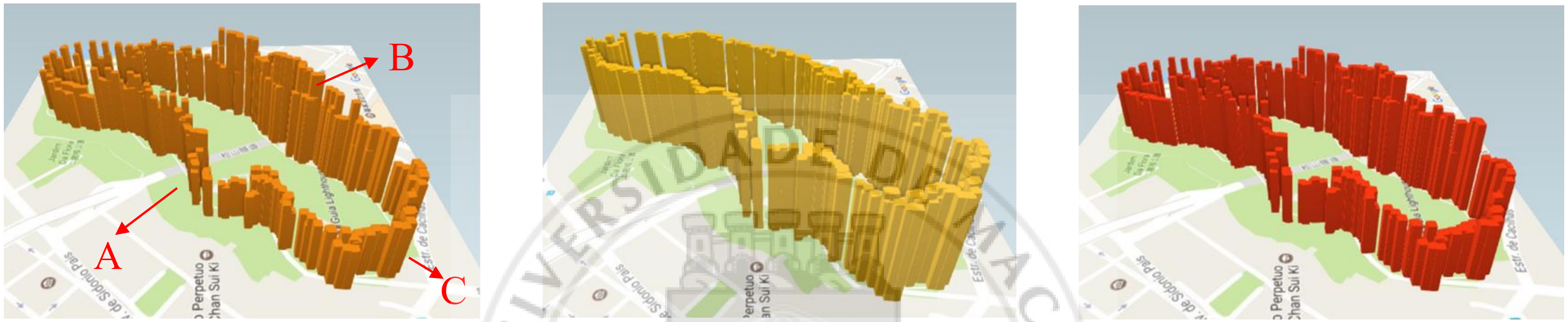
(a) (b) (c)

Figure 4.5.1 Morning loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in UM



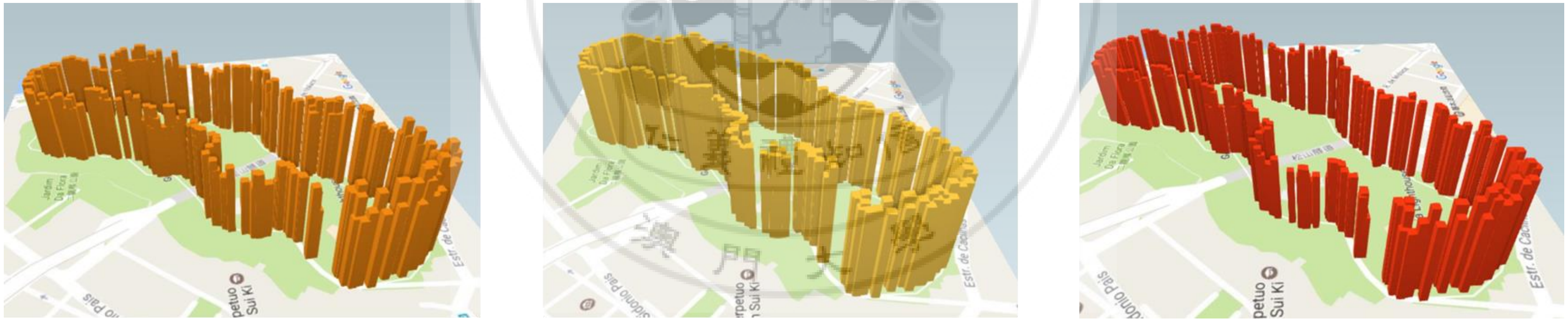
(a) (b) (c)

Figure 4.5.2 Night loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in UM



(a) (b) (c)

Figure 4.5.3 Morning loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in GP



(a) (b) (c)

Figure 4.5.4 Night loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in GP

(a) (b) (c)

Figure 4.5.5 Morning loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in SV

(a) (b) (c)

Figure 4.5.6 Night loops measurements of (a) BC and (b) PM2.5 mass concentrations, and (c) BC/PM2.5 ratio in SV

4.6 Exposure to BC and PM2.5 Comparison

The personal exposure to BC and PM2.5 between the results from this project and the referenced data from other paper studies were shown in Table 4.6.1 and Table 4.6.2. The individual inhalation rates were using by data in Table 2.1. Basically, the activity modes were supposed to be jogging with speed of 4.5 mph, inhalation rates were 2.23, 2.87 and 3.44 m^3/h for children, adult females and adult males, respectively. But in New York City aboveground and underground subway stations, assumed the activity mode was standing and inhalation rates were 0.93, 0.50 and 0.64 m^3/h for children, adult females and adult males, respectively. Inhalation dose could be calculated by using Equation 2.2 from Chapter 2 by assuming under 1 hour exposure for all cases.

Table 4.6.1 BC exposure and dose inhalation comparison (Unit for Et: µg/m³, D: µg)

Location	Et_BC	D_Children	D_Adult Females	D_Adult Males	Reference
Shanghai_ Outdoors	5.70	12.71	16.36	19.61	Lei *et al.*, 2016
Shanghai_ Transportation	7.60	16.95	21.81	26.14	Lei *et al.*, 2016
Mumbai_Ambient	6.40	14.27	18.37	22.02	Sandeep *et al.*, 2013
Brisbane_Outdoor	1.07	2.39	3.08	3.69	Williams and Knibbs, 2016
New York City_ aboveground stations	2.80	1.43	1.40	1.79	Vilcassim *et al.*, 2014
New York City_ underground subway stations	14.00	7.14	7.00	8.96	Vilcassim *et al.*, 2014
Macau_UM	3.20	7.14	9.18	11.01	This study
Macau_GP	2.75	6.13	7.89	9.46	This study
Macau_SV	3.47	7.74	9.96	11.94	This study
Macau_BG	2.03	4.46	5.74	6.88	This study

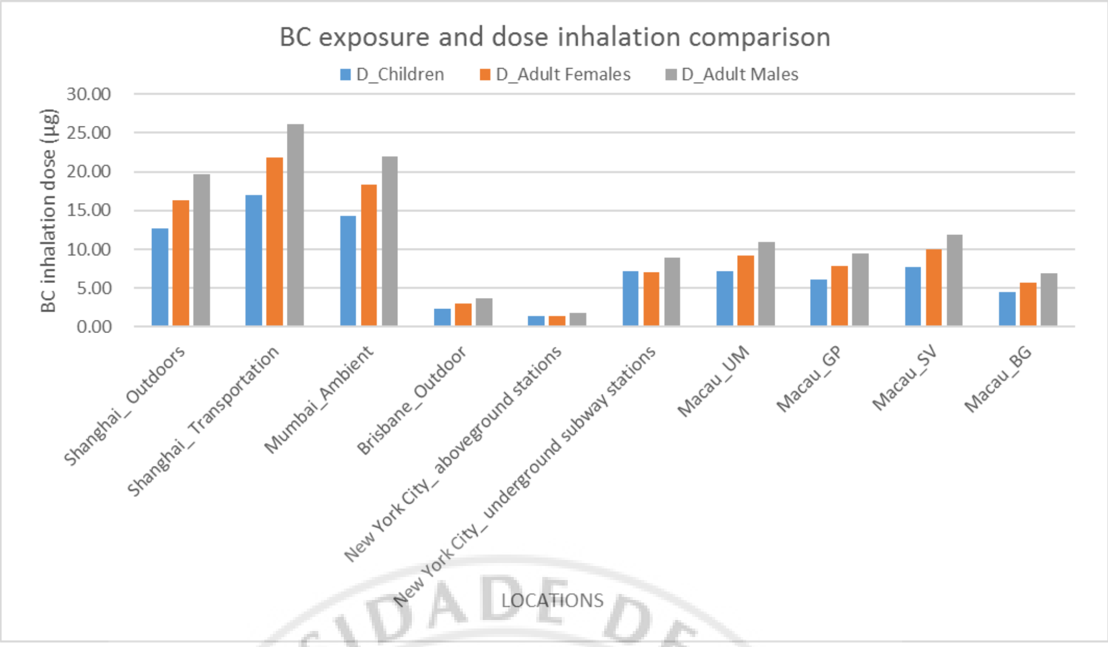


Figure 4.6.1 BC exposure and dose inhalation comparison

Figure 4.6.1 and Table 4.6.1 presented 1 hour dose inhalation with regard to BC exposure in different locations. The average BC concentration in various microenvironments were ranged from 1.07 µg/m³ of Brisbane_Outdoor to 14.00 µg/m³ of New York City_ underground subway stations. Levels of BC exposure was highest in Shanghai_Transportation, with a maximum of 16.95, 21.81 and 26.14 µg for children, adult females and adult males, respectively. New York City_ aboveground stations was with the lowest BC exposure with 1.43, 1.40 and 1.79 µg for children, adult females and adult males, respectively. For three locations of Macau, SV had highest BC exposure with 7.74, 9.96 and 11.94 µg for children, adult females and adult males, respectively. Exposure to BC in GP was the lowest with 6.13, 7.89 and 9.46 µg for children, adult females and adult males, respectively. By comparison, BC exposure in Macau's microenvironments were much lower than those in Shanghai and Mumbai but higher than those in Brisban and New York City. Among the three microenvironments in Macau, SV was presented as a high BC and PM2.5 exposure microenvironments. BC exposure condition in Macau was not good on the basis of the above result and analysis.

Table 4.6.2 PM2.5 exposure and dose inhalation comparison (Unit for Et: µg/m³, D: µg)

Location	Et_PM2.5	D_Children	D_Adult Females	D_Adult Males	Reference
Shanghai_ Outdoor	144.00	321.12	413.28	495.36	Lei *et al.*, 2016
Shanghai_ Transportation	124.00	276.52	355.88	426.56	Lei *et al.*, 2016
Mumbai_Ambient	45.40	101.24	130.30	156.18	Sandeep *et al.*, 2013
New York City_ aboveground stations	12.20	6.22	6.10	7.81	Vilcassim *et al.*, 2014
New York City_ underground subway stations	93.30	47.58	46.65	59.71	Vilcassim *et al.*, 2014
Macau_UM	27.19	60.63	78.04	93.53	This study
Macau_GP	23.69	52.83	67.99	81.49	This study
Macau_SV	28.57	63.71	82.00	98.28	This study
Macau_BG	19.34	43.04	55.39	66.39	This study

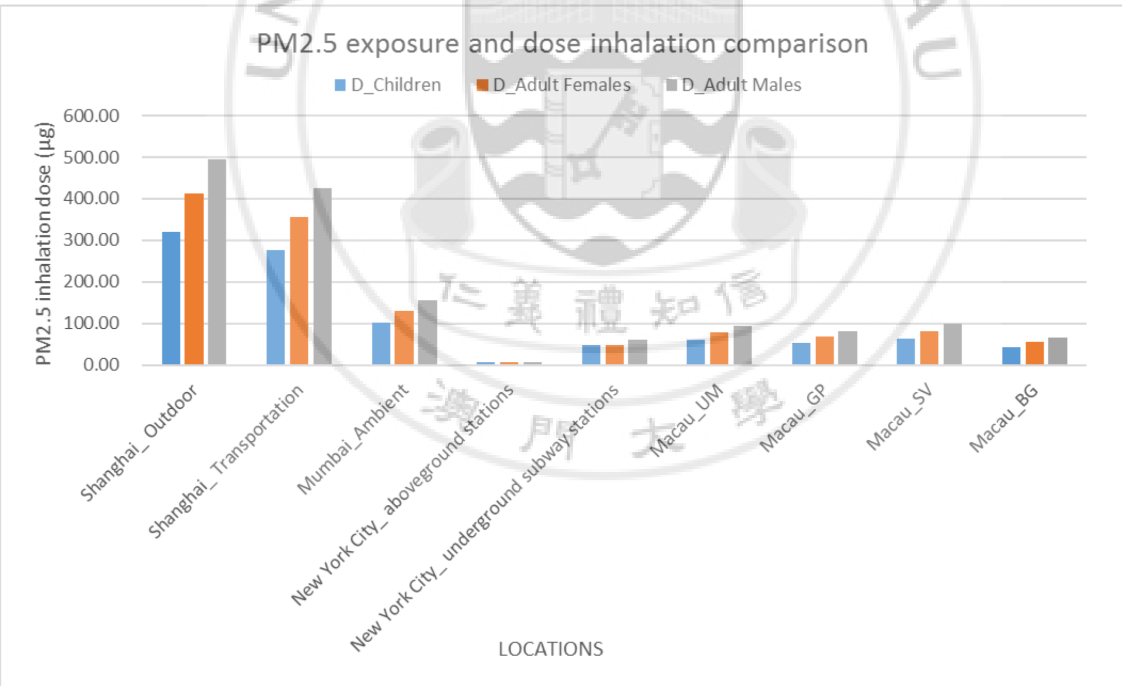


Figure 4.6.2 PM 2.5 exposure and dose inhalation comparison

From the above Table 4.6.2 and Table 4.6.2, the average PM2.5 concentration in various microenvironments were ranged from 12.20 µg/m³ of New York City_ aboveground stations to 144.00 μg/m³ of Shanghai_ Outdoor. Under 1 hour exposure, SV was presented as a high PM2.5 exposure microenvironments among the three locations in Macau with 63.71, 82.00 and 98.28 μg for children, adult females and adult males, respectively. Exposure to PM2.5 in GP was the lowest with 52.83, 67.99 and 81.49 μg for children, adult females and adult males, respectively. By compared with other cities, the results showed that the outdoor exposure of PM2.5 in Macau were much lower than that of other cities except New York City. Levels of PM2.5 exposure was highest in Shanghai_Outdoor with a maximum of 321.12, 413.28 and 495.36 μg for children, adult females and adult males, respectively. The condition of exposure to PM2.5 in Macau was not bad according to the above result though only represented three monitoring places.

4.7 Study Limitation

The study was conducted in a limited number of days. Data for black carbon and PM2.5 measurements can only be made daily during peak hours and off-peak hours (morning and evening), the amount of data was very limited and easier to result in error. In addition, the data collection duration was from August 2016 to November 2016, which was a very long time. Besides, the factors influencing the data in the survey of this project have not yet been fully considered, including trajectory analysis and meteorological analysis. Nevertheless, these sampling result can be correctly reflected the real-world BC and PM2.5 exposure status in Macau.

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

BC and PM2.5 mass concentration levels and individual exposure have been studied in three different locations in Macau including University of Macau (UM), Guia Park (GP) and Sai Van Lake (SV) in this project. BC ranged from 0.4 to 19.54 μg/m³, PM2.5 ranged from 2.9 to 97.44 μg/m³, and BC/PM2.5 ratio ranged from 1.60% to 44.93%. For the concentration variance, in terms of low CV value, GP was with the least dynamic BC concentration, while SV was monitored with the least dynamic PM2.5 concentration. The highest BC concentration was measured in SV, and PM2.5 in UM. In conclusion, the BC and PM2.5 concentrations in GP were measured to be relatively lower than the other two sites. It may be attributed to its height of about 52 meters. The high concentration in SV should be related to its high traffic flow surrounds it.

With regard to BC exposure, for three locations of Macau under 1 hour exposure through jogging, SV had considerably higher BC exposure level with 7.74, 9.96 and 11.94 μg for children, adult females and adult males, respectively. Exposure to BC in GP was the lowest with 6.13, 7.89 and 9.46 μg for children, adult females and adult males, respectively. For exposure to PM2.5, SV was presented as the highest PM2.5 exposure microenvironments among the three locations in Macau with 63.71, 82.00 and 98.28 μg for children, adult females and adult males, respectively. Exposure to PM2.5 in GP was the lowest with 52.83, 67.99 and 81.49 μg for children, adult females and adult males, respectively. In another word, SV behaved as a high BC and PM2.5 exposure microenvironments among the three locations in Macau. By compared with other cities, the exposure condition in Macau was neither very bad nor very good.

5.2 Recommendation

From the result of this project, the exposure in SV was the highest. Publicity who has habit to do jogging in SV should has more concern. GP is a good place for leisure and entertainment. In a day, evening is much more suitable for jogging in the open air because of lower exposure to BC and PM2.5. More broadly, findings in this project might be useful in drafting policies aiming at arranging sport activities in other locations and reducing health impact of air pollution in Macau. Last but not the least, controlling air pollution is a very tough and long-term task, it requires everybody's responsibility and effort.

REFERENCES

Adams, W. C. (1993) *Measurement of breathing rate and volume in routinely performed daily activities : final report, contract no. A033-205 /*. Sacramento, Calif. : The Division,. Available at:
https://searchworks.stanford.edu/view/2804386 (Accessed: 14 April 2017).

Amaral, S., de Carvalho, J., Costa, M. and Pinheiro, C. (2015) 'An Overview of Particulate Matter Measurement Instruments', *Atmosphere*, 6(9), pp. 1327–1345. doi: 10.3390/atmos6091327.

Begum, B. A., Hossain, A., Nahar, N., Markwitz, A. and Hopke, P. K. (2012) 'Organic and Black Carbon in PM 2.5 at an Urban Site at Dhaka, Bangladesh', *Aerosol and Air Quality Research*, 12, pp. 1062–1072. doi: 10.4209/aaqr.2012.05.0138.

Cheng, Y., Lee, S. C., Ho, K. F., Wang, Y. Q., Cao, J. J., Chow, J. C. and Watson, J. G. (2006) 'Black carbon measurement in a coastal area of south China', *Journal of Geophysical Research*, 111(D12), p. D12310. doi: 10.1029/2005JD006663.

DSEC (Macau Statistics and Census Service), 2016. Statistics of General, Transport and Communications Statistics, Available from:
http://www.dsec.gov.mo/default.aspx?lang=en-US&noredirect=true
(Accessed: January 14, 2017)

IOP Publishing 2009, “How important is black carbon for public health and climate?”, Available from: http://environmentalresearchweb.org/cws/article/opinion/66802 (Accessed: January 7, 2017)

Karanasiou, A., Minguillón, M. C., Viana, M., Alastuey, A., Putaud, J.-P., Maenhaut, W., Panteliadis, P., Močnik, G., Favez, O. and Kuhlbusch, T. A. J. (2015) ‘Measurement of elemental carbon (EC) and organic carbon (OC) Thermal-optical analysis for the measurement of elemental carbon (EC) and organic carbon (OC) in ambient air a literature review Measurement of elemental carbon (EC) and organic carbon (OC) Measurement of elemental carbon (EC) and organic carbon (OC)’, *AMTD Atmos. Meas. Tech. Discuss*, 8(8), pp. 9649–9712. doi: 10.5194/amtd-8-9649-2015.

Kaur, S., Nieuwenhuijsen, M. J. and Colvile, R. N. (2007) ‘Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments’, *Atmospheric Environment*, 41(23), pp. 4781–4810. doi: 10.1016/j.atmosenv.2007.02.002.

Kirchstetter, T. W. and Novakov, T. (2007) ‘Controlled generation of black carbon particles from a diffusion flame and applications in evaluating black carbon measurement methods’, *Atmospheric Environment*, 41(9), pp. 1874–1888. doi: 10.1016/j.atmosenv.2006.10.067.

Lei, X., Xiu, G., Li, B., Zhang, K. and Zhao, M. (2016) 'Individual exposure of graduate students to PM2.5 and black carbon in Shanghai, China', *Environmental Science and Pollution Research*, 23(12), pp. 12120–12127. doi: 10.1007/s11356-016-6422-x.

Li, B., Lei, X. ning, Xiu, G. li, Gao, C. yuan, Gao, S. and Qian, N. sheng (2015) 'Personal exposure to black carbon during commuting in peak and off-peak hours in Shanghai', *Science of the Total Environment*, 524–525, pp. 237–245. doi: 10.1016/j.scitotenv.2015.03.088.

Mok, K. M. and Hoi, K. I. (2005) 'Effects of meteorological conditions on PM10 concentrations - A study in Macau', *Environmental Monitoring and Assessment*. Kluwer Academic Publishers, 102(1–3), pp. 201–223. doi: 10.1007/s10661-005-6022-6.

Ni, M., Huang, J., Lu, S., Li, X., Yan, J. and Cen, K. (2014) 'A review on black carbon emissions, worldwide and in China', *Chemosphere*, 107, pp. 83–93. doi: 10.1016/j.chemosphere.2014.02.052.

Nyhan, M., Grauwin, S., Britter, R., Misstear, B., McNabola, A., Laden, F., Barrett, S. R. H. and Ratti, C. (2016) '"Exposure Track" - The Impact of Mobile Device Based Mobility Patterns on Quantifying Population Exposure to Air Pollution', *Environmental Science & Technology*, p. acs.est.6b02385. doi: 10.1021/acs.est.6b02385.

Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K. and Thurston, G. D. (2002) 'Lung Cancer, Cardiopulmonary Mortality, and Long-term

Exposure to Fine Particulate Air Pollution', *JAMA*. American Medical Association, 287(9), p. 1132. doi: 10.1001/jama.287.9.1132.

Research Note: # 94-11 How Much Air Do We Breathe? (no date). Available at: https://www.arb.ca.gov/research/resnotes/notes/94-11.htm (Accessed: 14 April 2017).

Sandeep, P., Saradhi, I. V and Pandit, G. G. (2013) 'Seasonal variation of black carbon in fine particulate matter (PM2.5) at the tropical coastal city of Mumbai, India.', *Bulletin of environmental contamination and toxicology*, 91(5), pp. 605–10. doi: 10.1007/s00128-013-1108-2.

Song, S., Wu, Y., Zheng, X., Wang, Z., Yang, L., Li, J. and Hao, J. (2014) 'Chemical characterization of roadside PM2.5 and black carbon in Macao during a summer campaign', *Atmospheric Pollution Research*, 5(3), pp. 381–387. doi: 10.5094/APR.2014.044.

TSI 2017, Available from:
http://www.tsi.com/dusttrak-ii-aerosol-monitor-8530/ (Accessed: February 26 2017)

US EPA, O. (2017) 'Particulate Matter (PM) Pollution'. Available at:
https://www.epa.gov/pm-pollution (Accessed: 16 April 2017).

Vilcassim, M. J. R., Thurston, G. D., Peltier, R. E. and Gordon, T. (2014) 'Black Carbon and Particulate Matter (PM 2.5) Concentrations in New York City's Subway Stations', *Environmental Science & Technology*, 48(24), pp. 14738–14745. doi: 10.1021/es504295h.

Wang, Y., Xing, Z., Zhao, S., Zheng, M., Mu, C. and Du, K. (2016) 'Are emissions of black carbon from gasoline vehicles overestimated? Real-time, in situ measurement of black carbon emission factors', *Science of the Total Environment*, 547, pp. 422–428. doi: 10.1016/j.scitotenv.2015.12.115.

Wang Z.S., Wu T., Duan X.L., Wang S., Zhang W.J., Wu X.F., Yu Y.J., 2009, Research on inhalation rate exposure factors of Chinese residents in environmental health risk assessment. Res Environ Sci 22:1171–1175 (in Chinese)

Wang, Z., Wu, Y., Zhou, Y., Li, Z., Wang, Y., Zhang, S. and Hao, J. (2014) 'Real-world emissions of gasoline passenger cars in Macao and their correlation with driving conditions', *International Journal of Environmental Science and Technology*. Springer Berlin Heidelberg, 11(4), pp. 1135–1146. doi: 10.1007/s13762-013-0276-2.

Wikipedia 2017, Macau,
Available from:
https://en.wikipedia.org/wiki/Macau (Accessed: January 6, 2017)

Williams, R. D. and Knibbs, L. D. (2016) 'Daily personal exposure to black carbon: A pilot study', *Atmospheric Environment*. Elsevier Ltd, 132, pp. 296–299. doi: 10.1016/j.atmosenv.2016.03.023.

World Health Organization (2016) ‘Ambient Air Pollution: A global assessment of exposure and burden of disease’, *World Health Organization*, pp. 1–131. doi: 9789241511353.

WHO Library Cataloguing-in-Publication Data, 2016, Ambient air pollution: A global assessment of exposure and burden of disease, ISBN 9789241511353

Xing, Y.-F., Xu, Y.-H., Shi, M.-H. and Lian, Y.-X. (2016) ‘The impact of PM2.5 on the human respiratory system.’, *Journal of thoracic disease*. AME Publications, 8(1), pp. E69-74. doi: 10.3978/j.issn.2072-1439.2016.01.19.

Zhao, P., Zhang, X., Xu, X. and Zhao, X. (2011) ‘Long-term visibility trends and characteristics in the region of Beijing, Tianjin, and Hebei, China’, *Atmospheric Research*, 101(3), pp. 711–718. doi: 10.1016/j.atmosres.2011.04.019.

APPENDIX A

SUMMARY TABLE 1. Mean Minute Ventilation (V_E, L/min) by Group and Activity for Laboratory Protocols.

ACTIVITY		Young Children	Children	Adult Females	Adult Males
Lying		6.19	7.51	7.12	8.93
Sitting		6.48	7.28	7.72	9.30
Standing		6.76	8.49	8.36	10.65
Walking:	1.5 mph	10.25	DNP	DNP	DNP
	1.875 mph	10.53	DNP	DNP	DNP
	2.0 mph	DNP	14.13	DNP	DNP
	2.25 mph	11.68	DNP	DNP	DNP
	2.5 mph	DNP	15.58	20.32	24.13
	3.0 mph	DNP	17.79	24.20	DNP
	3.3 mph	DNP	DNP	DNP	27.90
	4.0 mph	DNP	DNP	DNP	36.53
Running:	3.5 mph	DNP	26.77	DNP	DNP
	4.0 mph	DNP	31.35	46.03*	DNP
	4.5 mph	DNP	37.22	47.86*	57.30
	5.0 mph	DNP	DNP	50.78*	58.45
	6.0 mph	DNP	DNP	DNP	65.66*

Young Children, male and female 3-5.9 yr olds; Children, male and female 6-12.9 yr olds; Adult Females, adolescent, young to middle-aged and older adult females; Adult Males, adolescent, young to middle-aged and older adult males; DNP, group did not perform this protocol or N was too small for appropriate mean comparisons; *, older adults not included in the mean value since they did not perform running protocol at particular speeds.

SUMMARY TABLE 2. Mean Minute Ventilation (V_E, L/min) by Group and Activity for Field Protocols

ACTIVITY	Young Children	Children	Adult Females	Adult Males
Play	11.31	17.89	DNP	DNP
Car Driving	DNP	DNP	8.95	10.79
Car Riding	DNP	DNP	8.19	9.83
Yardwork	DNP	DNP	19.23+	26.07[a]/31.89[b]
Housework	DNP	DNP	17.38	DNP
Car Maintenance	DNP	DNP	DNP	23.21*
Mowing	DNP	DNP	DNP	36.55+
Woodworking	DNP	DNP	DNP	24.42+

Young Children, male and female 3-5.9 yr olds; Children, male and female 6-12.9 yr olds; Adult Females, adolescent, young to middle-aged and older adult females; Adult Males, adolescent, young to middle-aged and older adult males; DNP, group did not perform this protocol or N was too small for appropriate mean comparisons; *, older adults not included in mean value since they did not perform this activity; +, adolescents not included in mean value since they did not perform this activity; a, mean value for young to middle-aged adults only; b, mean value for older adults only.