The effects of Platform Screen Doors on air quality in underground subway platforms and train cabins

An empirical study conducted in Hong Kong's underground MTR platforms and trains using portable aerosol monitors

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1. Introduction

Underground rapid transit system has become an essential element of urban citizens' daily lives since the world's first underground mass transportation system started operations in London in 1863. After 153 years of expansion, there are more than 150 subway systems in the world in the year of 2016, servicing commuters in New York, Beijing, Tokyo, Barcelona, Seoul and other major cities in the world (UITP statistics, 2015). Its high efficiency, large capacity and many other unique benefits enable subway system to become one of the most popular transportation modes in urban areas where residents spend an average of 1-2 hours (12.5%-25%) of a working day underground commuting to and from work (UITP statistics, 2015). Among the world's busiest subway networks, Hong Kong's Mass Transit Railway (MTR) system runs 20 hours and 8,000 train trips per day, with an average daily ridership of 4.69 million (Hong Kong Government stats, 2016). Since its first operation in 1979, MTR is by far the most popular transportation mode in Hong Kong, accounting for 41% of the total 12 million public transport passenger journeys made daily (Hong Kong Government stats, 2016). Such heavy reliance on underground mass transit systems has aroused great interest in measurements of aerosol particles and studies of their health impacts on passengers. As light-weight portable monitors become available and more reliable than before, scholars in the field are no longer limited to physical constraints of traditional heavy and massive monitors. Studies on air circulation and indoor air quality in underground transportation networks have developed rapidly in recent years.

Previous studies suggest that air quality in built underground subway stations has a high dependence on a complex interplay of factors such as ventilation system, air conditioning system, train speed and frequency, wheel materials and braking mechanisms (Martins et al., 2016). In addition, piston effect, among other physical effects, also has a significant influence on air movements in underground subway stations (Morento et al., 2014; Pan et al. 2013). Piston effect describes a phenomenon where the confined air in underground platforms is forced to move along the tunnel as a subway train travels through relatively narrow tunnel. As the train approaches the platform, fresh air behind the back of the train is sucked into the platform due to the negative pressure formed at the tail, while the foul air is pushed out in the direction of the traveling train due to the positive pressure formed at the head. This movement of air generated by the moving of the train is similar to the operation of a mechanical piston. The generated piston wind naturally ventilates the subway station. In a study done in Barcelona's underground railway network, the influences of piston effects and tunnel ventilation are closely examined in multiple stations with different construction years, layouts and designs (Morento et al., 2014). The authors conclude that piston effect can play a significant role in air circulation and renewal in underground platforms, serving as natural ventilation and reducing energy consumptions (Morento et al., 2014).

Due to the distinctive characteristics of underground environment relative to street-level open-air environment, many subway networks have problems of ensuring underground indoor air quality. A confined space, a subway station promotes the accumulation of particulate matters infiltrated externally from ambient atmosphere and generated internally by subway train breaking and other mechanical operations (Nieuwenhuijsen et al., 2007;). In fact, high concentrations of suspended particles have been reported in many major subway systems around the world. According to Cheng and Yan's measurements in Taipei's mass rapid transit, the mean PM_{10} and $PM_{2.5}$ levels are approximately 51-65 μg/m^3 and 25-40 μg/m^3 respectively, around 10 units greater than those in ground-level indoor environments (Cheng et al., 2012). In Rome, PM_{10} and $PM_{2.5}$ concentrations were found to be 3.5 times higher in subway platforms and tunnels than in ambient streets (Ripanucci et al., 2006). Even in newer underground rail networks such as that of Long Angeles, the levels of PM_{10} and $PM_{2.5}$ were 2.5 and 2.9 times higher than those of the outside environment (Kam et al., 2011). Similar conclusions are reached in studies in London (Adams et al., 2001), Lisbon (Carvalho, 2013), Milan (Ozgen et al., 2016), Shanghai (Qiao et al., 2015) and many other cities around the world (Szeto, 2013). Generally, most studies concluded that concentrations of PM_{10} and $PM_{2.5}$ in underground transportation networks were strongly correlated with and were lower than those of airbone particles in ambient outdoors environments. In light of all of the above, many subway systems started to implement new technologies to improve air quality in burdened underground stations. Among the many cities that show leading efforts, Hong Kong has successfully improved air quality in underground stations by implementing effective ventilation system that utilizes auto roll filters and installed full height glass Platform Screen Doors (PSDs) in every running underground MTR stations (Hong Kong Legislative Council, 2012). In a most recent study done to compare air quality in different transportation modes, the authors concluded that PM concentrations in MTR stations are almost three times lower than those near roadside bus stations, and two times lower than those in buses or trams in the constantly busy streets in Hong Kong regardless of peak or non-peak hours (Che et al., 2016).

MTR has completed the Platform Screen Doors retrofit program by the year of 2007, successfully installed PSDs, including full-height (from platform ground to ceiling) and half-height (from platform ground to mid-air) PSDs, on all 74 platforms in 30 underground stations and ground-level and above-ground stations (MTR sites, 2016). It is the first retrofit program that is executed on a working metro system. Even though passenger safety is the priority of the PSD program, the MTR cooperation has stated that, with the sealing off of train tunnels, screen door installations have caused an overall energy savings of 15% in the 30 stations compared with energy consumption in 2002 (MTR sites, 2016). While Hong Kong's MTR has successfully preserved a better underground air quality than outdoor ambient environment in many stations, the effects of PSDs on air movement underground have yet to be closely examined. PSDs separate the platform from the tunnel, reducing the piston effect that creates air currents that renew the air in both the platforms and the tunnels (Son et al., 2013). On one hand, air in platforms is kept away from particulate matters generated by train breaking near tunnel areas. In this case, air in the platform is a lot more dependent on ventilation system. On the other hand, air in tunnels is kept away from the platform, trapping and storing more and more particulate particles within the tunnels. In this case, air renewal between platforms and tunnels generated by piston effects is significantly reduced and tunnel air become highly dependent on tunnel forced ventilation system. Since ventilation in the trains exchange air with tunnel air, which is bad relative to platform air, it is not unreasonable to hypothesize that while air quality in the platform can be effective preserved by active ventilation system, in-train air quality might be negatively affected due to the installment of PSDs.

With this speculation in mind, the main aim of this work is to examine the effects of PSDs on air quality in underground platforms and inside subway trains by presenting comparative results from the empirical measurements that took place in the platforms and train cabins of Hong Kong's MTR network from July to August, 2016. In particular, air quality indexes of concern in this study include $PM_{2.5}$ (and CO_2). Airbone particle concentrations are measured using two pairs of portable monitors Q-Track 7575 and Dust-Trak 8530 in two underground stations of the Island Line (the blue line) and in train cabins simultaneously. Three sets of measurements in total are collected during non-peak (10:00am to 12:00pm) in July 30th, 31st and August 1st, 2016. A round trip from Sai Wan Ho station (SWH) to Causeway Bay station (CWB) is designed for the purpose of measuring PM2.5 (and CO2) concentrations in the platforms and train cabins simultaneously, and while traveling along the line. The scope of the empirical research is to: 1) compare and analyze the concentrations of $PM_{2.5}$ (and CO_2) in underground platforms and train cabins, 2) compare the concentrations of $PM_{2.5}$ (and CO_2) in two underground platforms that share the similar layout but differ in ambient air and surrounding areas, 3) identify the variation of $PM_{2.5}$ (and CO_2) concentrations within trains influenced by the openings and closings of PSDs.

2. Sampling locations, equipment, and methodology

2.1 Description of Hong Kong and Hong Kong's MTR system

With a total land and sea area of 2,754 km^2, Hong Kong is home for more than 7.2 million residents of various nationalities. It is now ranked as the fourth most densely populated sovereign state. It is also the world's most visited city. Based on Hong Kong Government's Travel Characteristics Survey, Hong Kong, with high volumes of daily commuters and international visitors and shoppers from Mainland China, has the highest public transport travel rate in the world with an overwhelming rate of over 90%. The climate of Hong Kong is a monsoon-influenced humid subtropical climate, with annual average relative humidity of 78.0%, temperature of 28.8°**C** in July and 16.3°**C** in January. With high, oftentimes unbearable, humidity and temperature in the hot summer months of July and August, comfort ensurence in public transportations become of great concerns.

Characteristics of the Hong Kong geography, demography and climate spawn a highly sophisticated, efficient and convenient public transportation system. Among various transportation modes, the MTR is by far the most popular one. Of the ~12 million public transport journeys made every day, 41% are delivered by the MTR, 32% by diesel-fuelled franchised buses, 15% by Liquefied Petroleum Gas public light buses and 12% by others (Hong Kong Government stats, 2016). The MTR has been a provider of a safe, reliable and efficient way to travel around Hong Kong for daily commuters and travelers since 1979. As in the year of 2016, the entire system consists of ten subway lines and 12 light rail routes, extending all the way from the heart of Central and Causeway Bay to the New Territories and Lantau Island.

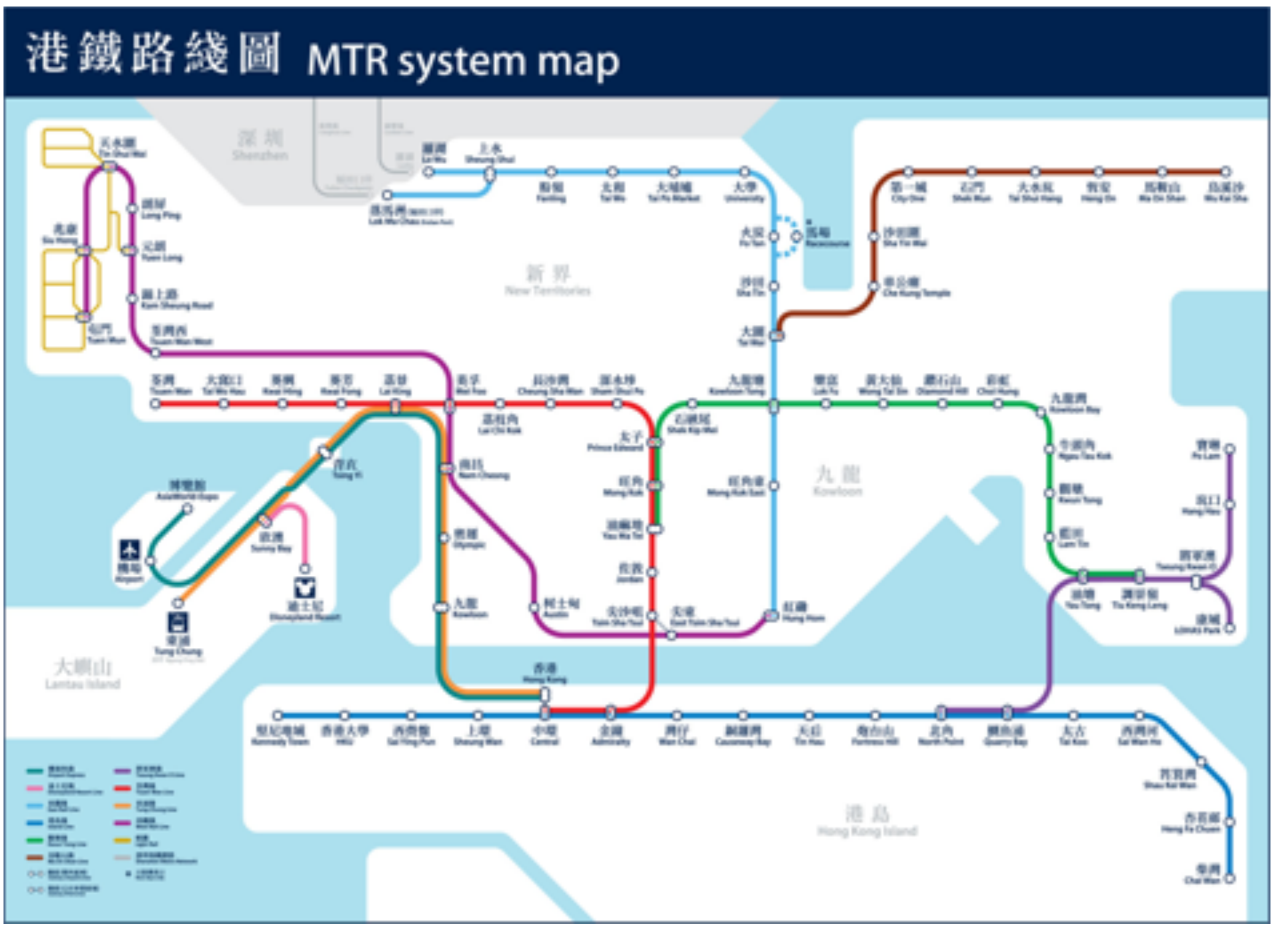

Fig 1: MTR system map

Methodology of this empirical study is carefully designed under the consideration of factors affecting study results proposed by Ho, Szeto Ying in a systematic overview of 26 papers that studied air quality in the underground mass transportation environments around the world (Szeto, 2013). Factors that might lead to significant influence to the results of air quality measurements in underground subway systems include the year of construction, train specification and infrastructure, study timing, sampling location and consistency. In order to ensure the quality of measurements, all of the above were taken into accounts.

2.2 Sampling Locations

An on-site study of conditions of PSDs installments and stations layout in all 87 railway stations is conducted prior to the design of sampling locations (Table 1). Among the 87 stations, 30 are underground and have full-height PSDs installed. 57 are ground-level or elevated (mostly along the East Rail Line, the oldest among the ten subway lines) with full-height, half-height or no PSDs installed.

Name	**Commencement**	**Total number of stations (including connecting stations)**	**Number of underground stations**
East Rail Line	October 1st, 1910	14	0
Kwun Tong Line	October 1st, 1979	15	10
Tsuen Wan Line	May 17th, 1982	16	11
Island Line	May 31st, 1985	**17**	**15**
Tung Chung Line	June 21st, 1998	8	3
Airport Express	July 6th, 1998	5	2
Tseung Kwan O Line	August 18th, 2002	8	4
West Rail Line	December 20th, 2003	12	4
Ma On Shan Line	December 21st, 2004	9	0
Disneyland Resort Line	August 1st, 2005	2	0
Total		87*	30#

* Total number of stations are calculated by subtracting the 19 connecting stations from the sum of the numbers of stations in each line (14+15+16+17+8+5+8+12+9+2-19=87).

Total number of underground stations are calculated by subtracting the 19 connecting stations from the sum of the numbers of underground stations in each line (10+11+15+3+2+4+4-19=30).

Table 1. a summary of ten MTR lines

Measurements were conducted along the Island Line, one of the 10 lines of the MTR, running from *Kennedy Town* in the Central and Western District, a popular tourist spot, busy commercial and core financial district, to *Chai Wan* in the Eastern District, a less populated and visited residential area with smaller commercial shopping malls (Fig 2). The line first opened on 31 May 1985, currently traveling through 10.1 miles in 34 minutes along its route, serving 17 stations in total. The line is indicated as the blue line in the official MTR map. The Island Line was chosen to be the sampling location, because firstly, it is the major railway line in serving the Hong Kong Island, which is one of the busiest districts in Hong Kong, serving a great amount of daily commuters and tourists daily. Secondly, its construction year is recent relative to the other major lines that serve more than ten stations, namely East Rail Line (1910), Kwun Tong Line (1979) and Tsuen Wan Line (1982). The Island Line thus has many newly adopted technologies that are representative of MTR's efforts to ensure the air quality in underground stations. In addition, unlike the older railway lines, the Island Line consists mostly of underground stations (15 out of 17), extending all the way from *Kennedy Town* station (Western terminus) to *Shau Kei Wan* station, with *Heng Fa Chuen* as the only ground level platform and *Chai Wan* (Eastern terminus) as the only elevated station, which works for the purpose of studying air quality in underground subway stations (Table 1).

Fig 2: A map of the Island Line

Measurements are conducted in two underground stations, *Sai Wan Ho* and *Causeway Bay*, both constructed in the same year of 1985. *Sai Wan Ho* and *Causeway Bay* share a similar station layout with two single-track tunnels serving two directions in two levels (Fig 3). The similar layout and year of construction also allow us to control the variability that might be caused by the different designs of the two stations. In addition, the design of single track in two different levels allows us to minimize the influence of arrivals and departures of trains and the openings and closings of the PSDs from the other direction. In addition, while *Causeway Bay* station is located in a crowded, narrow, busy and popular commercial area, *Sai Wan Ho* station serves mostly residents a few stops away from the central area of the Hong Kong Island. Since MTR underground stations obtain intake air from outdoors, this contrast allow us to investigate the effect of ambient air on underground air quality both in the platforms and trains.

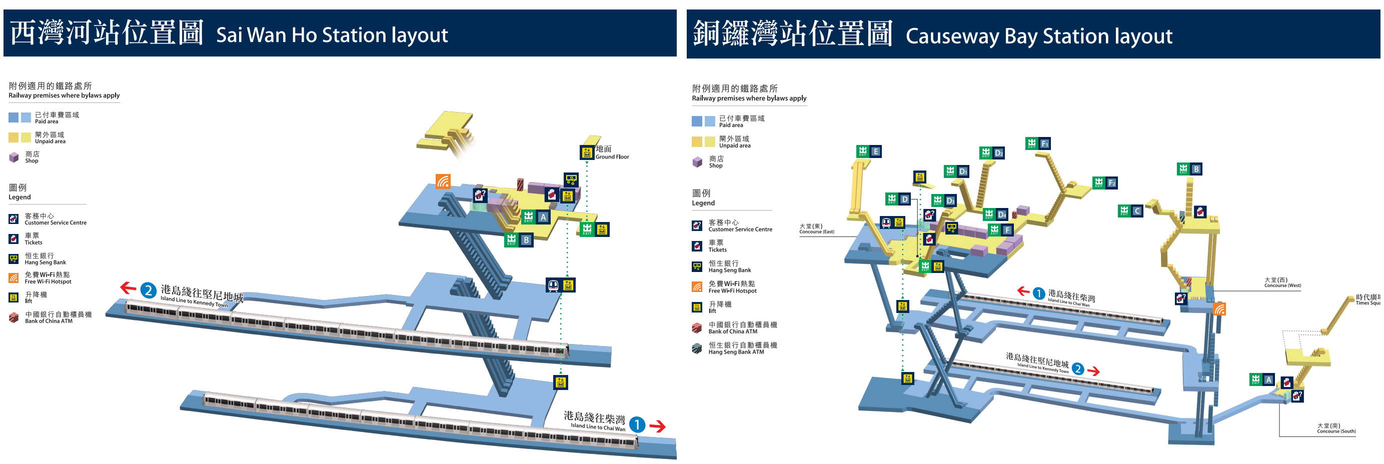

Fig 3: Sai Wan Ho and Causeway Bay layout diagrams

2.3 Route design and measurement protocol

Three days of intensive data collection were carried out along the designed route on July 30th, July 31st, August 1st in 2016. In order to minimize unwanted human influence and other potential factors that a high passenger volume might cause the fluctuation of our results, measurements are carried out in non-peak hours (10:00am – 12:00pm) in the MTR system, for rush hours in Hong Kong is infamously crowded. A sudden increase of passenger volumes will affect the concentrations of PM, for it might cause the re-suspension of located particles.

In each sampling day, the designed route started and ended in the south bus station at HKUST. The journey includes a outward trip from HKUST to Sai Wan Ho (①), three measurements at Sai Wan Ho station, a trip from Sai Wan Ho to Causeway Bay (②), three measurements at Causeway Bay station, a trip from Causeway Bay to Sai Wan Ho (③) and a return trip from Sai Wan Ho back to HKUST (④). (Fig 4) In the outward trip from HKUST to Sai Wan Ho and the return trip from Sai Wan Ho to HKUST, researchers travel side by side for the purpose of calibrations against the two pairs of monitors.

Fig 4. Design of sampling fixed route in the Hong Kong map

2.3.1 sampling in Sai Wan Ho and Causeway Bay stations

After arrival at Sai Wan Ho station, one researcher, carrying portable equipments (Dust-Trak numbered 8530133822, Q-Trak numbered 7575X1343003) in a backpack with tubes stored in nose-level, stands in the middle of the train platform to the direction to Chai Wan, 3 feet away from the middle PSD (Fig 5). Simultaneously, another person carrying the another set of portable monitors (Dust-Trak numbered 8530143810, Q-Trak numbered

7575X1343001) departs from the adjacent underground station (Tai Koo), board the train to the direction of Chai Wan, stand near the middle train door (car no.4, door no.3)[1], pass through Sai Wan Ho station while facing the first person standing in the platform, get off in the next station (Shau Kai Wan) and return to Tai Koo station (Fig 5). Such procedure is repeated three times. After the third set of measurements, both researchers take the train to Causeway Bay station from the Sai Wan Ho station. Both researchers get off at Causeway Bay station, where the previous procedure is repeated for three times as well.

Fig 5. simultaneous measurements in train cabins and platforms in Sai Wan Ho and Causeway Bay station.

2.3.2 fixed trip from Sai Wan Ho to Causeway Bay and from Causeway Bay to Sai Wan Ho

During the train ride from Sai Wan Ho to Causeway Bay and from Causeway Bay to Sai Wan Ho, one person carrying one set of monitors (Dust-Trak numbered 8530143810, Q-Trak numbered 7575X1343001) stands one feet away from the door and the other carrying another set of instruments (Dust-Trak numbered 85301338 22, Q-Trak numbered 7575X1343003) stands in the middle of the train cabin (Fig 6). Both researchers collect samples in cabin no.4 near door no.3. This process is to investigate the effect of PSDs on air quality in traveling trains by comparing PM2.5 and CO2 concentrations near and far away from the train doors.

[1] In the Island Line, trains have eight cabins in total. Each cabin has five doors.

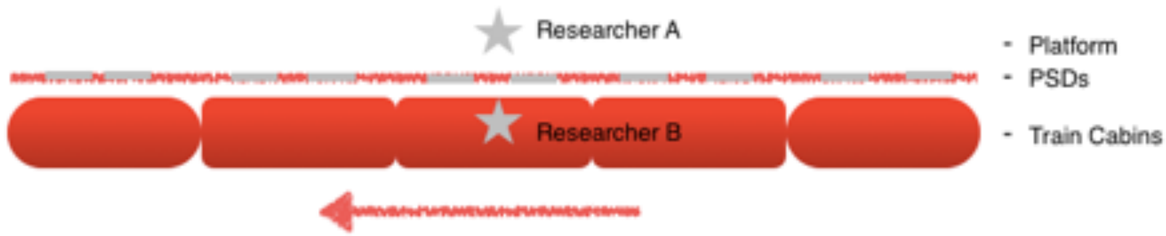

Fig 6.

2.4 Matters of interest

While there are many indexes that indicate air quality, this study focuses on the concentrations of Fine Particles ($PM_{2.5}$) –particulate matters with aerodynamic diameter less than or equal to a 2.5 µm cut point, for its notable health impacts on commuters, regardless of age and gender. Numerous epidemiological studies have demonstrated the associations between exposure to air pollution and increased mortality, with PM2.5 plays an especially important role in adverse impact on pulmonary and cardiovascular functions (Pope et al., 2006; Nieuwenhuijsen et al., 2007). Relative to larger particles, particles indicated by PM2.5 can be breathed more deeply into the lungs, remain suspended for longer periods of time, penetrate more readily into indoor environments, and are transported over much longer distances. While the United States Environmental Protection Agency (EPA) considers both PM2.5 and PM10 at the standard concentrations to measure air quality, PM 2.5 was found to have a more significant impact on human health (Nieuwenhuijsen et al., 2007). While PM10's story ends at the lungs, PM2.5 can pass from our lungs into our blood supply and be carried throughout our bodies thereby making them "the invisible killer." In fact, according to a follow-up analysis of the Adventist Health Study of Smog (AHSMOG) cohort study related to air pollution, lung cancer, and nonmalignant respiratory disease (either as the underlying or a contributing cause) were more strongly associated with $PM_{2.5}$ than with $PM_{10.}$

(Other than $PM_{2.5}$, this paper also studies carbon dioxide (CO_2) density for many well-known adverse health impacts caused by high concentrations of CO_2, including restlessness, headaches, dizziness, and increased heart rate and blood pressure. CO_2 in underground subways stations comes mainly from passengers' respirations. Since it has been concluded that CO_2 highly correlated with the number of passengers, CO2 density is a good indication of passenger volume.)

2.5 Instrumentation and quality control

Modeled after a recent study done in Hong Kong that compares air quality in different transportation modes, including buses, trams and MTR stations, this study utilizes available portable air quality monitors provided by the Environment Studies division in Hong Kong University of Science and Technology. Two TSI Dust-Trak II (model 8530) aerosol monitors were used to monitor $PM_{2.5}$ concentrations and two TSI Q-Trak (model 7575) were used to collect data of CO_2 density. Each Dust-Trak paired with a Q-Trak and stored in a padded backpack designed to minimize instrument tilt and vibration, and the sampling tubes were situated at nose level to measure at a typical breathing level for a standing passenger. There are two identically designed backpacks with the same instrument setup for the purpose of obtaining simultaneous measurements in different locations. The TSI Dust-Trak II aerosol monitor model 8530 is a battery-operated laser photometer which gives a real-time digital reading. Measurements of particulate matters are based on 90°C light scattering technique. The TSI Q-Trak model 7575 is a battery-based monitor that is connected with an Indoor Air Quality (IAQ) probe. It provides simultaneous readings of measurements of five elements in the indoor environment, CO_2, CO, temperature, relative humidity and pressure. Both the Dust-Trak and Q-Trak are set to a log interval of one second.

2.5.1 Calibration against HKUST supersite

Previous studies have reported that the Dust-Trak monitor overestimates PM2.5 by a factor of two to four compared to reference methods that use mass balance method, a more reliable method (Che et al., 2016). Therefore, before measurements started on July 30th, the two pairs of monitors were calibrated against monitors in Air Quality Research Supersite at Hong Kong University of Science and Technology, located in Clear Water Bay, Sai Kung, Hong Kong. The reference instrument in HKUST is a Thermo Fisher Scientific SHARP, measuring air quality for 24 hours at the one-minute resolution. Portable instruments were put into a white-box designed for the purpose of data comparison between fixed-site monitors and portable monitors at the same height of measuring tubes of the station. The PM2.5 concentrations measured the Dust-Trak appeared to be three times (with omissions of relatively small decimal digits) higher than the data obtained from at HKUST supersite. All $PM_{2.5}$ measurements from the Dust-Trak were adjusted to a more reliable parameter by dividing the whole set of data by a factor of three.

2.5.2 Side-by-side measurement

Before and after each day of sampling starting and ending in Sai Wan Ho station, two researchers travel side by side to compare data collected by the two pairs of monitors before separating to different sampling locations from *Sai Wan Ho* and after the designed route was completed. The mean ratio of PM2.5 concentration measured by the Dust-Trak used for platform and middle of cabin measurements (numbered 8530133822) to that by the Dust-Trak used for in-cabin and near doors measurements (numbered 8530143810) is 0.8891 (Fig 7). To remove the mean bias, measurements from the Dust-Trak numbered 8530133822 were adjusted by a factor of 0.8891. Measurements from both paired instruments appeared to agree almost completely after applying the loading correction.

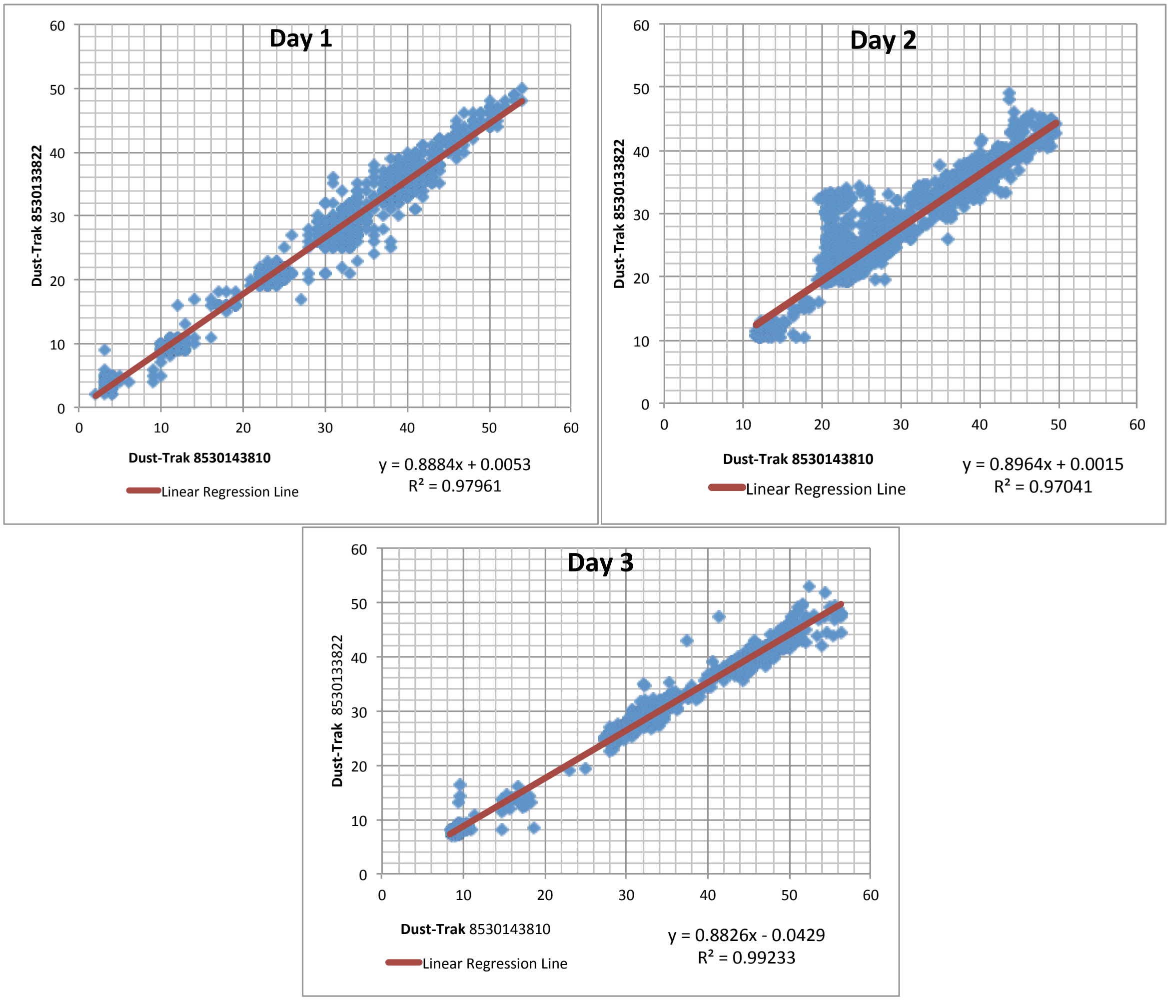

Fig 7. Linear regression lines of side-by-side measurements from each sampling day. Mean slope is calculated as followed: (0.8884+0.8964+0.8826)/3=0.8891.

Based on measurements from the two Q-Trak, the inter-run average temperature along the fixed route was 27.8°C with a standard deviation of 2.1°C; the average relative humidity was 63.5%rh with a standard deviation of 5%rh. There was no significant difference between each day of measurements for either temperature or relative humidity using the t-test. (The inter-hour coefficient of variance for temperature was in all three days and was for relative humidity.) Given the small variability in temperature, relative humidity and ambient concentration, they are not likely to significantly contribute to the variability in measured concentrations. Furthermore, correlation coefficients between PM2.5 and temperature and those of PM2.5 and humidity are very small.

2.5.3 Other quality control efforts

Other efforts to assure data quality include careful instrument checks, zeroing, time synchronizations and log sheets completions immediately before and after each sampling day. During each sampling session, instruments were constantly checked by researchers. Date times in all two Dust-Track, two Q-Track monitors and two digital watches are synchronized with the time posted by the Hong Kong Observatory. Log sheets A – 1 and A-2 are designed for the better preparation and maintenance of the monitors before and after each measurement (Appendix A). Log sheets B and C are designed for the better documentations of the data collected (Appendix B) At each special point, researchers will take down the time of the relevant event that happened. These log sheets are essential because further data analysis was based on these documentations.

Measurements from two pairs of monitors were downloaded, inspected and analyzed immediately after each sampling session which ended at around 1:00pm each sampling day. *Trak Pro*, a custom software provided by the TSI company is used to import data and Microsoft Excel is used to conduct further data analysis. Potential data quality issues (a steep hike of plunge of data, negative readings) were flagged for subsequent evaluation and resolution. A small number of records owning to instrument malfunction or human errors were removed from the final data set.

2.6 Data analysis

After each day of measurement, six sets of data (~six minutes) comparing $PM_{2.5}$ concentrations, CO2 density, CO density, temperature, humidity and pressure in train cabins and those in platforms, two sets of data (~20 minutes) comparing the same indexes near train doors and those in the middle of train cabins, and two sets of data (~60 minutes) comparing the same indexes in the platforms of two stations are collected. After three days of sampling, there are 30 set of data (~258 minutes) are collected. Since measurements of one-second resolution, this study analyzes a total sample size of 15480.[2] All sets of data for the purpose of comparison are tested using the t-test assuming homoscedastic (equal variance) at a significance level of 0.05. The differences of all comparative sample means after calibrations are proven to be statistically significant. Therefore, we are able to draw conclusions about the data we obtained. Data are analyzed using Microsoft Excel and MATLAB.

Measurements of ambient air quality from fixed-site monitors are used as a reference for inter-daily variability near Causeway Bay (the Central district) and Sai Wan Ho (the Eastern district). The measurements are provided by the Hong Kong Environmental Protection Department (HKEPD) and they are collected in one-hour resolution. The accessibility of air quality monitoring data from the HKEPD provides a valuable opportunity to investigate the relationship between underground indoor air quality and ambient air quality. Data collected underground from portable equipments were adjusted to one-hour resolution to perform data comparison.

3. Results and discussion

3.1 Comparison between air quality in the platforms and in train cabins

A summary of the simultaneous $PM_{2.5}$ concentrations in the platforms and train cabins in Sai Wan Ho and Causeway Bay station is presented by Fig 8 and Table 2. In Sai Wan Ho station, the means of $PM_{2.5}$ concentrations in train cabins in three sampling days all exceed the means of $PM_{2.5}$ concentrations in the platform, with an average difference of 2.09 $\mu g/m^3$. A similar observation can be made in Causeway Bay, with an average difference of 4.24 $\mu g/m^3$. Based on the five-number summary of sampling data, the positive difference between $PM_{2.5}$ concentrations in train cabins and in platforms is consistent. Almost all minimums, first quartiles, medians, third quartiles and maximums in the train cabins are higher than those in the platforms in each corresponding sampling session. It is also interesting to note that while the $PM_{2.5}$ concentrations in train cabins are higher than the $PM_{2.5}$ concentrations in both Sai Wan Ho and Causeway Bay station, the average difference in Causeway Bay is nearly two times higher than in Sai Wan Ho.

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[2] Sample size n = 258 * 60 = 15489. The unit is second.

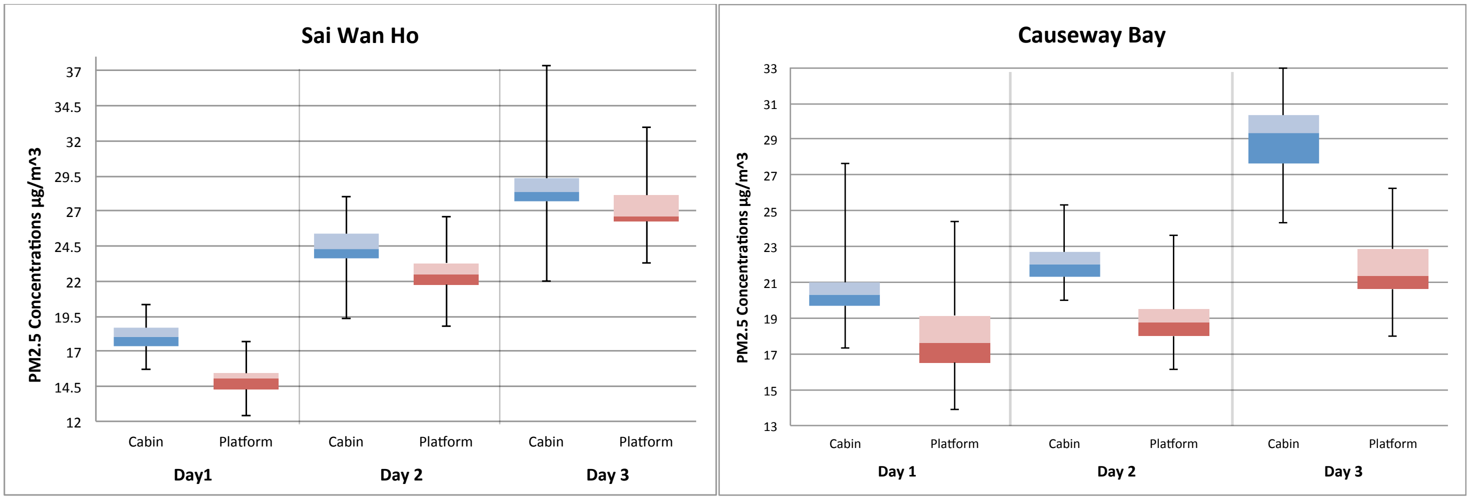

Fig 8. Comparisons of $PM_{2.5}$ concentrations in train cabins and in platforms in Sai Wan Ho and Causeway Bay station shown in box-plots. Note: the Sai Wan Ho chart uses a different y range (12-37 with 10 2.5-intervals) from that of the Causway Bay chart (13-33 with 10 2-intervals).

Station	Five-number Summary	Day 1		Day 2		Day 3	
		Cabin (µg/m^3)	Platform (µg/m^3)	Cabin (µg/m^3)	Platform (µg/m^3)	Cabin (µg/m^3)	Platform (µg/m^3)
Sai Wan Ho	Min	15.67	12.37	19.33	18.75	22.00	23.24
	Q1	17.33	14.28	23.67	21.74	27.67	26.24
	Median	18.00	15.05	24.33	22.49	28.33	26.62
	Q3	18.67	15.43	25.33	23.24	29.33	28.12
	Max	20.33	17.73	28.00	26.62	37.33	32.99
	Mean	17.93	14.91	24.51	22.60	28.61	27.28

Station	Five-number Summary	Day 1		Day 2		Day 3	
		Cabin (µg/m^3)	Platform (µg/m^3)	Cabin (µg/m^3)	Platform (µg/m^3)	Cabin (µg/m^3)	Platform (µg/m^3)
Causeway Bay	Min	17.33	13.87	20.00	16.12	24.33	18.00
	Q1	19.67	16.50	21.33	18.00	27.67	20.62
	Median	20.33	17.62	22.00	18.75	29.33	21.37
	Q3	21.00	19.12	22.67	19.50	30.33	22.87
	Max	27.67	24.37	25.33	23.62	33.00	26.24
	Mean	20.33	18.10	22.08	18.91	28.98	21.67

Table 2. Five-number summary and means of $PM_{2.5}$ concentrations in train cabins and in platforms of Sai Wan Ho and Causeway Bay station.

This result supports the hypothesis that the air quality in the trains is poorer than that in the platforms in underground subway stations in Hong Kong. While there are many possible explanations for this result, the influences of platform screen doors are of notable account. Many studies have acknowledged the significant role Piston effect plays in renewing air between tunnels and platforms in underground subway stations.() However, with the installation of platform screen doors, the natural air circulation crated by piston wind is obstructed. Particulate matters generated and accumulated in the tunnels are harder to escape. Therefore, while the air quality in the platforms are better preserved by the PSDs, the air quality in the tunnels are less effectively maintained. Since, air quality in the platform depends highly on forced ventilation system that exchanges air from the ambient environment and air quality in the trains are highly influenced by the ventilation system that sucks air from the tunnels, it is not surprising to observe a higher concentrations of $PM_{2.5}$ in train cabins.

There are also other possible accounts for this result. Compared to the platform, train cabin is a more confined area with a higher density of people. Passengers' movements in the train and the strong ventilation winds in the train cabin when the train is moving might contribute to the resuspension of particulate matters located on the train floor. To improve air quality in train cabins, the MTR needs to ensure the air quality in underground tunnels. Maintaining an effective tunnel ventilation system can one of the many possible solutions.

3.2 Comparison of $PM_{2.5}$ concentrations near train doors and in the middle of train cabins

A summary of $PM_{2.5}$ concentrations in different locations (near train doors and in the middle of train cabins) in trains by time series is presented by Fig 9. The fluctuations of $PM_{2.5}$ concentrations in both locations show a similar and consistent pattern in both stations and in all sampling days. Every time when the train arrived at a station, the $PM_{2.5}$ concentrations experienced a jump from the peak when the doors opened, and when the train departed from the station, the $PM_{2.5}$ concentrations showed a constant trend to increase when the doors closed. During the travel from one station to another (from doors close to doors open), the $PM_{2.5}$ concentrations accumulated and reached a peak when the train was

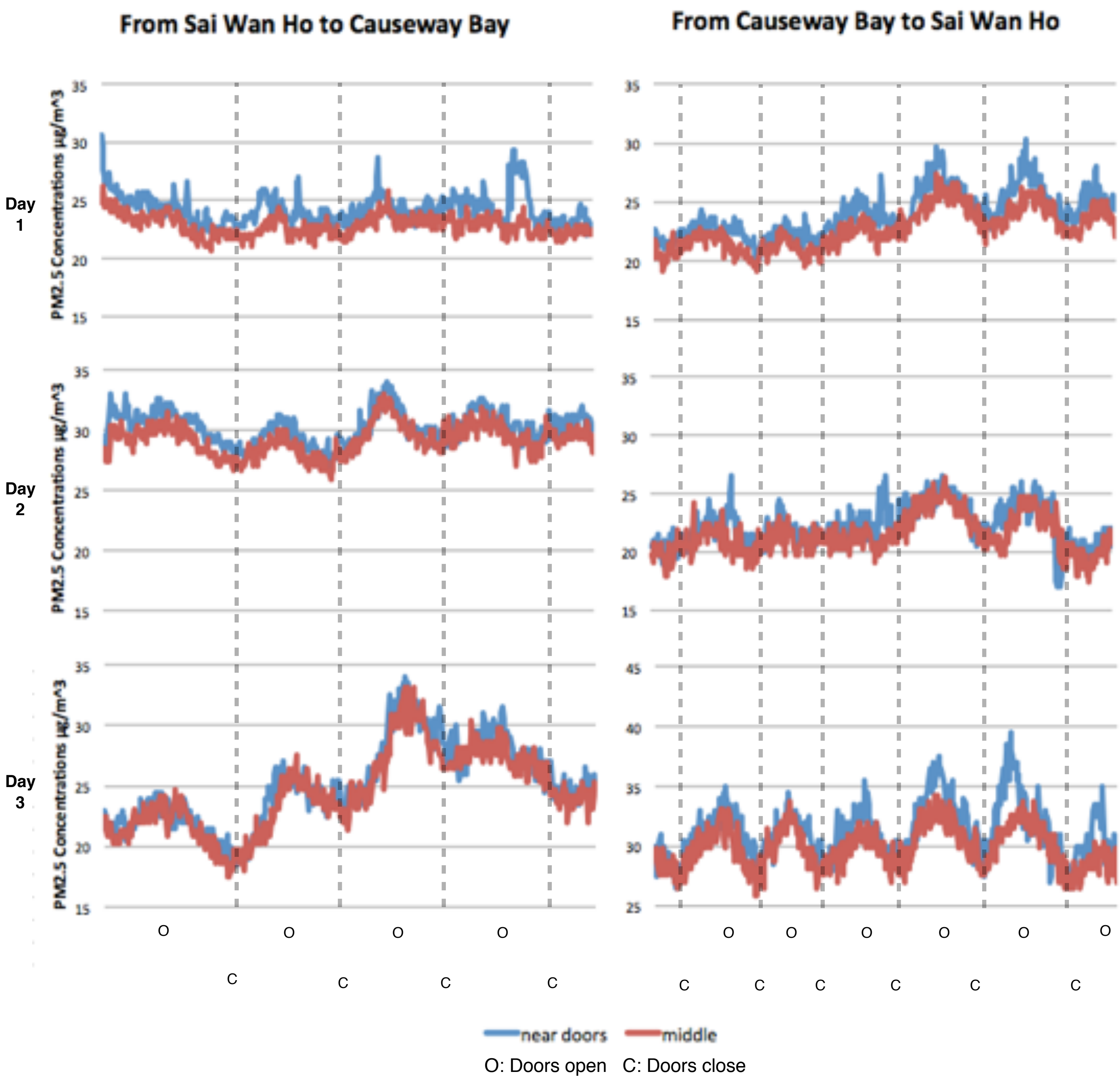

Fig 9. Comparisons of $PM_{2.5}$ concentrations in different locations in train cabins (near doors vs. middle). The horizontal axis represent the time that the train doors open when the train arrives at the train station. Note: the range of $PM_{2.5}$ concentrations from Causeway Bay to Sai Wan Ho chart in day 3 (25-45 with 5 5-intervals) is different from the others (15-35 with 5 5-intervals).

approaching the platform (doors not yet opened). When the doors opened, the $PM_{2.5}$ concentrations experienced a sudden decrease almost every time. There are also discernible pulses of $PM_{2.5}$ concentrations right after the doors opened. These pulses are more obvious near the train doors than in the middle of train cabins.

This result indicates that the air quality in the train deteriorates gradually during the train's travel from one station to another. It is not until the reopening of train doors that the indoor air quality starts to ameliorate, and the improvement happens almost right after the train doors open and the train cabins become accessible from the platform again. This can be explained by the differences of $PM_{2.5}$ concentrations between train cabins and platforms. As shown above, air quality indicated by $PM_{2.5}$ concentrations in train cabins is worse than that in the platforms, due to the influence of PSDs among other reasons. Passengers boarding the train dilute the $PM_{2.5}$ concentrations in train cabins by introducing cleaner air from the platforms.

The sudden pulses appeared immediately after the train doors open can be explained by the open access to the tunnels. Tunnel airs penetrate the train cabins and the platforms through the gap between the train and the platforms when the trains doors are open. Because of the installation of PSDs, the only access to tunnel air from trains and platforms is when the train doors and PSDs are open for passengers to get off and board the train. The observation that the $PM_{2.5}$ concentrations near the train doors experienced steeper pulses than in the middle of cabin implies that the tunnel air is much worse than the air in the trains or platforms. In addition, in both stations and all sampling days, the $PM_{2.5}$ concentrations near train doors appear to be higher than the simultaneous $PM_{2.5}$ concentrations in the middle of the train. All of these results support the previous assumption that the installation of PSDs on the one hand improve air quality in the platforms and on the other hand make it harder to ensure air quality in the tunnels and consequently trains.

3.3 Comparison between SWH and CWB stations

A summary of $PM_{2.5}$ concentrations in Sai Wan Ho and Causeway Bay station in box plots can be found in Fig 10. In three sampling days, the $PM_{2.5}$ concentrations in Causeway

Bay station appears to be higher than the $PM_{2.5}$ concentrations in Sai Wan Ho station in the first day, while the $PM_{2.5}$ concentrations in Sai Wan Ho station appears to be higher than the $PM_{2.5}$ concentrations in Causeway Bay station in the second and the third day. In the first day of sampling, while $PM_{2.5}$ concentrations in Sai Wan Ho station has a mean of 13.24 μg/m^3, $PM_{2.5}$ concentrations in Causeway Bay station has a higher mean of 15.65 μg/m^3 compared to Sai Wan Ho. In the second and third day, while $PM_{2.5}$ concentrations in Sai Wan Ho station has a mean of 20.16 μg/m^3 and 24.57 μg/m^3 respectively, $PM_{2.5}$ concentrations in Causeway Bay station has a lower mean of 16.18 μg/m^3 and 18.81 μg/m^3 respectively compared to Sai Wan Ho. Even though the first day of data tells us otherwise, the general trend here is the air quality indicated by $PM_{2.5}$ concentrations in Sai Wan Ho is worse than that in Causeway Bay, with an average difference of 2.44 μg/m^3.[3] Based on the five-number summary of the $PM_{2.5}$ concentrations in the two stations, the positive difference between $PM_{2.5}$ concentrations in Sai Wan Ho and in Causeway in day two and day three is consistent and offset the negative difference observed in the first day (Table 3).

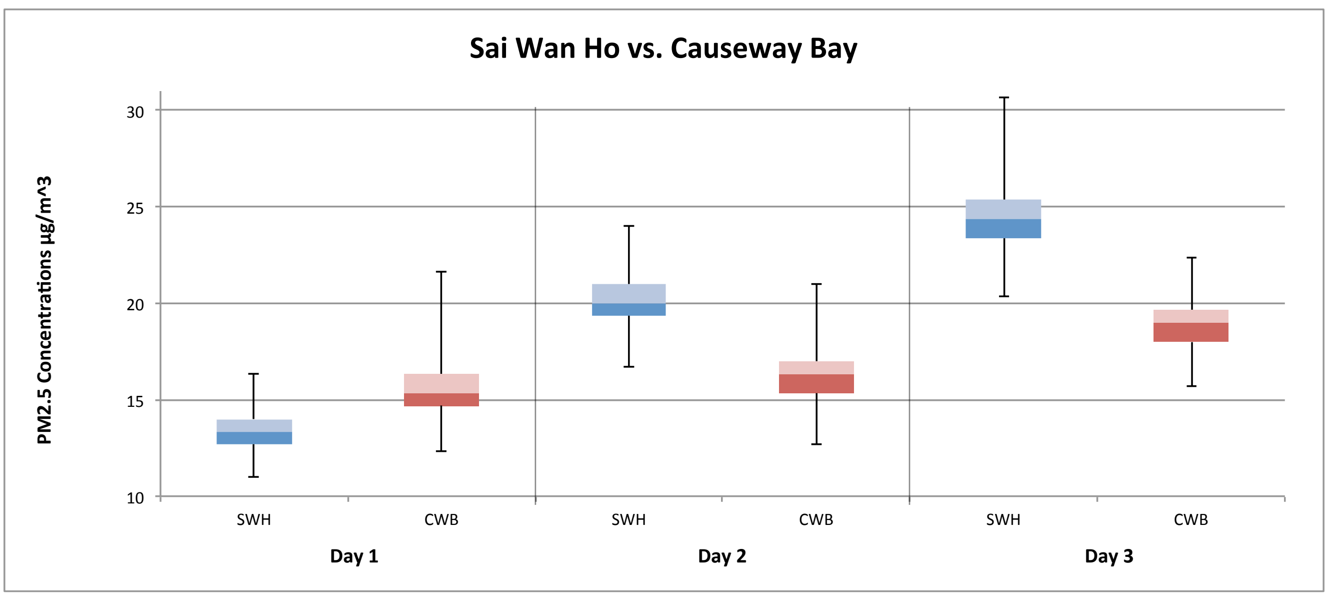

Fig 10. Comparisons of $PM_{2.5}$ concentrations in Sai Wan Ho and Causeway Bay station shown in box-plots.

[3] The average difference is calculated as followed: [(13.24-15.65)+(20.16+16.18)+(24.57-18.81)]/3=2.443333.

Five-number Summary	Day 1		Day 2		Day 3	
	SWH (µg/m^3)	CWB (µg/m^3)	SWH (µg/m^3)	CWB (µg/m^3)	SWH (µg/m^3)	CWB (µg/m^3)
Min	11.00	12.33	16.67	12.67	20.33	15.67
Q1	12.67	14.67	19.33	15.33	23.33	18.00
Median	13.33	15.33	20.00	16.33	24.33	19.00
Q3	14.00	16.33	21.00	17.00	25.33	19.67
Max	16.33	21.67	24.00	21.00	30.67	22.33
Mean	**13.24**	**15.65**	**20.16**	**16.18**	**24.57**	**18.81**
Ambient air	**23.00**	**33.60**	**33.30**	**34.30**	**23.70**	**60.30**

Table 3. Five-number summary of $PM_{2.5}$ concentrations in Sai Wan Ho and Causeway Bay station and comparisons between mean indoor air and mean ambient air.

This difference is interesting because previous studies have shown that indoor air in underground subway stations is positively correlated to ambient air quality. In addition, Causeway Bay is located in the busy central district of the Hong Kong Island with much more visitors and traffics than the residential area where the Sai Wan Ho station locates. There are far more passengers in Causeway Bay station than Sai Wan Ho station. Therefore, it is not irrational for one to expect that the indoor air quality in Causeway Bay is worse than that in Sai Wan Ho. However, based on the data collected for this study, while the ambient $PM_{2.5}$ concentrations of Sai Wan Ho station are lower than the ambient $PM_{2.5}$ concentrations of Causeway Bay, the indoor $PM_{2.5}$ concentrations of Sai Wan Ho station are observed to be higher than the ambient $PM_{2.5}$ concentrations of Causeway Bay. The correlation coefficient obtained from this data set is as small as 0.016298478. This interesting result can be explained by the difference in ventilation systems, air conditioning systems, depths and designs of the two stations, train speed and frequency and other operational conditions. Since Causeway Bay is a more visited commercial area in Hong Kong, the MTR might installed a more effective ventilation mechanism to the station. Furthermore, Causeway Bay station has more exits than the Sai Wan Ho station, which might dilute the platform $PM_{2.5}$ concentrations. The small sample size can also contribute to this interesting result different from conclusions reached by previous studies with much larger sample sizes.()

In addition, in the three sampling days, ambient $PM_{2.5}$ concentrations seem to be higher than the $PM_{2.5}$ concentrations in both Sai Wan Ho and Causeway Bay station, with the greatest difference as high as 41.49 μg/m^3 observed in the third day of measurements in Causeway Bay station. The ambient $PM_{2.5}$ concentrations in Causeway Bay are higher than the ambient $PM_{2.5}$ concentrations in Sai Wan Ho in each sampling day, with an average difference of 16.07 μg/m^3.[4] The average difference between ambient $PM_{2.5}$ concentrations and underground $PM_{2.5}$ concentrations is 7.34 μg/m^3 for Sai Wan Ho station and 25.85 μg/m^3.[5] The difference appears to be larger in Causeway Bay. This might also be explained by the more effective efforts the MTR uses to ensure air quality underground in popular commercial areas where a significant amount of passengers commute daily. In contrast, Sai Wan Ho services less commuters each day and the station might alternately activate the ventilation system to save energy. Despite of this interesting result different from what previous scholars have established, the measurements of ambient $PM_{2.5}$ concentrations and indoor $PM_{2.5}$ concentrations in both stations strengthens the observation that indoor air quality in underground MTR stations is better than outdoors ambient air made by previous studies conducted in Hong Kong.

4. Concluding remarks

The studies utilizes portable areosol monitors Dust-Trak and Q-Trak to investigate indoor quality in underground MTR stations in urban Hong Kong. Methodology was carefully designed to control various variables and make meaningful simultaneous comparisons between various locations in both underground platforms and train cabins. Three days of measurements were carried out along the Island line in July and August of 2016. A total sample of 15480 data in one-second resolution was collected. The following main conclusions are drawn:

- $PM_{2.5}$ concentration differs substantially between train cabins and underground platforms of both Sai Wan Ho and Causeway Bay station. $PM_{2.5}$ concentrations in train

[4] The average difference is calculated as followed: [(33.60-23.00)+(34.30-33.30)+(60.30-23.70)]/3=16.066667.

[5] The average differences are calculated as followed: [(23-13.24)+(33.30-20.16)+(23.70-24.57)]/3=7.343333; [(33.60-15.65)+(34.30-16.18)+(60.3-18.81)]/3=25.853333.

cabins are observed to be 2-4 μg/m^3 higher than $PM_{2.5}$ in platforms depending on which station. Such consistent difference could be explained by the difference of air quality in underground platforms and tunnels.

- There are many possibilities that might caused the $PM_{2.5}$ concentration difference between platforms and tunnels. One of the most prominent accounts is the installation of PSDs, which interferes the natural air circulation generated by the piston effect in underground subway systems.
- There are discernible pulses in $PM_{2.5}$ concentration when the train doors open for passengers to board and get off the subway train. This phenomenon is more obvious near the train doors than in the middle of the cabin, which is closer to the tunnel air.
- $PM_{2.5}$ concentrations are consistently higher near the train doors than in the middle of the cabins along the round trip between Sai Wan Ho and Causeway Bay. This higher concentration near train doors can also be explained by the closer distance to the tunnel air.
- In-train air quality deteriorate when the subway train travels from one station to the other and ameliorate when train cabins are reconnected to the platform air.
- $PM_{2.5}$ concentration significantly differs between MTR underground stations' air quality and ambient air quality. MTR successfully maintained a lower $PM_{2.5}$ concentration in underground subway stations compared to the outdoor air.
- Ambient $PM_{2.5}$ concentration near Causeway Bay are higher than the ambient $PM_{2.5}$ concentrations near Sai Wan Ho, with a mean difference of 16.07 μg/m^3 in all sampling days.
- In this study, ambient $PM_{2.5}$ concentration and indoor $PM_{2.5}$ concentration show a poor correlation while previous studies suggest otherwise. This can be caused by the different ventilation system used in Sai Wan Ho and Causeway station, among other equally accountable operational differences between the two stations.

While this study fell short of sample size due to the small time frame, the availability of resources and the small scope of the project, the methodology can be applied to subway network systems outside of Hong Kong to conduct simultaneous measurements in train cabins and platforms. Results drawn from this study can serve as a start point for researchers in the field to further studies on new technologies to ensure air quality underground and to be extended to the scope of building environment-friendly and "smart cities."

5. Acknowledgement

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6. Limitations

Due to the small scope of the project and the small research time frame compared to existing studies, this study obtained a relatively small sample size. Therefore, the results obtained from the three days of measurements can only be applied to that specific time period.There is also an influence of time delay in the comparison between the ambient $PM_{2.5}$ concentration of Sai Wan Ho and Causeway Bay due to the design of methodology. The ambient $PM_{2.5}$ concentration of Sai Wan Ho is in 10 am and Causeway Bay in 11 am, which might contribute to the gap between the $PM_{2.5}$ concentration near the two stations. There is also the influence of weather. Typhoon Nida approached Hong Kong at the night of August 1^{st}, and it was the first major typhoon of the year in Hong Kong; a No.8 signaling was raised at 8:40 pm. Air quality in both underground and outdoors might be affected before, during and after the landing of the typhoon.

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Appendix A - Logsheet A

Logsheet A - Backpack 1

Equipments Check: to be completed before and after measurement

DustTrak SN: 8530143810 .

QTrack SN: 7575X1343001 .

Date (dd/mm/yyyy): ________ .

Researcher: ________ .

Start Time (hh:mm:ss): ________ .

End Time (hh:mm:ss): ________ .

Before Measurement:

Equipments Check

Item	DustTrak Cassette + PM2.5 filter(Y/N)	Set Folder Name	Zero Cal (Y/N)	Time Interval (mm:ss)	Memory (%)	Power Status (%)	Time Sync (Y/N)	remark
DustTrak								
QTrak								
Watch								

Note: *If memory is less than 90%, all data need to be deleted before measurement.*

Supplements Check

Item	Check	**Item**	Check
Logsheet A		Pen	
Logsheet C		Backup AA batteries	
Remarks:			

After Measurement:

Equipment Check

Item	Condition (Normal / Need Repair)	Power Status (%)	Memory (%)	Power Off (Y/N)	Remarks
DustTrak					
QTrak					
Watch					

Logsheet A - Backpack 2

Equipment Check: to be completed before and after measurement

DustTrak SN: 8530133822 .

QTrack SN: 7575X1343003 .

Date (dd/mm/yyyy):________________.

Researcher: ________________________.

Start Time (hh:mm:ss):____________.

End Time (hh:mm:ss):______________.

Before Measurement:

Equipments Check-1

Item	DustTrak Cassette + PM2.5 filter(Y/N)	Set Folder Name	Zero Cal (Y/N)	Time Interval (mm:ss)	Memory (%)	Power Status (%)	Time Sync (Y/N)	remark
DustTrak								
QTrak								
Watch								

Note: *If memory is less than 90%, all data need to be deleted before measurement.*

Supplements Check-1

Item	Check	**Item**	Check
Logsheet A		Pen	
Logsheet B		Backup AA batteries	
Remarks:			

After Measurement:

Equipment Check-1

Item	Condition (Normal / Need Repair)	Power Status (%)	Memory (%)	Power Off (Y/N)	Remarks
DustTrak					
QTrak					
Watch					

Appendix B - Logsheet B

Logsheet B

Comparative measurement: Platform

Date (dd/mm/yyyy):________________________. Researcher: ______________________.

DustTrak SN: 8530133822 . QTrack SN: 7575X1343003 .

Weather conditions: a. Temperature: ____________;

b. Humidity: ____________;

c. Wind: ____________;

d: Sunny Cloudy Rainy (Circle one that applies).

Comparative measurement design:

Fixed routes for researcher (A) who stays in the platform:

1. Travel from UST to Sai Wan Ho
2. Stay in Sai Wan Ho station
3. Travel from Sai Wan Ho to Causeway Bay
4. Stay in Causeway Bay station
5. Travel From Causeway Bay to Sai Wan Ho
6. Travel from Sai Wan Ho to UST

** In the "remarks" section, report any events that might be associated with peaks in measured concentrations of PM, CO, CO2. These events include, but not limit to, a smoker passing by, a sudden increase in passenger volume.*

1. From UST to Sai Wan Ho:

- walk side by side with another researcher

Event	Time (hh:mm:ss)	Remarks*
UST South Bus Station		
11 Bus - board		
11 Bus - arrive		
Hang Hau - borad		
Quarry Bay - arrive		
Quarry Bay - board		
Sai Wan Ho - arrive		

2. First Station: Sai Wan Ho (round trip starts here)

constant standing position:

- middle of platform: **door No.3, car No.4.**
- 3 feet away from PSDs (Fig 1)

Event	Time (hh:mm:ss)	Remarks*
Sai Wan Ho - platform		
First Train arrives		
First Train leaves		
Second Train arrives		
Second Train leaves		
Third Train arrives		
Third Train leaves		

Note: only take down train arrival and departure times when you are face to face with another researcher in train cabins.

2. Travel from Sai Wan Ho to Causeway Bay:

Island Line to Kennedy Town Direction
- side by side with another researcher
- **middle of the 4th train cabin**

Event	Time (hh:mm:ss)	Remarks*
Sai Wan Ho - borad		
Tai Koo		
Quarry Bay		
North Point		
Fortress Hill		
Tin Hau		
Causeway Bay - arrive		

Note: take down times when doors open at each station.

3. Second Station: Causeway Bay

constant standing position:

- middle of platform: **door No.3, car No.4.**
- 3 feet away from PSDs (Fig 1)

Event	Time (hh:mm:ss)	Remarks*
Causeway Bay - platform		
First Train arrives		
First Train leaves		
Second Train arrives		
Second Train leaves		
Third Train arrives		
Third Train leaves		

Note: only take down train arrival and departure times when you are face to face with another researcher in train cabins.

4. Travel from Causeway Bay to Sai Wan Ho (round trip completed here)

Island Line to Chai Wan Direction
- side by side with another researcher
- **middle of the 4th train cabin**

Event	Time (hh:mm:ss)	Remarks*
Causeway Bay - borad		
Tin Hau		
Fortress Hill		
North Point		
Quarry Bay		
Tai Koo		
Sai Wan Ho - arrive		

5. Travel from Sai Wan Ho to UST

- side by side with another researcher

Event	Time (hh:mm:ss)	Remarks*
Sai Wan Ho - board		
Quarry Bay - arrive		
Quarry Bay- board		
Hang Hau - arrive		
11 Bus - board		
11 Bus - arrive		
UST South Bus Station		

Constant Standing Positions

Fig 1: In platforms

Fig 2: In trains

Logsheet C

Platform and train spontaneous measurement: Train

Date (dd/mm/yyyy):__________________________. Researcher: ________________________.

DustTrak SN: 8530143810 . QTrack SN: 7575X1343001 .

Weather conditions: a. Temperature: ______________;

b. Humidity: ______________;

c. Wind: ______________;

d: Sunny Cloudy Rainy (Circle one that applies).

Fixed Route Design:

Fixed routes for researcher (B) who travels in train cabins:

1. Travel from UST to Tai Koo
2. Travel through Sai Wan Ho station (Tai Koo - Shau Kai Wan) three times
3. Travel from Sai Wan Ho to Tin Hau
4. Travel through Causeway Bay station (Tin Hau - Wan Chai) three times
5. Travel from Causeway Bay to Sai Wan Ho
6. Travel from Sai Wan Ho to UST

** In the “remarks" section, report any events that might be associated with peaks in measured concentrations of PM, CO, CO2. These events include, but not limit to, a smoker passing by, a sudden increase in passenger volume.*

1. From UST to Tai Koo:

- side by side with another researcher

Event	Time (hh:mm:ss)	Remarks*
UST South Bus Station		
11 Bus - board		
11 Bus - arrive		
Hang Hau - borad		
Quarry Bay - arrive		
Quarry Bay - board		
Tai Koo- arrive		

2. Travel through Sai Wan Ho station (Tai Koo - Shau Kai Wan) three times:

Island Line to Chai Wan direction

- 3 feet away from train **door No. 3, car No. 4** (Fig 2)
- face the other researcher when passing through Sai Wan Ho station

1) 1st time:

Event	Time (hh:mm:ss)	Remarks*
Tai Koo - board		
Sai Wan Ho - doors open		
Sai Wan Ho - doors close		
Shau Kai Wan - arrive		

2) 2nd time:

Event	Time (hh:mm:ss)	Remarks*
Tai Koo - board		
Sai Wan Ho - doors open		
Sai Wan Ho - doors close		
Shau Kai Wan - arrive		

3) 3rd time:

Event	Time (hh:mm:ss)	Remarks*
Tai Koo - board		
Sai Wan Ho - doors open		
Sai Wan Ho - doors close		
Shau Kai Wan - arrive		

3. Travel from Sai Wan Ho to Tin Hau:

Island Line to Kennedy Town Direction
- side by side with another researcher
- 1 feet away form **door No. 3, car No. 4**

Event	Time (hh:mm:ss)	Remarks*
Sai Wan Ho - borad		
Tai Koo		
Quarry Bay		
North Point		
Fortress Hill		
Tin Hau - arrive		

4. Travel through Causeway Bay (Tin Hau - Wan Chai) three times:

Island Line to Chai Wan Direction
- 3 feet away from train **door No. 3, car No. 4** (Fig 2)
- face the other researcher when passing through the Causeway Bay station

1) 1st time:

Event	Time (hh:mm:ss)	Remarks*
Tin Hau - board		
Causeway Bay- doors open		
Causeway Bay - doors close		
Wan Chai - arrive		

2) 2nd time:

Event	Time (hh:mm:ss)	Remarks*
Tin Hau - board		
Causeway Bay- doors open		
Causeway Bay - doors close		
Wan Chai - arrive		

3) 3rd time:

Event	Time (hh:mm:ss)	Remarks*
Tin Hau - board		
Causeway Bay- doors open		
Causeway Bay - doors close		
Wan Chai - arrive		

5. Travel from Causeway Bay to Sai Wan Ho (round trip completed)

Island Line to Chai Wan Direction

- side by side with another researcher
- 1 feet away form **door No. 3, car No. 4**

Event	Time (hh:mm:ss)	Remarks*
Causeway Bay - borad		
Tin Hau		
Fortress Hill		
North Point		
Quarry Bay		
Tai Koo		
Sai Wan Ho - arrive		

5. Travel from Sai Wan Ho to UST

- side by side with another researcher

Event	Time (hh:mm:ss)	Remarks*
Sai Wan Ho - board		
Quarry Bay - arrive		
Quarry Bay - board		
Hang Hau - arrive		
11 Bus - board		
11 Bus - arrive		
UST South Bus Station		

Remarks: