Particulate matter concentrations and heavy metal contamination levels in the railway transport system of Sydney, Australia

Marwa Mohsen, Mohammad Boshir Ahmed, John L Zhou*

School of Civil and Environmental Engineering, University of Technology Sydney, 15 Broadway, Ultimo NSW 2007, Australia

Corresponding author:

Prof John L Zhou

School of Civil and Environmental Engineering

University of Technology Sydney

15 Broadway,

Ultimo NSW 2007

Australia

Email: junliang.zhou@uts.edu.au

Abstract

Sampling campaign was conducted over six weeks to determine particulate matter (PM) concentrations from Sydney Trains airport line (T2) at both underground and ground levels using DustTrak. Dust samples were collected and analysed for 12 metals (Fe, Ca, Mn, Cr, Zn, Cu, Pb, Al, Co, Ni, Ba and Na) by atomic emission spectroscopy. Average underground PM_{10} and $PM_{2.5}$ concentrations from inside the trains were 2.8 and 2.5 times greater than at ground level. Similarly, PM_{10} and $PM_{2.5}$ concentrations on underground platforms were 2.7 and 2.5 times greater than ground level platforms. Average underground PM concentrations exceeded the national air quality standards for both PM_{10} (50 μg/m^3) and $PM_{2.5}$ (25 μg/m^3). Correlation analysis showed a strong to moderate association between PM concentrations at ground level and background PM concentrations (r^2 from 0.952 to 0.500). The findings suggested that underground PM concentrations were less influenced by the ambient background than at ground level. The metal concentrations decreased in the order of Fe, Cr, Ca, Al, Na, Ba, Mn, Zn, Cu, Ni, Co and Pb. The pollution index (PI) and enrichment factor (EF) values were calculated to identify the levels and sources of contamination in the underground railway microenvironments. PM was remarkably rich in Fe with a mean concentration of 73.51 mg/g and EF of 61.31, followed by Ni and Cr. These results noticeably indicated a high level of metal contamination in the underground environments, with the principal contribution from track abrasion and wear processes.

Keywords: Sydney railway; PM_{10}; $PM_{2.5}$; Heavy metals; Contamination indices

1. Introduction

Particulate matter (PM) is one of six air pollutants that have been regulated worldwide (Atkins et al., 2010). Short term and long term exposure to elevated levels of PM has been strongly associated with the development of respiratory and cardiovascular diseases as well as carcinogenic problems, as reported by the World Health Organisation (WHO, 2013). An estimate from WHO (2002) showed about 800,000 premature deaths per year were caused by short term and long term exposure to $PM_{2.5}$, highlighting the severity of the risk from PM exposure. In addition, epidemiological and toxicity studies have shown that elevated concentration of PM and their chemical compositions can cause serious respiratory problems (Epton et al., 2008; Kim et al., 2015; Liu et al., 2014); cardiovascular problems (Brook et al., 2010; Farraj et al., 2015; Lopez et al., 2006); and increase carcinogenic risks (Gray et al., 2015; Hamra et al., 2014; Lopez et al., 2006). The possible adverse effects of PM can occur directly from PM accumulation inside human bodies through ingestion, dermal contact or inhalation, and from contaminants such as heavy metals in PM (Kampa and Castanas, 2008).

As a result of ever-growing human population and traffic volumes, people in urban areas especially megacities are heavily dependent on the railway network as a vital transport mode (Song et al., 2016). Despite the fact that the time spent in travelling by train on the railway network is relatively short, high PM concentrations and the associated harmful chemical composition in high density population environments can cause serious health problems (Fridell et al., 2010; Karlsson et al., 2005).

There have been many studies to evaluate PM concentrations in the railway and underground networks, most of which have shown elevated levels of PM in the underground when compared with the ambient background measurements and street levels. Personal exposure levels of $PM_{2.5}$ for the commuters of the London underground rail were up to 8 times higher than three different ground level commuting modes (bicycle, bus, car) (Adams et al., 2001). Another study from Paris showed that PM_{10} and $PM_{2.5}$ concentrations in the central railway station were 5–30 times higher than those measured on streets (Raut et al., 2009). Furthermore, a study from the Los Angeles metro system showed that the average concentrations of PM_{10} and $PM_{2.5}$ were about 2 times higher in the underground platforms and the train carriages compared to the ground level light rail stations and carriages (Kam et al., 2011a). Previous railway studies reported different results in terms of PM concentrations which were justified by major factors that can significantly affect the air quality measurements such as the age of the metro network, the braking system used, the ventilation system and the availability of an air conditioning system, the frequency of the trains' passage, in addition to other operating factors (Aarnio et al., 2005; Abbasi et al., 2011; Moreno et al., 2014; Namgung et al., 2016).

In terms of the chemical composition, studies have found that PM in the railway environments was highly enriched with different heavy metals specifically Fe, Cr, Cu, Mn and Ni (Aarnio et al., 2005; Perrino et al., 2015; Salma et al., 2009; Querol et al., 2012). These metals are generally produced by the friction, wear and abrasion processes for the wheels, rail lines and the break system.

Sydney as the capital city of NSW with a large population of more than 5 million people has different transport modes to cope with the needs of its residents. Due to the fact that it covers a wide urban area, the major transport mode used in Sydney is the private car followed by buses and trains (Bureau of Transport Statistics, 2015). So now, major research focus on PM has been on private cars, buses and tunnels, only a limited number of studies have been conducted on PM from Sydney transport systems (Knibbs et al., 2009; Knibbs and Morawska, 2011). To the best of our knowledge, no detailed study to evaluate Sydney railway microenvironments in terms of PM concentrations and associated metal contamination levels has been produced to date. Currently, the patronage of Sydney train is about 328 million customer journeys are taken annually in Sydney trains network; this number is expected to increase annually to meet the increasing demand of the population in Sydney (Bureau of

Transport Statistics, 2015). Therefore, with such a significant number of journeys by urban population in Sydney, it is important to assess the PM contamination and its associated metal contaminants in the Sydney railway system and their potential impact on human health.

The aim of this study was therefore to evaluate PM and metal contamination from the Sydney railway system. The specific objectives were to measure PM_{10} and $PM_{2.5}$ levels at both underground and ground level platforms and inside train carriages, to assess the concentrations and potential sources of selected metals in the underground platforms.

2. Experimental methodology

2.1. Sampling sites

For PM concentration assessment, the Sydney Airport Line (T2), shown in Fig. 1, was sampled during 6-weeks sampling period from the 28th September to the 4th November 2015. Line T2 links the western suburbs to the Sydney CBD, passing through Sydney Airport and including the international and domestic terminals. About 21 km of length was included in the data collection of PM_{10} and $PM_{2.5}$ running from Revesby Station to Central Station. Particles were measured from inside the train carriages and at the platforms at both ground and underground levels (**Fig. 1**). At the same time, the corresponding particles from two fixed air quality monitoring stations were recorded for comparison. Further investigations were carried out at three different operating levels of Town Hall Station during a second sampling period from the 22nd February to the 4th March 2016 (2 weeks), with the aim to assess the effect of the platform depth levels on PM concentrations (**Table 1**).

The T2 line was chosen for this study due to its diverse operating levels (ground and underground levels), and very high traffic volumes daily. Part of the chosen line operates at the ground level, stopping at four stations connecting Revesby to Wolli Creek Station with a total length of 13.7 km. The other part runs inside the underground tunnel connecting Wolli Creek to Central Station with a total length of 7.3 km. This line was also chosen for sampling due to its high annual number of journeys growth rate of 15.6% and its high annual patronage number of 20.5 million commuters (Bureau of Transport Statistics, 2014). Measurements from Central Station represented the ground level platform data, while the underground measurements were collected from Green Square Station. The station has two platforms on the sides and two tracks at the middle. This type of design is better for the air exchange through underground tunnels and PM levels are expected to be less than the stations with single platform and track (Colombi et al., 2013). To compare the particle measurement with the urban background data, two fixed air quality stations located near the T2 line and platforms were chosen to collect data. These stations are operated by the NSW Office of Environment and Heritage (NSW OEH) whose data can be accessed through their website.

The first air quality monitoring station was Rozelle station located at 4.6 km and 5.6 km from Central and Green Square Stations, respectively. The second air quality station considered was Earlwood Station at Beaman Park located at a distance of 1-9 km from the train line (T2) being studied.

For the metal analysis, seven dust samples were collected: two samples from Green Square Station (GS1, GS2), two samples from Town Hall Station (TH1, TH2), one sample from Mascot Station, and two samples from Sydney Park as background (BG1, BG2), as detailed in Table 1. Samples BG1 and BG2 were collected from Sydney Park located at a distance of 2-4.5 km from the sampled platforms to represent the urban background reference values (**Fig. 1**).

2.2. Monitoring instruments and sampling campaigns

A portable light scattering photometer called DustTrak (model 8532) purchased from TSI Inc. USA was used for PM concentration measurements. The photometer runs by the means of a rechargeable lithium ion battery, eliminating the need for an external power supply. PM_{10} and $PM_{2.5}$ inlets were used to continuously measure concentrations of these two size fractions at a logging interval of 2 min. The instrument flow rate was set to 3 L/min by the manufacturer and was calibrated regularly with an external flow meter during the sampling campaign (as recommended by the manufacturer). A clean filter was used at the beginning of each sampling day to ensure a zero calibration for the model. The inlet impactors were periodically removed and cleaned, and the impactor plates were re-greased every other day using the oil provided by the manufacturer.

The sampling campaign was carried out from 28th September to 4th November 2015 (six weeks) on different working days at any time from 9 am to 5 pm. On the platforms, the sampling started with 30 min for PM_{10} followed by another 30 min for $PM_{2.5}$ at each level (ground or underground level). Sampling from inside the train carriages also began with PM_{10} for 15 min at underground level followed by 15 min for ground level; afterwards the same process was applied after changing the sampling inlet to measure $PM_{2.5}$. The results collected from the sampling campaigns were divided into four sets of data: (i) PM_{10} inside the train, (ii) PM_{10} on the platforms, (iii) $PM_{2.5}$ inside the train, and (iv) $PM_{2.5}$ on the platforms. Each set of data was subdivided into two groups depending on the measuring level (ground level and underground level). The DustTrak device was carried out at the breathing level of commuters in compliance with recommendations and practices reported in other studies (Gulliver and Briggs, 2004; Ma et al., 2012; Moore and Figliozzi, 2011). To further investigate the effect of the operating levels (ground and underground), an additional sampling campaign was conducted from 22nd February to 4th March 2016 at the Town Hall Station (platforms and concourse level) for 30 min at each level to measure PM_{10}. Measurements were taken for 15 min from two different locations at the platforms on each level. The sampling started from the highest underground level (Town Hall concourse) moving down to the first underground level (Town Hall 1) and then to the lowest underground level (Town Hall 2).

To achieve the objectives of this study, we used data from two fixed monitoring stations provided by the NSW Office of Environment and Heritage (NSW OEH) to represent the background PM concentrations from ambient sources. The average data from the two fixed air quality stations (Earlwood and Rozelle) were recorded at the same time as the sampling from the railway.

In addition, dust samples were collected from the rail platforms over the period 1-19 March 2016, which were used for metal analysis. Dust samples were collected using a new plastic brush and dustpan from three different zones (left corner, middle, right corner) along the platforms, each one with an area of 2.5 × 2 m^2 at a distance of 40 cm away from the platforms' edge (**Fig. 2**). This method of sampling has been successfully applied in many studies to investigate the level of metal contamination in urban dust and soil samples (Charlesworth et al., 2003; Kamani et al., 2015; Saeedi et al., 2012). A random amount of about 300 g dust was collected on the platforms over a period of 3 days, stored in a new sealed plastic bag, properly labelled, and sieved through a 75-μm stainless steel sieve once in the laboratory. This process was repeated on five planforms (2 from Green Square, 2 from Town Hall, 1 from Mascot) to obtain five dust samples for metal analysis. Microscopic analysis of PM was carried out using scanning electron microscope (SEM) (Zeiss Evo-SEM). Each time, 1-g of sieved sample was digested and diluted according to the USEPA 3050B method using strong acid solution (US EPA 1996). Then sample solutions were analysed for metal concentration using the microwave plasma - atomic emission spectroscopy (MP-AES). Stringent quality control procedures using internal standards, reagent blanks and calibration curves for the 12 metals were followed.

2.3. Quality assurance of PM measurement

Comparability results between the light scattering measurement method and other methods usually used in the air quality fixed monitoring stations have shown some differences. Therefore, a correction factor was usually determined and used to obtain accurate measurements from the scattering methods (Cheng, 2008; Kam et al., 2011a; Yanosky et al., 2002). To assess the level of accuracy for the collected data from Sydney railway environments, the DustTrak was taken to a fixed air quality station (Liverpool Station) run by TEOM. The objective was to compare the data from both sources collected at the same time. The test was performed in October 2015, during the period of the first sampling campaign for 5 h (10 am to 3 pm). The regression analysis performed by SPSS showed that the TEOM measurements were within 2% of the DustTrak measurements for PM (Y = 0.98 X) with a regression coefficient (r^2) of 0.87, which means there is no need to use a correction factor. In addition, calibration and continuous cleaning processes were undertaken, as mentioned previously, in compliance with the manufacturer recommendations to ensure the best measurement accuracy. During the dust collection period, samples were collected from three different locations at the platforms (left end, middle, and right end) with 4.5 m between neighbouring sites to ensure that the collected samples can accurately represent the whole site in terms of metal contamination analysis.

2.4. Analytical method

Mean concentration values of PM were classified under eight different groups based on the railway microenvironments along with two set of values from the fixed monitoring stations to represent the background measurements. Differences in PM sources between the ground level, underground level and the urban background environment were determined by correlation analysis performed using SPSS (version 22).

Following this, the concentrations of 12 metal were determined using the MP-AES. To consider the level of contamination by metals in the underground railway platforms, the pollution index (PI) was determined using equation (1) and the results were interpreted using PI categorisation given in **Table 2**.

$$PI = \frac{C_{\text{railway}}}{C_{\text{background}}} \qquad \text{equation (1)}$$

where $C_{railway}$ (mg/g) represents the mean metal concentration from the subway measurements for a specific metal being measured, while $C_{background}$ (mg/g) represents the corresponding value of that metal from the background (i.e. Sydney Park).

To investigate the main sources of these metals (natural or anthropogenic), a common approach was applied in this study using the normalised enrichment factor (EF) to calculate the degree of enrichment relative to a crustal source. EF was calculated using equation (2). The results were then interpreted using the EF categorisation suggested in **Table 2**.

$$EF_e = \frac{(Ce/Cr)sample}{(Ce/Cr)background} \qquad \text{equation (2)}$$

where EF_e represents the enrichment factor for metal (e), $(C_e)_{sample}$ and $(C_r)_{sample}$ are the mean concentrations values of the specific (e) element and the reference element in the subway dust sample, respectively. $(C_e)_{background}$ and $(C_r)_{background}$ are the mean concentrations values of the same specific element and the same reference element measured from the background dust samples.

In addition, Pearson's correlation analysis was conducted for the target metals (**Table 3**). Al is highly abundant in earth's crust, hence Al in the dust samples can be derived from crustal sources rather than subway sources. Therefore, Al was used as a normalisation element in the calculations of EF values. Al has also been widely used as a normalisation factor in previous metal analysis studies (Chen et al. 2007; Kam et al. 2011b; Kamani et al. 2015; Karbassi et al. 2008).

3. Results and discussion

3.1. Particle size analysis and PM concentrations at ground and underground levels

Dust samples from the platforms were analysed by scanning electron microscope (SEM) to determine the particle size. The produced images showed that particles' diameter in the Sydney underground platforms dust was predominantly finer than 10 µm **(Fig. 3)**. In addition, chemical analysis of PM using the dust samples should provide a good indication about the metal components of PM_{10} and $PM_{2.5}$ in the railway environments.

The data obtained over six weeks of sampling are summarised in **Table 4** representing mean concentration values of PM_{10} and $PM_{2.5}$ from the railway microenvironments. Table 4 also shows the mean concentration values measured by the TEOM method from two fixed air quality stations to represent the ambient PM levels. In general, both size fractions were elevated at the railway underground microenvironments. Measurements of PM_{10} and $PM_{2.5}$ from inside the train carriages showed that the average concentrations at the underground level were higher than at ground level by approximately 2.8 and 2.5 times, respectively. Similarly PM_{10} and $PM_{2.5}$ concentrations on the platforms were 2.7 and 2.5 times higher at the underground level. These findings are consistent with previous studies carried out in different railway and metro networks in the world, showing that underground metro systems are the most polluted environments in terms of PM (Aarnio et al., 2005; Cheng and Yan, 2011; Kam et al., 2011a; Perrino et al., 2015; Ye et al., 2010). Underground tunnels are fully enclosed environments with a complete reliance on ventilation systems; hence the surrounding air quality is likely to be dominated by the internal environment.

The elevated concentrations of PM at the underground levels have been mainly attributed to non-exhaust particles from nearby railway sources such as wheel tracks, brakes, overhead power lines wear and abrasion (Moreno et al., 2015; Namgung et al., 2016; Olofsson, 2011; Querol et al., 2012). To investigate the effect of these sources in the Sydney underground system, results from the second sampling period showed that PM_{10} concentrations in Town Hall Station were noticeably different depending on the measurement location. **Fig. 4** shows that on the lowest platform level (TH2) with a complete reliance on the mechanical ventilation system of the station, PM_{10} concentrations could reach double the concentrations observed from the concourse level which has a mixed method of ventilation (natural and mechanical). Correlation analysis between three levels of measurements (n = 10) revealed a weak correlation between the Town Hall concourse measurements, where no trains are passing, and the two lower level platforms (TH1 and TH2) with a correlation factors of 0.39 and 0.37, respectively. At the same time, Town Hall 1 and Town Hall 2 measurements were strongly correlated with each other with a factor of 0.84. Despite the difference between PM_{10} concentrations between the two underground platforms, their strong correlations indicated that they shared the same sources of PM which can be mainly attributed to the train operation activities.

Another important observation to consider is the ratio between $PM_{2.5}$ and PM_{10} to assess the fine particle proportion. The results can help future epidemiological studies to estimate the potential health risks associated with exposure to PM. Results show very slight differences in $PM_{2.5}/PM_{10}$ ratio between the platforms and the train carriages. Commuters are exposed to relatively higher levels of the $PM_{2.5}$ than PM_{10} when travelling inside the train at both the ground and underground levels. At the underground levels, $PM_{2.5}/PM_{10}$ inside the train was approximately 0.76, while on the platforms it was 0.73. For the ground level, $PM_{2.5}/PM_{10}$ ratios from inside the train and from the platforms measurements were 0.85 and 0.81, respectively. Similar results were reported by the Los Angeles Metro study, showing that commuters were exposed to lower levels of fine particles while waiting on the metro platforms by a factor of 6% (Kam et al., 2011a). Such studies suggested that lower coarse fraction inside the trains was possibly the result of the air-conditioning systems, which were able to eliminate more coarse particles from the air than fine fractions (Kam et al., 2011a; Martins et al., 2015).

Higher standard deviation (SD) values were observed for PM measurements inside train carriages at both the ground and underground levels. This is likely due to the fact that PM concentrations can be significantly affected by the air coming from the platforms when a train stops at a station and the doors open, allowing commuters movement. As a result, PM measurements inside the train carriages will be significantly affected by the air quality and air flow directions around the platforms.

3.2. Comparison between PM concentration from Sydney railway microenvironments and ambient air

Correlation analysis was performed to assess the influence of the surrounding sources on PM_{10} and $PM_{2.5}$ in the railway microenvironments. The level of impact from background sources can be very different depending on the surrounding conditions. A study undertaken in the Prague underground railway system showed a strong association between ambient PM and particles from the underground microenvironments despite the statistically significant differences between the two measurements ($P < 0.001$) (Braniš, 2006). Another study from Taipei Rapid Transit network showed that both PM_{10} and $PM_{2.5}$ concentrations were highly influenced by ambient PM with correlation coefficients of 0.72 and 0.78, respectively (Cheng et al., 2008). On the other hand, regression analysis for the Los Angeles Metro suggested PM concentrations from the subway line (underground) were considerably less influenced by ambient conditions, compared with ground level concentrations (Kam et al., 2011a). Similar results from a recent study in the Barcelona subway system indicated higher concentrations of PM from the underground tunnel by up to 6.7 times compared to outdoor environments with a weak association between the two sources (Martins et al., 2015). At underground levels, particles from ambient sources may penetrate into the enclosed train tunnels and the platforms through air corridors and ventilation openings, adding more PM to the local railway sources.

Fig. 5 illustrates the correlation analysis between PM concentrations from different railway microenvironments and PM concentrations from background measurements. The PM (PM_{10} and $PM_{2.5}$) data from the platforms were assessed against the PM data from the Rozelle air quality station, whereas PM data from inside the train carriages running at both the ground and underground levels were assessed against PM concentrations from Earlwood air quality satiation. The results showed a strong positive association between PM_{10} and $PM_{2.5}$ from the ground level platforms and background PM data with r^2 values of 0.843 and 0.952, respectively (**Fig. 5**a-b). PM_{10} concentration was well below the Australian standards of 50 µg/m^3, and $PM_{2.5}$ concentration was also under the allowable national standards of 25 µg/m^3. For underground platforms, a very weak correlation was observed between PM concentrations and background PM with r^2 values of 0.072 for PM_{10} and 0.210 for $PM_{2.5}$ (**Fig. 5**c-d). In addition, PM_{10} and $PM_{2.5}$ at underground platforms exceeded the national air quality standards during almost all sampling days. These results indicated that PM concentrations at ground level platforms were significantly influenced by the ambient background sources, while the impact of which on PM concentrations at underground platforms was not apparent. The PM results from inside the train carriages showed similar trend in terms of association with ambient background particle concentrations (**Fig. 5**e-h). At ground levels, the correlation coefficient (r^2) values were 0.500 for PM_{10} and 0.823 for $PM_{2.5}$, indicating a moderate to strong positive correlation. In comparison, the PM concentrations in underground carriages showed a weak correlation with background for both PM_{10} (r^2 = 0.123) and $PM_{2.5}$ (r^2 = 0.264), suggesting potentially little impact from the background on PM abundance inside train carriages in the underground.

Higher concentrations of PM from underground microenvironments along with the moderate to weak correlations coefficients confirmed the presence of additional local railway PM sources. Particles generated from the railway environment accumulated inside the trains and on the platforms over time due to their enclosed conditions leading to elevated levels of PM. To further confirm that, two paired sampled t-tests were carried out to compare the ground and underground levels of $PM_{2.5}$ from inside the train and those of PM_{10} from the platforms. The results showed that at 95% confidence interval, both $PM_{2.5}$ and PM_{10} at the underground were significantly different to those at ground level ($P < 0.005$).

Adverse health effects associated with exposure to PM are well documented based on their concentrations and the chemical composition (Anderson et al., 2012; Gray et al., 2015; Liu et al., 2014; Valavanidis et al., 2008). To estimate the potential health risks associated with exposure to elevated concentrations of PM, 24 h monitoring measurements should be presented to comply with the global air quality standards which are normally stated in terms of daily or annual mean concentrations per cubic metre. Underground measurements were above the allowable Australian Standards, posing potential threat to passengers.

3.3. Comparison of PM from Sydney train with global railway systems

Since the first operation of electrical powered trains introduced in the Sydney railway system, continuous improvements have been applied to ensure reliable and environmentally friendly practices for this transport mode. To assess the level of PM exposure in the Sydney railway system, the mean values of PM_{10} and $PM_{2.5}$ from Sydney and worldwide railway systems were summarized (**Table 5**). Some of these systems are relatively new systems which have only been operating for the last two decades; some of them are equipped with the latest clean operation technologies to ensure the lowest pollution levels. It is worth noting that all systems included in **Table 5** were electrified powered systems and the main PM was assumed to be from non-exhaust sources. Current results showed that PM_{10} and $PM_{2.5}$ at ground and underground levels were within or less than the range of other railway systems (**Fig. 6**). Sydney railway PM levels were very close to the Los Angles system or may be better especially if considering that all data from this study were only collected during weekday's rush hours. Ground and underground concentrations from inside the trains were better in the Los Angeles and Taipei systems suggesting that their air conditioning systems technology are more efficient to remove the particles. However, PM concentrations from the platforms of Sydney system were less than in other systems suggesting that the ventilation system design and technology could be more efficient in Sydney. The effect of the ventilation systems can be clearly noticed from Seoul study by the exceptional high levels of PM in all microenvironments due to the lack of mechanical ventilation system (Park and Ha, 2008). Wind velocity is another factor which might affect the outdoor particles levels. Studies found a strong negative correlation between wind velocity and PM concentrations (Braniš, 2009; Jones, 2010). The mean value of wind speed at the time of sampling as obtained from the Australian Bureau of Meteorology was relatively high, at about 23 km/h in Sydney CBD and Sydney Airport areas. With this magnitude of wind velocity, it is likely that there was efficient air dispersion hence reduced PM concentrations.

The Sydney railway system has a relatively low level of PM pollution compared with other railway systems based on the ratio between the railway and the background mean concentrations. The results showed that the ratio of PM_{10} and $PM_{2.5}$ between different railway microenvironments and urban backgrounds ranged between 0.9 and 5.4 in comparison to 0.52 and 2.8 for the Los Angeles railway system (Kam et al., 2011a); 5-30 for Paris underground railway station (Raut et al., 2009); and 4-14 for Naples (Italy) Metro system (Cartenì et al., 2015). The notable differences can be mainly attributed to differences in rail system age and condition, ventilation and brakes systems, geographic level of measurements (e.g. tunnel depth), the monitoring methods (e.g. DustTrak, TEOM), surrounding metrological conditions and other factors which might significantly affect PM concentrations. Studies have also shown remarkable improvements in reducing PM concentrations after the installation of the platform screen doors (PSDs) which act as a physical barrier to isolate the air quality on the platforms (Kim et al., 2012; Ma et al., 2012; Martins et al., 2015).

3.4 Metal concentration analysis

Table 6 shows the mean concentration values (mg/g) for the twelve metals based on the results of MP-AES analysis of dust samples from the railway platforms and the background samples. The most significant differences between the two environments are the dominance of Fe in the subway platforms samples, and of Ca in the background samples. The mean concentrations of metals from all five railway platforms followed the order of Fe, Cr, Ca, Al, Na, Ba, Mn, Zn, Cu, Ni, Co, and Pb dominated remarkably by Fe with a mean concentration value of 73.51 mg/g, which is almost 7.5% of the total dust weight. In comparison to the background measurements, commuters on Sydney underground platforms are exposed to substantially higher levels of some of these metals. The Fe concentration was almost 20 times greater than the background results suggesting that the railway environment has additional local sources of Fe which need to be carefully considered when estimating the potential human health implications that might result from personal exposure. The substantial presence of Fe has also been reported in other subway studies suggesting that the wear and abrasion processes in the rail lines, wheels and the brake system are the main sources of Fe and other metal substances (Kam et al., 2011b; Ma et al., 2012; Martins et al., 2016; Moreno et al., 2015).

3.5 Pollution index (PI) for metals

Fig. 7 illustrates the results of the PI values in the Sydney railway using the mean concentration values presented in **Table 6**. Based on the suggested categorisation, the PI values varied widely across the different metals. Three out of twelve metals showed very high contamination levels; these were Fe, Ni, and Cr with PI values of 19.6, 8.53 and 6.8 respectively. Mn was within the considerable range with a PI value of 3.6, while Ba, Cu and Zn were considered to be moderate with PI values of 2.3, 1.2 and 1.4, respectively. The rest of the measured metals indicated no contamination from the subway sources since their PI values were all < 1. Consistent with other studies, PI values from the Sydney railway system indicate moderate to very high contamination levels by heavy metals (Cui et al., 2016; Kam et al., 2011b; Moreno et al., 2017; Nieuwenhuijsen et al., 2007).

3.6 Enrichment factors (EF) for metals

Enrichment factor values (**Table 7**) decreased in the order of Fe, Ni, Cr, Mn, Ba, Zn, Cu, Co, Ca, Al, Pb and Na. The results showed that Fe was the most enriched element with an EF value of 61.3 (extremely severe), followed by Ni (EF = 26.7) indicating severe anthropogenic origins and then Cr (EF = 21.3). By contrast, EF values for Co, Ca, Al, Pb and Na indicated crustal origins. From the mean concentration values in **Table 6**, it can be observed that the concentrations of Co, Cu and Zn from the railway were less or about the same as those from the background measurements. However, their EF values indicated different contamination levels (moderate to minor enrichment). The main source of Zn in the railway microenvironments is its use as a coating layer for the steel tracks to prevent excessive corrosion; in addition, it could be from street level vehicles (Chen et al., 2009; Kam et al., 2011b).

A high EF value (> 3) indicates that these elements have actually been produced by subway sources (e.g. rail and brake friction and abrasion). These sources are local and have no effect on the vicinity of the background site. However, they can significantly affect the surrounding railway microenvironments. The results are consistent with findings from previous subway studies, indicating the same enriched set of metals in the subway microenvironments, although in different orders (Kam et al., 2011b; Qiao et al., 2015; Salma et al., 2009).

4. Conclusions

The concentrations of PM and metals were measured in the Sydney railway system both on the platforms and inside train carriages at the ground and underground levels. The results demonstrated that the underground microenvironments in the railway system had a higher PM concentration than the ground level measurements by a factor of 2.8 for PM_{10} and 2.5 for $PM_{2.5}$. Commuters were exposed to relatively higher levels of $PM_{2.5}$ than PM_{10} when riding inside the train carriages. The $PM_{2.5}/PM_{10}$ ratio was lower when measured from the platforms at both levels suggesting that the air conditioning system inside the train carriages was efficient in removing more PM_{10} than $PM_{2.5}$. All ground level PM concentrations were less than the national air quality standards, while underground PM levels exceeded the standards during almost all sampling days indicating the potential to cause different health problems to commuters. However, unless a 24 h monitoring data are available with details about their chemical composition, the potential health risks associated with exposure to PM cannot be fully considered. Heavy metal concentrations for the underground platforms were also observed in this study by MP-AES. Determinations of PI values indicate that Fe, Ni and Cr were substantially higher than the background values. EF analysis showed that seven metals were enriched in the range of being extremely severe to moderate, and Fe was the most abundant metal in the underground platforms. High EF values indicate that these metals are mainly from local railway anthropogenic sources such as the wear and abrasion processes of the rail lines, wheels and brake system. The observed results provide a comprehensive assessment of PM levels and their metal content in the railway environments. The results can be used to assess potential health risks due to the commuters' exposure to PM in the railway systems. Further research is needed to conduct longer term measurement of PM and other associated contaminants e.g. carcinogens on PM in order to provide a more comprehensive and thorough risk characterisation and control.

Acknowledgments

The authors would like to thank Sydney Trains for allowing us to access the airport line (T2) train carriages and platforms. We would like to thank Christopher Royal from Sydney Trains for his special support and information. The findings and opinions in this paper are independent of, and not formally endorsed by Sydney Trains.

References

Aarnio, P., Yli-Tuomi, T., Kousa, A., Mäkelä, T., Hirsikko, A., Hämeri, K., Räisänen, M., Hillamo, R., Koskentalo, T., Jantunen, M., 2005. The concentrations and composition of and exposure to fine particles ($PM_{2.5}$) in the Helsinki subway system. Atmos. Environ. 39 (28), 5059-66.

Abbasi, S., Wahlström, J., Olander, L., Larsson, C., Olofsson, U., Sellgren, U., 2011. A study of airborne wear particles generated from organic railway brake pads and brake discs. Wear 273 (1), 93-9.

Adams, H., Nieuwenhuijsen, M., Colvile, R., McMullen, M., Khandelwal, P., 2001. Fine particle ($PM_{2.5}$) personal exposure levels in transport microenvironments, London, UK. Sci. Total Environ. 279 (1), 29-44.

Anderson, J.O., Thundiyil, J.G., Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. J. Med. Toxicol. 8 (2), 166-75.

Aktins, A., Bignal, K., Zhou, J.L., Cazier, F., 2010. Profiles of polycyclic aromatic hydrocarbons and polychlorinated biphenyls from wood pellet combustion. Chemosphere 78, 1385-1392.

Braniš, M., 2006. The contribution of ambient sources to particulate pollution in spaces and trains of the Prague underground transport system. Atmos. Environ. 40 (2), 348-56.

Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diez-Roux, A.V., Holguin, F., Hong, Y., Luepker, R.V., Mittleman, M.A., 2010. Particulate matter air pollution and cardiovascular disease an update to the scientific statement from the American Heart Association. Circulation 121 (21), 2331-78.

Bureau of Transport Statistics 2014. Train Statistics 2014, Transport for NSW, Australia.

Bureau of Transport Statistics 2015. Transport for NSW 2014-15 Annual Report Volume 1, Transport for NSW, Australia.

Cartenì, A., Cascetta, F., Campana, S., 2015. Underground and ground-level particulate matter concentrations in an Italian metro system. Atmos. Environ. 101, 328-37.

Charlesworth, S., Everett, M., McCarthy, R., Ordonez, A., De Miguel, E., 2003, A comparative study of heavy metal concentration and distribution in deposited street dusts in a large and a small urban area: Birmingham and Coventry, West Midlands, UK, Environ. Int. 29(5), 563-73.

Chen, Z., Shi, Y., Jiao, B., Zhao, H., 2009, Ultrasonic nondestructive evaluation of spot welds for zinc-coated high strength steel sheet based on wavelet packet analysis, J. Mater. Process. Technol. 209(5), 2329-37.

Cheng, Y.H., Lin, Y.L., Liu, C.C., 2008. Levels of PM_{10} and $PM_{2.5}$ in Taipei rapid transit system. Atmos. Environ. 42 (31), 7242-9.

Cheng, Y.H., Yan, J.W., 2011. Comparisons of particulate matter, CO, and CO_2 levels in underground and ground-level stations in the Taipei mass rapid transit system. Atmos. Environ. 45(28), 4882-91.

Colombi, C., Angius, S., Gianelle, V., Lazzarini, M., 2013. Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system. Atmos. Environ. 70 (31), 166-178.

Cui, G., Zhou, L., Dearing, J., 2016. Granulometric and magnetic properties of deposited particles in the Beijing subway and the implications for air quality management. Sci. Total Environ. 568, 1059-68.

Cusack, M., Talbot, N., Ondráček, J., Minguillón, M., Martins, V., Klouda, K., Schwarz, J. Ždímal, V., 2015. Variability of aerosols and chemical composition of PM10, PM2.5 and PM1 on a platform of the Prague underground metro. Atmos. Environ. 118, 176-83.

Epton, M.J., Dawson, R.D., Brooks, W.M., Kingham, S., Aberkane, T., Cavanagh, J.A.E., Frampton, C.M., Hewitt, T., Cook, J.M. McLeod, S. 2008. The effect of ambient air pollution on respiratory health of school children: a panel study. Environ. Health 7, 16.

Farraj, A.K., Walsh, L., Haykal-Coates, N., Malik, F., McGee, J., Winsett, D., Duvall, R., Kovalcik, K., Cascio, W.E., Higuchi, M., 2015. Cardiac effects of seasonal ambient particulate matter and ozone co-exposure in rats. Part. Fibre Toxicol. 12, 12.

Fridell, E., Ferm, M., Ekberg, A., 2010. Emissions of particulate matters from railways–Emission factors and condition monitoring. Transport. Res. Part D Transport Environ. 15(4), 240-245.

Gray, D.L., Wallace, L.A., Brinkman, M.C., Buehler, S.S. La Londe, C., 2015. Respiratory and cardiovascular effects of metals in ambient particulate matter: a critical review. Rev. Environ. Contam. Toxicol. 234, 135-203.

Gulliver, J., Briggs, D.,2004. Personal exposure to particulate air pollution in transport microenvironments. Atmos. Environ. 38 (1), 1-8.

Hamra, G.B., Guha, N., Cohen, A., Laden, F., Raaschou-Nielsen, O., Samet, J.M., Vineis, P., Forastiere, F., Saldiva, P. Yorifuji, T., 2014. Outdoor particulate matter exposure and lung cancer: a systematic review and meta-analysis. Environ. Health Perspect. 122 (9), 906-911.

Kam, W., Cheung, K., Daher, N. Sioutas, C., 2011a. Particulate matter (PM) concentrations in underground and ground-level rail systems of the Los Angeles Metro. Atmos. Environ. 45 (8), 1506-16.

Kam, W., Ning, Z., Shafer, M., Schauer, J., Sioutas, C. 2011b. Chemical Characterization of Coarse and Fine Particulate Matter (PM) in Underground and Ground-level Rail Systems of the Los Angeles Metro. Environ. Sci. Technol. 45(16), 6769–76.

Kamani, H., Ashrafi, S.D., Isazadeh, S., Jaafari, J., Hoseini, M., Mostafapour, F.K., Bazrafshan, E., Nazmara, S. and Mahvi, A.H., 2015. Heavy metal contamination in street dusts with various land uses in Zahedan, Iran. Bull. Environ. Contam. Toxicol. 94(3), 382-386.

Kampa, M., Castanas, E., 2008. Human health effects of air pollution. Environ. Pollut. 151(2), 362-367.

Karlsson, H.L., Nilsson, L., Möller, L., 2005. Subway particles are more genotoxic than street particles and induce oxidative stress in cultured human lung cells. Chem. Res. Toxicol. 18(1), 19-23.

Kim, K.-H., Ho, D.X., Jeon, J.S., Kim, J.C., 2012. A noticeable shift in particulate matter levels after platform screen door installation in a Korean subway station. Atmos. Enviorn. 49, 219-23.

Kim, K.-H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136-43.

Knibbs, L.D., de Dear, R.J., Morawska, L. Mengersen, K.L., 2009. On-road ultrafine particle concentration in the M5 East road tunnel, Sydney, Australia. Atmos. Environ. 43 (22), 3510-9.

Knibbs, L.D., Morawska, L., 2011. An investigation of commuter exposure to ultrafine particles in Sydney. Air Qual. Climate Change 45 (2), 15.

Li, T.T., Bai, Y.H., Liu, Z.R., Li, J.L., 2007. In-train air quality assessment of the railway transit system in Beijing: a note. Transport. Res. Part D Transport Environ. 12 (1), 64-7.

Liu, L., Yu, L.Y., Mu, H.J., Xing, L.Y., Li, Y.X., Pan, G.W., 2014. Shape of concentration-response curves between long-term particulate matter exposure and morbidities of chronic bronchitis: a review of epidemiological evidence. J. Thorac. Disease 6 (7), 720.

Lopez, A.D., Mathers, C.D., Ezzati, M., Jamison, D.T., Murray, C.J., 2006. Global and regional burden of disease and risk factors, 2001: systematic analysis of population health data. Lancet 367 (9524), 1747-57.

Ma, C.J., Matuyama, S., Sera, K., Kim, S.D., 2012. Physicochemical properties of indoor particulate matter collected on subway platforms in Japan. Asian J. Atmos. Environ. 6 (2), 73-82.

Martins, V., Moreno, T., Minguillón, M.C., Amato, F., de Miguel, E., Capdevila, M., Querol, X., 2015. Exposure to airborne particulate matter in the subway system. Sci. Total Environ. 511, 711-22.

Moore, A., Figliozzi, M., 2011. Bus Stop Air Quality: An Empirical Analysis of Shelter Orientation Effects on Transit User's Exposure to Particulate Matter. Western ITE Conference Proceedings.

Moreno, T., Kelly, F.J., Dunster, C., Oliete, A., Martins, V., Reche, C., Minguillón, M.C., Amato, F., Capdevila, M., de Miguel, E., 2017. Oxidative potential of subway PM2.5. Atmos. Environ. 148, 230-8.

Moreno, T., Martins, V., Querol, X., Jones, T., BéruBé, K., Minguillón, M.C., Amato, F., Capdevila, M., de Miguel, E. Centelles, S., 2015. A new look at inhalable metalliferous airborne particles on rail subway platforms. Sci. Total Environ. 505, 367-75.

Moreno, T., Pérez, N., Reche, C., Martins, V., de Miguel, E., Capdevila, M., Centelles, S., Minguillón, M., Amato, F. Alastuey, A., 2014. Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design. Atmos. Environ. 92, 461-8.

Namgung, H.G., Kim, J.B., Woo, S.H., Park, S., Kim, M., Kim, M.S., Bae, G.N., Park, D. Kwon, S.B., 2016. Generation of Nanoparticles from Friction between Railway Brake Disks and Pads. Environ. Sci. Technol. 50 (7), 3453-61.

NEPC 2015. Air quality standards, Australian Governemt - Department of Environment, https://www.environment.gov.au/protection/air-quality/air-quality-standards.

Nieuwenhuijsen, M., Gomez-Perales, J., Colvile, R., 2007. Levels of particulate air pollution, its elemental composition, determinants and health effects in metro systems. Atmos. Environ. 41(37), 7995-8006.

Olofsson, U., 2011. A study of airborne wear particles generated from the train traffic—Block braking simulation in a pin-on-disc machine. Wear 271(1), 86-91.

Park, D.U., Ha, K.C., 2008. Characteristics of PM10, PM2.5, CO_2 and CO monitored in interiors and platforms of subway train in Seoul, Korea. Environ. Int. 34 (5), 629-34.

Perrino, C., Marcovecchio, F., Tofful, L., Canepari, S., 2015. Particulate matter concentration and chemical composition in the metro system of Rome, Italy. Environ. Sci. Pollut. Res. 22 (12), 9204-9214.

Qiao, T., Xiu, G., Zheng, Y., Yang, J., Wang, L., Yang, J., Huang, Z., 2015, 'Preliminary investigation of PM 1, PM 2.5, PM 10 and its metal elemental composition in tunnels at a subway station in Shanghai, China', Transport. Res. Part D Transport Environ. 41, 136-46.

Querol, X., Moreno, T., Karanasiou, A., Reche, C., Alastuey, A., Viana, M., Font, O., Gil, J., Miguel, E.d. Capdevila, M., 2012. Variability of levels and composition of PM_{10} and $PM_{2.5}$ in the Barcelona metro system. Atmos. Chem. Phys. 12 (11), 5055-76.

Raut, J.C., Chazette, P., Fortain, A., 2009. Link between aerosol optical, microphysical and chemical measurements in an underground railway station in Paris. Atmos. Environ. 43 (4), 860-8.

Saeedi, M., Li, L.Y., Salmanzadeh, M., 2012. Heavy metals and polycyclic aromatic hydrocarbons: pollution and ecological risk assessment in street dust of Tehran. J. Hazard. Mater. 227, 9-17.

Salma, I., Posfai, M., Kovacs, K., Kuzmann, E., Homonnay, Z., Posta, J., 2009. Properties and sources of individual particles and some chemical species in the aerosol of a metropolitan underground railway station. Atmos. Environ. 43(22), 3460–3466.

Song, M., Zhang, G., Zeng, W., Liu, J., Fang, K., 2016. Railway transportation and environmental efficiency in China. Transport. Res. Part D Transport Environ. 48, 488-498.

US EPA 1996, Method 3050B: Acid digestion of sediments, sludges and soils (revision 2).

Valavanidis, A., Fiotakis, K., Vlachogianni, T., 2008. Airborne particulate matter and human health: toxicological assessment and importance of size and composition of particles for oxidative damage and carcinogenic mechanisms. J. Environ. Sci. Health Part C 26 (4), 339-62.

WHO 2002. The World Health Organization Report 2002: Reducing Risks, Promoting Healthy Life.

WHO 2013. Health Effects of Particulate Matter: Policy Implications for Countries in Eastern Europe, Caucasus and Central Asia, World Health Organization Regional Office for Europe.

Ye, X., Lian, Z., Jiang, C., Zhou, Z., Chen, H., 2010. Investigation of indoor environmental quality in Shanghai metro stations, China. Environ. Monitor. Assess. 167 (1-4), 643-51.

Zhang, J., Deng, H., Wang, D., Chen, Z., Xu, S., 2013. Toxic heavy metal contamination and risk assessment of street dust in small towns of Shanghai suburban area, China. Environ Sci. Pollut. Res. 20(1), 323–332.