DELIVERABLE 2

Historical PM level and chemical composition database

Action A1

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Historical PM level and chemical composition database

Content

Subway systems in major cities can be viewed as a transport lifeline, helping to improve the quality of urban infrastructure, relieve road traffic congestion, as well as to fill gaps in other public transports and road surface capacity (Vasconcellos, 2001). They also reduce air pollution above ground: Silva et al. (2012) concluded that a subway strike in São Paulo led to a significant increase in daily mean PM_{10} (particulate matter below 10 microns in size) concentrations (by 45-60%) due to extra road traffic.

The operation of underground urban rail systems, which began in the middle of the 19th century, these days carries more passengers per trip in some urban areas than any other transport mode, so that many millions of people worldwide spend a proportion of their daily time in underground trains. However, the underground system is a confined space that may permit concentration of contaminants either infiltrating from the outside atmosphere or generated internally. In this context, a number of studies have been conducted to assess the levels of PM and its chemical composition in subway systems.

The first comprehensive subway commuters' exposure study was conducted in Boston at the end of the 1980s (Chan et al., 1991), focused on exposure to gasoline-related volatile organic compounds (VOCs), and was followed by further studies assessing levels of air pollution in subway systems. After more than a decade of research, different air pollutants such as PM (e.g. Furuya et al., 2001; Seaton et al., 2005; Park et al., 2012; Querol et al., 2012), PAHs (Furuya et al., 2001), carbon monoxide (Cheng et al., 2011), nitrogen dioxide (Klepczyńska-Nyström et al., 2011), ozone (Awad et al., 2002), metals (Kang et al., 2008; Karlsson et al., 2008; Park et al., 2012; Moreno et al., 2015), and different biological pollutants (Awad, 2002; Hwang et al., 2010) have all by now been measured using off-line samplers and/or real-time monitors.

The monitoring equipment and location used has varied in these different studies and in some cases have led to contrasting conclusions, making it difficult to compare results between subway systems. Some studies have reported higher levels of PM in the subway system (e.g London, Barcelona, Stockholm) compared to other modes of transport and street canyons, while other studies reported lower levels in the subway system (e.g. Hong Kong, Guangzhou, and Mexico City). Studies comprising chemical characterisation all agree however on the high contribution of Fe, which is usually associated with friction processes between wheel and rail, brake abrasion, and the abrasion of power cables and third rails. Similarly, a common enrichment in Cu compared to outdoor levels is generally attributed to copper lines for power transmission, while Mn is (like Fe) released from abrasion of the subway rail and the train wheels.

It has been argued that current levels of PM and toxic matter are unlikely to lead to any significant excess health effects in commuters (Nieuwenhuijsen et al., 2007 and references therein). Nevertheless, in contrast some studies have concluded that subway particles have a higher oxidative potential than ambient particles outdoors. For example, in Steenhof et al. (2011), the authors investigated the in-vitro toxicity of PM collected at different sites in the Netherlands and concluded that the underground samples showed the largest decrease of

metabolic activity in murine macrophages compared to traffic and urban background sites. In the Paris subway system, Bachoual et al. (2007) concluded that PM has transient biological effects and that lung inflammatory and structural cells could be targets of subway PM_{10} exposure. These authors found that the high levels of Fe in the subway samples (comprising around 52% of PM_{10} mass) were not a single prominent causative factor of the PM's biological effects. Consequently, it is reasonable to conclude, using the precautionary principle, that PM levels should be controlled and reduced where possible.

A literature review of recent studies conducted in subway systems worldwide (Figure 1) is documented in this report, and summarised as a database in Table 1, which includes information on the location of the study, time duration of the study, measuring equipment used, frequency of the samples, number of samples collected and species analysed, as well as the type of main pollution sources identified. Parameters characterised in each subway system have been summarised by city in Table 2. Finally average values of each parameter studied in each study are shown in Annexe A at the end of this report.

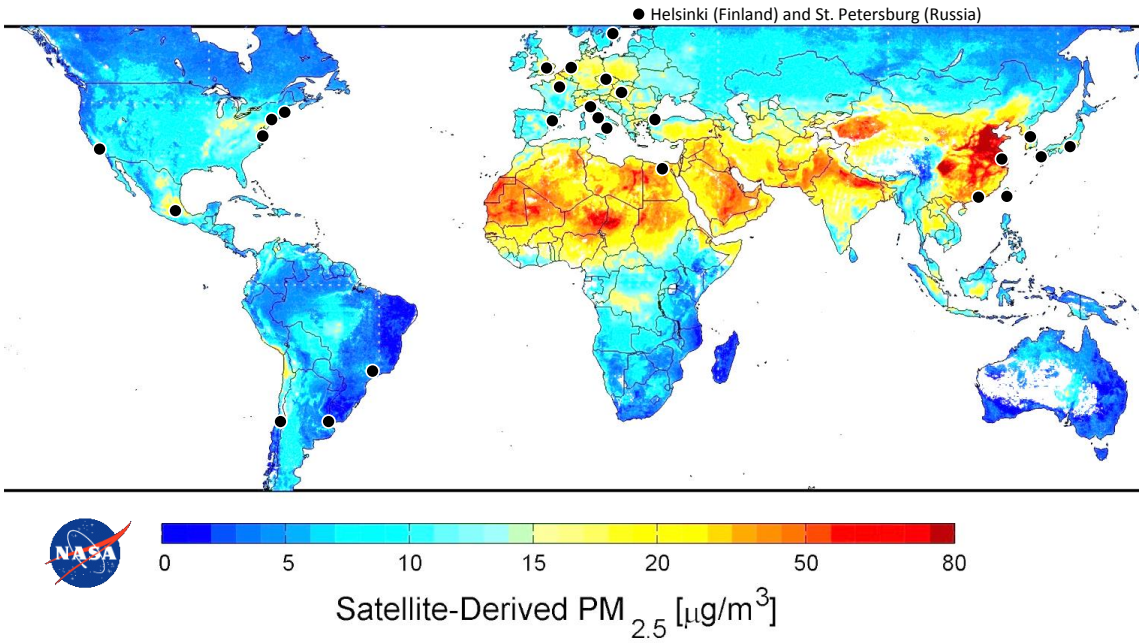

Figure 1. Location of cities where studies of subway air quality have been published. World map from NASA showing satellite-derived $PM^{2.5}$ concentrations in ambient air.

1. LITERATURE ON SUBWAY SYSTEMS IN EUROPE

The **Stockholm** underground system has been extensively characterised, with data available since 1983 (Colmsjö et al., 1990). Johansson and Johansson (2003) reported PM_{10} and $PM_{2.5}$ concentrations of 470 and 260 μgm^{-3}, respectively, during weekdays; these levels being a factor 5-10 higher than the corresponding values measured in one of the busiest streets in central Stockholm. Authors reported a slight reduction of PM levels (13% PM_{10}, 10% $PM_{2.5}$) during a few days when walls and tracks were washed using water, indicating that particles from tunnel walls and tracks make only a minor contribution. On the other hand, concentrations were observed to follow closely the train traffic intensity. This relationship between train traffic and PM_{10} concentrations was also observed by Gustafsson et al. (2012), who reported lower levels (PM_{10}= 88-247 μgm^{-3}). They found particle number concentrations of 900-6000 particles cm^{-3} in the size range 0.01-0.7 µm. This study reported chemical characterization of PM_{10} samples, showing mean Fe levels up to 360 µg m^{-3}. According to Midander et al. (2012), mean PM_{10} and $PM_{2.5}$ levels in the subway system of the city centre were 160μgm^{-3} and 60μgm^{-3}, respectively, with particles predominantly consisting of iron, oxygen and carbon. Mean Elemental Carbon (EC) and Organic Carbon (OC) concentrations of 10 µg m^{-3} and 28 μgm^{-3}, respectively, were reported for total PM. Mean Fe concentration was 4.4 µg m^{-3} for total PM. On the other hand, mean particle number concentration in the platform of this station (12000#cm^{-3}) was 4 times lower than outdoor. On-line Black Carbon (BC) measurements were also conducted in this study (7.5 μgm^{-3} on average). Regarding health effects, Karlsson et al. (2008) investigated the bioreactivity of subway particles, revealing an apparently higher genotoxicity than several other particles (street, road tire or wood), and concluded that genotoxicity of subway particles was due to redox-active surfaces rather than soluble iron. Klepczyńska-Nyström et al. (2012) reported that airway inflammatory responses after exposure in the subway environment of Stockholm differ between asthmatic and healthy human. Environmental exposure was extensively characterised in this study (PM_{10} = 242 µg m^{-3}, $PM_{2.5}$= 77 μgm^{-3}, ultrafine particle number concentration= 8280#cm^{-3}; NO= 58 μgm^{-3}, NO_2= 24 μgm^{-3}, Fe in PM_{10}=58.6 μgm^{-3}, Ba in PM_{10}= 1.0 μgm^{-3}, Mn in PM_{10}= 0.5 μgm^{-3}, Cu in PM_{10}= 0.8 μgm^{-3}). Abbasi et al. (2012) focused on the characterisation of size-resolved chemical composition; three peaks at 280, 350, and 600 nm in diameter were identified in the fine region during braking. Fe, Si, Al, Ca, Cu, and Zn with a diameter around 0.25-0.32 µm were identified as the main components. Regarding processes, wheel-rail creep during train acceleration and curve negotiation were concluded to play a crucial role in generating particles from wheel-rail contact.

Some of the highest average levels of PM were measured in the **London** subway system. According to Seaton et al. (2005), $PM_{2.5}$ concentrations at platforms ranged between 270 and 480 μgm^{-3}, and particle number concentrations between 14000 and 29000 # cm^{-3}. $PM_{2.5}$ concentrations in train cabins were lower (130-200 μgm^{-3}), while particle number concentrations were relatively higher (17000-23000 # cm^{-3}). The dust at platforms comprised approximately 67% by mass iron oxide, 1-2% quartz, and traces of other metals, the residue being volatile matter. Taking account of durations of exposure, drivers and station staff were

observed to have maximum exposures of about 200 μgm^{-3} over eight hours; in comparison to this the occupational exposure standard for welding fume, as iron oxide, is 5 mgm^{-3} over an eight hour shift. Toxicology showed the dust to have cytotoxic and inflammatory potential at high doses.

Passenger exposure to PM_{10} during subway commuting also showed seasonal differences in **Prague** (Braniš et al., 2006). Mass concentrations inside train were significantly higher in winter (125.5 μgm^{-3}) compared to summer (82.3 μgm^{-3}).

The indoor air quality in the subway system of **Istanbul** was characterised in Sahin et al. (2012). Mean PM_{10} concentrations at platforms during normal hours ranged between 58 and 213 μgm^{-3}, and between 59 and 201 μgm^{-3} during rush hours. 15-30% of the inhalable PM of size>2.1 µm was determined as Fe-containing particles. In mass terms, Fe concentrations ranged between 10.3±1.6 μgm^{-3} and 28.2±19.6 μgm^{-3}. A commuting study was carried out by Onat and Stakeeva (2013) using four public transport modes: bus, subway–bus, car and walking. Lower $PM_{2.5}$ concentrations were observed inside the subway-bus (45.4 ±18.6 μgm^{-3} for rush hours and 39.9±16.0 μgm^{-3} for non-rush hours) than inside the bus and walking, probably due to the PM filtering of cabin air by the air conditioning system.

Carbonaceous compounds were widely characterised in the subway of **Helsinki** (Aarnio et al., 2005), where the concentrations of EC (4.0 μgm^{-3}), OC (7.4 μgm^{-3}), BC (6.3 μgm^{-3}) and ultrafine particle number (31000 $\#cm^{-3}$) were rather similar to those in ambient air, while $PM_{2.5}$ concentrations were significantly higher at the subway platform (60 μgm^{-3} vs 10 μgm^{-3} at urban background). The most enriched element was Fe (29±7 μm^{-3}). Results concerning passenger exposure showed that a 30 min commuting plus 9 min stay at the stations per day increased the exposure to $PM_{2.5}$ mass by only approximately 3% compared to staying in an urban traffic environment, although the exposure to iron in $PM_{2.5}$ increased nearly 200%, to Mn 60% and to Cu 40%.

The time variation of PM_{10} mass concentration was studied in the subway of **Budapest** (Salma et al., 2007), which exhibited two peaks, one at approximately 7:00h and the other at approximately 17:00h. Mean PM_{10} concentration for working hours was high (155±55 μgm^{-3}), with 72% of the mass associated with the PM_{10-2} size fraction. Around 40% of the PM_{10-2} mass in the subway was made of Fe, and the contributions of Si and Ca were approximately 3% each. In the PM_2 size fraction, Fe and S showed the greatest contributions of 46% and 2.5%, respectively. In Salma et al. (2009), it was concluded that hematite was a major Fe-bearing species in the PM_{10-2} size fraction, its mass contribution to the Fe being 36% (34 mgm^{-3}). In the $PM_{2.0}$ size fraction approximately 7% of the dissolved Cr was present as Cr(VI), which was different from that for the urban aerosol. It is suggested in this publication that the increased adverse health effects of aerosol particles in subways with respect to ambient outdoor particles is linked to the differences in the oxidation states, surface properties or morphologies.

The subway stations of **Milan** were investigated by Colombi et al. (2013). Weekday PM_{10} concentrations were found to range between 105 μgm^{-3} and 283 μgm^{-3} at the platform, with higher levels recorded at stations with narrow tunnels. The number of trains scheduled during the hour was the same as the number of concentration peaks. A cluster analysis showed that wheel, brake and track (characterised by Fe, Mn, Sb and Ba oxides) contributed 40-73% of total PM_{10} mass, and electric cable wear (characterised by Cu and Zn oxides) 2-3%.

In Loxham et al. (2013) the elemental composition of size fractionated underground PM in **Amsterdam** was compared with that from a woodstove, a road wear generator, and a road tunnel PM. Underground PM was notably rich in Fe, accounting for greater than 40% by mass, and several other transition metals (Cu, Cr, Mn, and Zn). According to these authors, scanning electron microscopy revealed that a component of the coarse fraction of underground PM has a morphology indicative of generation by abrasion, absent for fine and ultrafine particulates, which may be derived from high-temperature processes. Underground PM generated ROS in a concentration- and size-dependent manner.

Ripanucci et al. (2006) studied two lines of the subway system of **Rome**, focusing on the analysis of dust granulometric classes PM_{10}, respirable fraction, respirable combustible dust, and the organic, metallic, siliceous, and fibrous components. Authors found that dust concentrations in the tunnels and platforms were three times higher than at the entrances to the underground railway stations, with a maximum PM_{10} value of 479 μgm^{-3} (351 μgm^{-3} on average). Iron and silica were the major components found in the dust. Authors concluded that drivers and station staff were exposed to an additional value of 11 μgm^{-3} and 10 μgm^{-3}, respectively, and gave recommendations to improve the air quality in the subway system, such as upgrading the ventilation system for the artificial air supply and installing adequate extraction fans at the ventilation ducts opened along the tunnels.

An intensive particulate sampling campaign was carried out in January 2014 measuring the PM concentrations in the **Naples** subway system (Carteni et al., 2015). PM_{10} concentrations measured in the monitored underground station platforms ranges between 172-262 μgm^{-3}, while the average $PM_{2.5}$ concentration ranges between 45 and 60 μgm^{-3}. Real-time estimations of PM levels were carried out inside the trains travelling both in ground-level and underground sections. The results show that high concentrations of both PM_{10} (average values between 58 μgm^{-3} and 138 μgm^{-3}) and $PM_{2.5}$ (average values between 18 μgm^{-3} and 36 μgm^{-3}) were also measured inside trains. Authors estimated that every passenger spends on average about 70 min per day exposed to high levels of PM.

In the underground of St. Petersburg bacteria and microfungi were characterized and quantified (Bogomoloca and Kirtsideli, 2009). The specificity of fungal flora was shown to be dependent on the depth of the station, while ventilation and the number of passengers were two factors that significantly affect fungal density in air. Bacterial concentrations in the air were significantly higher than fungal ones (for a specific station 115 $CFUm^{-3}$ of bacteria vs. 1.6 $CFUm^{-3}$ of microfungi).

The air quality subway system of **Barcelona** has been recently investigated through intensive measurement campaigns. Querol et al. (2012) focused on the characterization of PM levels and their metal content. These authors reported that PM levels inside the trains in summer were amongst the lowest reported for worldwide subway systems (11-32 μgm^{-3} $PM_{2.5}$) due to the air conditioning system. Mean levels at platforms were 46 and 125 μgm^{-3} in a new and an old line, respectively. A principal component analysis distinguished three different sources: brake abrasion, outdoor contribution and wheel-rail abrasion. The elements with the highest enrichment were those associated with wheel or brake abrasion products (Ba, Fe, Cu, Man, Cr, Sb, As Mo, Co, Sr, among others), with Fe_2O_3 being the dominant mineral particle. Authors observed that the implementation of Platform Screen Door (PSD) systems resulted in reductions of both PM levels and metal concentrations, and it was calculated that the contribution of commuting by subway was estimated to account for around 10% of the daily exposure. The initiative to study air quality in the Barcelona metro was further developed by Moreno et al. (2014) who assessed the role on PM levels of the train piston effect and concluded that subway platform air quality varies greatly depending on ventilation and station design and that in some stations PM levels can double if tunnel ventilation is switched off. In Moreno et al. (2015), the authors proposed a general model to explain the origin of most subway FePM. They concluded that most particles breathed on subway are ferruginous, commonly carbonaceous, and nanometric in size, and that they derive dominantly from mechanical processes of sliding and wear at the brake-wheel and wheel-rail interfaces, with minor contributions from high temperature processes. Fe-particles were observed to have flake shapes, commonly with inhomogeneous chemistry (Ba/Zn/Cu) and undergo progressive atmospheric oxidation from metal Fe to magnetite/hematite. In a more recent study, Martins et al. (2015) recorded average $PM_{2.5}$ concentrations on the platforms in the Barcelona subway operating hours ranging from 20 to 51 and from 41 to 91 μgm^{-3} in warmer and colder periods of the year, respectively, mainly related to the seasonal changes in the subway ventilation systems. Variations in average PM concentrations between underground stations were observed to depend on ventilation, air conditioning systems, characteristics/design of each station and the train frequency.

2. LITERATURE ON SUBWAY SYSTEMS IN ASIA

The subway is the main means of public transit in the **Seoul** metropolitan area. As a response to increasing public concerns regarding indoor air quality in underground environments, several studies have been carried out to characterise the distribution of PM in the urban subway system of Seoul. Kim et al. (2008) reported average PM_{10} and $PM_{2.5}$ concentrations in the subway driver cabins of 311.5 and 125.5 μgm^{-3}, respectively. Kang et al. (2008) identified 4 major types of subway particles on an underground platform, based on their chemical compositions: Fe-containing, soil-derived, carbonaceous, and secondary nitrate and/or sulphate particles. Fe-containing particles were associated with wear processes at rail-wheel-brake interfaces, while the others were thought to be introduced mostly from the outdoor urban atmosphere. Fe containing particles were the most common ones, with relative

abundances in the range 61-79%. In Kim et al. (2010a), air quality was assessed in six selected subway stations, particle matter was captured at platforms, and 11 types of metals were analysed. The results showed that the mean concentration of Fe was the highest (average 8.7 μgm^{-3}) out of the metals in PM, followed by Cu (2.5 μgm^{-3}), K (1.8 μgm^{-3}), Ca (1.0 μgm^{-3}), Zn (0.6 μgm^{-3}), Ni (0.4 μgm^{-3}), Na (0.3 μgm^{-3}), Mn (0.1 μgm^{-3}), Mg (0.05 μgm^{-3}), Cr (0.03 μgm^{-3}) and Cd (0.008 μgm^{-3}). Kim et al. (2010b) calculated a contribution of Fe-containing particles around 38-88% during summertime, 50% of these particles were encountered as iron oxide containing C and approximately 20% of them were found as iron oxide containing Si, Ca and C. Jung et al. (2012a) concluded that most of the magnetic airborne subway particles of the <2.5 µm in size fraction at platforms were relatively harmless iron metal, and that the different composition of the Fe-containing particles was associated with different ballast types. Similarly, Eom et al. (2013) found that the majority of airborne subway particles collected in the underground subway stations tunnels were found to be magnetite, hematite, and iron metal. The efficiency of mitigation strategies based on the use of magnetic filters to remove PM was assessed in subway tunnels by Son et al. (2014). Authors obtained a maximum removal efficiency of PM_{10} (52%), $PM_{2.5}$ (46%), and PM_1 (38%) at a 60 Hz fan frequency using double magnetic filters. The effect on PM levels of the installation of platform screen doors (PSD) was evaluated by Kim et al. (2012). The installation of PSD system at the subway was more efficient for removing coarse fraction of PM infiltrating from subway railway into the passenger platform, levels before the installation being 116±25.4 μgm^{-3} for PM_{10} and 66.2±22.9 μgm^{-3} for $PM_{2.5}$; reducing to 97.2±44.7 μgm^{-3} for PM_{10} and 58.1±29.2 μgm^{-3} for $PM_{2.5}$ after PSD installation. The piston effects were also reduced, so the transfer of PM within the subway system was restricted. Kim et al. (2013) showed that the effectiveness of a subway cabin air purifier (SCAP) was higher for the coarse fraction, the $PM_{2.5}/PM_{10}$ ratio of the SCAP-installed car being around 7% higher than the car without SCAP.

To date, only two studies on air quality in subway systems include source apportionment analysis, and both have been carried out in Seoul, one focused on air pollution sources in subway passenger cabins (Park et al., 2012), and the other in the subway tunnel (Park et al., 2014). In Park et al. (2012), authors reported mean PM_{10} concentrations of 65.7 μgm^{-3}, PM_{10} was concluded to consist of 52.5% inorganic components, 10.2% anions and 37.3% other materials including organic and inorganic cations. Fe was the most abundant element and significantly correlated ($p < 0.01$) with Mn (r= 0.97), Ti (r=0.91), Cr (r= 0.88), Ni (r= 0.89), and Cu (r= 0.88). The PM_{10} sources characterized by PMF were soil and road dust sources (27.2%), railroad-related sources (47.6%), secondary nitrate sources (16.2%), and a chlorine factor mixed with a secondary sulphate source (9.1%). Overall, railroad-related sources contributed the most to PM_{10} subway cabin air. On the other hand, Park et al. (2014) revealed a similar chemical composition in the subway tunnel. PM_{10} consisted of 40.4% inorganic species, 9.1% anions, 4.9% cations, and 45.6% other materials. The iron fraction was the highest, contributing 36.1% of the PM_{10} levels. According to Positive Matrix Factorization (PMF) analysis, major contributors in the subway tunnel were rail, wheel, and brake wear (59.6%), oil combustion (17.0%), secondary aerosols (10.0%), electric cable wear (8.1%), and soil and road

dust (5.4%). The internal sources (rail, wheel, brake, and electric cable wear) were the major contributors of PM_{10} in the subway tunnel (67.7%).

Several studies focused on the health effects of particles in the subway system have been carried out in Seoul. Jung et al. (2012b) reported levels of polycyclic aromatic hydrocarbons (PAHs) in a subway tunnel. PAH concentrate of PM_{10} in the subway tunnel was found to be lower than that of PM_{10} in ambient air. In this study it was suggested that additive or synergistic effects by unidentified chemicals as well as PAHs contained in organic extracts of subway PM_{10} may induce genotoxic effects. The concentration of culturable airborne bacteria and fungi at subway stations has been investigated in several studies, all of them agree on an important dependency on the depth of subway station and on the construction year. Cho et al. (2006) reported that the highest average concentration of fungi (1574 $cfum^{-3}$) was observed during the morning commute hour from 8:00 to 9:00, associated with the highest number of passengers. Fungi concentrations in subway stations were higher than outdoor concentrations. Hwang et al. (2010) detected concentrations of total airborne bacteria ranging from not detected to 4997 $cfum^{-3}$, with an overall geometric mean of 191 cfu m^{-3} and concluded that PSD seemed to reduce concentrations. At four of the studied stations concentrations were found to exceed the Korean indoor bioaerosol guideline. In Hwang and Park (2014) authors studied the concentrations of culturable airborne bacteria at platform floors. It was also concluded that concentrations were lower in stations with PSD and in which gram-negative bacteria were not detected.

Organic aerosols have been studied in depth in the subway system of **Shangai** (Zhang et al., 2012). Mean levels of major aromatic and chlorinated hydrocarbons were higher indoors than outdoors (Trichloroethylene: 3.6±0.5 μgm^{-3}), Tetrachloroethylene: 1.3±0.5 μgm^{-3}), while BTEX (benzene, toluene, ethylbenzene, xylene) inside the stations were predominantly transported from outdoor (vehicle-related emissions). Guo et al. (2014) measured mean $PM_{2.5}$ and PM_1 concentrations of 121.9±13.6 μgm^{-3} and 88.7±7.5 μgm^{-3}, respectively. A complete chemical characterization for the coarse and fine PM fraction was carried out, and authors observed that Fe, Cu, Cr, Mn, Ni, Mo, Zn, Ba, Se and Pb have highly increased concentrations in the stations of subway lines in comparison with ambient air. Fe (14.3 μgm^{-3} in coarse PM and 19.9 μgm^{-3} in fine PM) was the most abundant metal, mainly as magnetite and hematite. In Lu et al. (2015) authors reported that all the mass concentrations of Shanghai subway $PM_{2.5}$ collected at the platforms were higher than National Air Quality standard. Fe, Na, Mg, K, Mn, Ba, Li, Cr, Ni, Cu, Ga, Sr, Pb, Be, V, As, Se, Rb, Ag, Cd, Tl, Bi mass concentrations in subway $PM_{2.5}$ were found to be higher than those in ambient $PM_{2.5}$. Fe in the subway (6.6 ±4.2 μgm^{-3}) was 10 times higher than outdoor, and was present as Fe^{2+}. According to authors, potential free radical generation ability of heavy metals could imply health risks.

As in Barcelona, seasonal PM variations were obtained in the subway of **Tokyo** (Furuya et al., 2001), with lower levels in summer (30-85 μgm^{-3}) than in winter (85-120 μgm^{-3}). The elements that were observed at high concentrations in the subway suspended PM were Fe, Ba, Cu, and Ca. Fe showed the highest concentrations, being 30-60 times higher than those

aboveground. PAH collected at the subway stations during this study showed similar concentrations and characteristics to those observed in the outdoor urban atmosphere.

Cheng et al. (2008) observed that PM levels inside underground stations in **Taipei** and outdoors were positively correlated, indicating that PM levels in the subway system were influenced significantly by outdoor ambient PM levels. Average PM_{10} levels inside trains and on station platforms were 10-97μgm^{-3} and 11-137 μgm^{-3}, respectively, and average $PM_{2.5}$ levels were 8-68 μgm^{-3} and 7-100 μgm^{-3}, respectively. PM_{10} and $PM_{2.5}$ levels in the subway stations were about 0.65-1.53 times and 0.89-1.75 times, respectively, those for urban ambient air. On the other hand, particle number concentrations on the platforms resulted 0.4-0.7 times lower than those in outdoor environments (Cheng and Yan, 2011). In this study, CO concentrations were measured, ranging between 0.30 and 0.48 ppm.

Ma et al. (2012) estimated the characteristics of indoor PM collected on subway platforms by the cooperative approach of semi-bulk and single particle analyses. The size-resolved PM and its number concentration were measured on the platform in a heavily travelled subway station in **Fukuoka**, Japan. The average particle number concentration varied across the ranges of 10-40 L^{-1}, 7000-1800 L^{-1}, 2000-5000 L^{-1}, 10000-23000 L^{-1}, and 95000-115000 L^{-1} at the aerodynamic particle sizes of >5 µm, 2-5 µm, 1-2 µm, 0.5-1 µm, 0.3-0.5 µm, respectively. PM_{10} concentration was nearly 3-4 times higher than those of urban outdoor ambient levels. The elements observed at high concentrations were Fe, Si, Ca, S, and Na.

PM_{10} and $PM_{2.5}$ levels were recorded during commuting in the subway system of **Hong Kong** (Chan et al., 2002). Authors reported that filters in the air-conditioning system are capable of removing a large portion (2.5-10 µm) of PM_{10}. Mean PM_{10} and $PM_{2.5}$ concentrations were 44 μgm^{-3} (23-85 μgm^{-3}) and 33 μgm^{-3} (21-48 μgm^{-3}), respectively.

3. LITERATURE ON SUBWAY SYSTEMS IN THE AMERICAS

Workers and commuters' exposure through the subway has been studied in detail in the **New York** subway system. Chillrud et al. (2004) analysed the causes of metal exposures by high-school students for 24 hours and reported that the subway was the most important source . more specifically steel dust in the New York subway system was the dominant source of airborne exposures to iron (26 μgm^{-3}), manganese (240 ngm^{-3}) and chromium (84 ngm^{-3}). According to Morabia et al. (2009), total $PM_{2.5}$ exposures did not differ much between car, subway, and walking (respectively, 21.4, 30.6, and 26.5 $\mu g/m^3 \cdot min$), but the metabolic equivalent rate was significantly lower for car travel than for subway travel or walking. Grass et al. (2010) calculated that the subway worker's mean time-weighted $PM_{2.5}$ exposure was 52 μgm^{-3} with a median of 27 μgm^{-3}, and a range of 6-467 μgm^{-3}. The observed concentrations of $PM_{2.5}$ iron (7 μgm^{-3}), manganese (75 ngm^{-3}), and chromium (27 ngm^{-3}) fell well below occupational standards.

During the summer of 2000, measurements of ultrafine particles, $PM_{2.5}$, and particle-bound PAHs were carried out outdoors and in indoor microenvironments in **Boston**, including the subway system (Levy et al., 2012). For the subway, while ultrafine PM concentrations were not especially elevated inside the subway or on the subway platform, $PM_{2.5}$ concentrations were higher than in most nontransportation microenvironments (67 μgm^{-3} on average). PAHs in subway platforms were concluded to be mostly associated with outdoor urban atmosphere emissions.

Sioutas (2011) and Kam et al. (2011) reported data on the physical and chemical characterization of personal exposure to airborne PM (PM) in the **Los Angeles** subways. The average PM_{10} concentrations for the subway line at station platforms and inside the train were 78 μgm^{-3} and 31.5 μgm^{-3}, respectively. Subway platforms and train have levels double those of the above ground light rail way platforms and trains, especially for the coarse fraction (2.4-2.9 times). PM from the underground subway line generates greater ROS activity per volume than PM from the ground-level light-rail line and from ambient air (65% higher). For the coarse fraction, Fe was calculated to account for 27% of PM_{10} concentrations in the underground samples, 6% in the ground level line samples and 2% in the ambient site samples. These percentages were slightly different for the fine fraction, 32% of PM_{10} concentrations in the underground samples, 3% in the ground level line samples and 1% in the ambient site samples. Mn, Cr, Co, Ni, Cu, Ba, Mo, Cd, Eu were also enriched in the subway, especially in the fine fraction. It was found that elements in the subway system account for a lower solubility than elements in the ground rail line and in ambient air. According to the authors, the piston effect of a subway train provides an explanation for how outdoor air can enter the underground subway environment.

Microbial counts have been also performed in the subway system of **Washington D.C.** (Birenzvige et al., 2003), where authors detected bacillus spores and concluded that less than 1% of the aerosols present were candidates for biological origin. The most prevalent particles were salt particles (NaCl) and iron-containing particles.

Relatively low PM levels have been recorded in the subway system of **Mexico City** owing to the used of trains equipped with rubber wheels. Commuters' exposure to $PM_{2.5}$, CO, and benzene was evaluated by Gómez-Perales et al. (2004). $PM_{2.5}$, CO and benzene concentrations were 61 μgm^{-3}, 7ppm and 4ppb on average, respectively. Total carbon was the most abundant component, comprising almost 50% of $PM_{2.5}$. In Mugica-Álvarez et al. (2012), authors collected samples of PM_{10} and $PM_{2.5}$ using High Vol and MiniVol devices on the platform of a subway station in Mexico City and in an outdoor location close to it, using such devices. The largest particles concentrations were found from 6:00 to 14:00. $PM_{2.5}$ levels ranged between 60 μgm^{-3} and 93 μgm^{-3} (6% higher than outside), and PM_{10} levels were 20% larger than outside, ranging from 88 to 145 μgm^{-3}. Greater Fe, Cu, Ni, Cr and Mn concentrations were quantified in the subway samples as compared to the outdoor particles. Differences indoor-outdoor regarding Fe concentrations were especially significant (60% higher for PM_{10}, and 40% higher for $PM_{2.5}$).

The personal exposure to PM in commuters was also evaluated in different transport modes (bicycle, bus, car and subway) in **Santiago de Chile** (Suárez et al., 2014). Results for the subway system showed the highest $PM_{2.5}$ mean concentrations (62.4 μgm^{-3} on average), and the lowest particle number concentrations (42500 $\#cm^{-3}$ on average) among all the selected transport modes.

According to Murruni et al. (2009), TSP concentrations inside stations in the subway system of **Buenos Aires** and outdoors were poorly correlated, indicating that TSP levels in the subway were mainly influenced by internal sources. TSP levels were found to be between 152 and 270 μgm^{-3} in the platforms of the stations, 3 times higher than those for urban ambient air. Results showed that the most enriched element was Fe, the levels of which ranged from 8 to 86 μgm^{-3}.

4. LITERATURE ON SUBWAY SYSTEMS IN AFRICA

Microbial indicators associated with suspended dust have been studied in detail in the underground system of **Cairo** (Awad et al., 2002), where it was observed that higher average concentrations were recorded at the surface than in tunnel stations. Mechanical ventilation in the tunnel station reduces and removes particles >5µm whereas natural ventilation at the surface station possible removes smaller particles and leaves larger ones suspended. High ozone concentrations in the tunnel were attributed to the effects of electrical charge from train daytime lamps, and insufficient ventilation.

5. REVIEW STUDIES

Comprehensive reviews of recent research into particle emissions from rail vehicles have been presented in three main works (Nieuwenhuijsen et al., 2007; Salma, 2009; Abbasi et al., 2013). These studies have highlighted that although measured PM concentrations in the different studies are not always directly comparable because of differences in the age of the rail system, tunnel ventilation, wheel type, braking system, and operating mode, measurement instruments and methods, chemical and size characteristics of PM and type of environment investigated (e.g. inside train, inside station), all the studies available in the literature conclude that the PM concentrations at underground station platforms are consistently higher (2-10 times) than at the street level, with PM_{10} levels at platforms ranging approximately between 40 μgm^{-3} and 470 μgm^{-3}, and $PM_{2.5}$ levels between 20 μgm^{-3} and 350 μgm^{-3}. Salma (2009) pointed out that in air-conditioned subway vehicles, mean concentrations are generally smaller by 15-20% than the levels for platforms, suggesting that filtration provided by air conditioners is an effective way in reducing (coarse) mass concentrations. Querol et al. (2012) and Cartenì et al. (2015) included a summary of exposure levels for different commuting modes in a number of cities of the world. For the subway system PM_{10} inside trains ranged between 15 and 800 μgm^{-3} approx., and $PM_{2.5}$ between 15 and 250 μgm^{-3} approx.

Table 1. Studies included in this report, detailing information on the location of the study, time duration of the study, measuring equipment used, frequency of the samples, number of samples collected and species analysed, as well as the type of main pollution sources identified.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Amsterdam (The Netherlands)	3 days	Versatile Aerosol Concentration Enrichment System	1/day	3	10-2.5, <2.5, <0.18 µm	NO_3^-, SO_4^{2-}, Cl^-, Fe, Cu, As, Mn, Zr, Mo, Sn, V, Cr, Ni, Nb, Hf, Ca, Mg, Zn, Ba, Sb, Rb, Cd, Pb, Al, Ti, Sr, Sc, La, Hg, Li, B, Na	wheels, brakes, rails, contact wires	Loxham et al., 2013
Barcelona (Spain)	13 days	Grimm 1108, IAQ-CALC 7525	-	-	-	-	-	*Moreno et al., 2014*
Barcelona (Spain)	119 days	Airborne Sample Analysis Platform system (ASAP 2800, polyurethane foam substrates)	1/8 days	-	<10 µm	C, O, Na, Mg, Al, Si, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Zn, As, Sn, Sb, Ba	Wheels, rails, brakes, electrical supply system	*Moreno et al., 2015*
Barcelona (Spain)	20 days	A high volume sampler MCVPM1025 (quartz microfiber filters), Grimm 1107, DustTrak DRX TSI,	1/day	39	<10, <2.5 µm	Cl^-, SO_4^{2-}, NO_3^-, NH_4^+, OC, EC, Fe, Ca, Al, Ba, Mg, Cu, Mn, Zn, Na, K, Ti, Cr, Sr, Zr, Mo, Sb, Sn, Ni, As, Pb, V, Co, P, W, Li, Hf, Rb, Nb, Ge, Ga, U, Y, Th, Ta, Cd, Bi	Brake abrasion, outdoor contribution, wheel-rail abrasion	*Querol et al., 2012*
Barcelona (Spain)	221 days	DustTrak 8533, High Volume Sampler CAV-A/MSb (MCV), IAQ-Calc 7545	-	-	<2.5 µm	-	Abrasion and wear of rail tracks, wheels and braking pads	Martins et al., 2015
Boston (USA)	-	DustTrak 8520, P-Trak 8525, PAS 2000CE, Q-Trak 8551	-	-	<2.5 µm	PAHs	-	*Levy et al., 2002*
Budapest (Hungary)	2 days	TEOM 1400a, Gent-type stacked filter unit aerosol sampler (nuclepore polycarbonate filters)	-	2	10-2, <2 µm	Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Rb, Sr, Y, Zr, Nb, Mo, Ba, Pb	Electric conducting rail and bow sliding collectors, rails and wheels wear, wind erosion of construction materials	*Salma et al., 2007*
Budapest (Hungary)	2 days	Stacked-filter unit sampler (Nucleopore polycarbonate membrane filters),	2/day	4	10-2, <2 µm	Fe, O, Ca, Mg, C, Si, Ca, Cl, Fe, Si, C, Mn, Ni, Cr,	Mechanical desintegration of steel, sparking between the electric conducting rail and collectors	Salma et al., 2009
Buenos Aires (Argentina)	30 days	Portable AirCon-2 pump with Millipore polycarbonate filters,	1/day	30	Total suspended particulate	Fe, Zn, Cu	Contact wires, collectors	*Murruni et al., 2009*
Cairo (Egypt)	7 days	All Glass Impinger AG31 filter, cellulose nitrate membrane filters	1/week	-	Total suspended particulate	-	-	*Awad et al., 2002*
Fukuoka (Japan)	6 hours	Three-stage multi nozzle cascade impactor (Nuclepore® polycarbonate filter), OPC RION, Dust scan Scout,	-	-	>10, 10-2.5, <2.5 µm	Fe, Si, Ca, S, Na, Mg, Al, K, Mn, Zn,	Train/Rail mechanical abrasion, Train-Rail melting/sparkling, Ballast/Coated abrasive, Gravel/Cement beneath track	*Ma et al., 2012*

Table 1. Continued.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Helsinki (Finland)	16 days	Eberline FH62 I-R with $PM_{2.5}$ inlet, EPA-WINS impactor (Pall Teflo filters), differential mobility particle sizer (DMA 3010), particle counter 3025, aethalometer AE 16, virtual impactor (quartz fibre filters), P-Trak 8525	-	23	<2.5 µm	Al, Ca, Cl, Cr, Cu, Fe, K, Mn, Ni, P, Pb, S, Si, Ti, V, Zn, OC, EC	Wheel–rail interface, the current collector, and the conductor rail	*Aarnio et al., 2005*
Hong Kong (China)	75 days	DustTrak 8520	-	-	<2.5, <10 µm	-	-	*Chan et al., 2002*
Istanbul (Turkey)	35 days	Thermo Partisol FRM Model 2000 Airsampler, Anderson ACFM cascade impactor	-	-	>9, 9–5.8, 5.8–4.7, 4.7–3.3, 3.3–2.1, 2.1–1.1, 1.1–0.7, 0.7–0.4 and <0.4 µm	Cu, Fe	wheels, brakes, rails, catenaries	*Şahin et al., 2012*
Istanbul (Turkey)	10 days	Real–time aerosol monitor pDR 1200 model, particle counting device (model 3016, Lighthouse)	-	-	<2.5 µm	-	-	*Onat and Stakkeva., 2013*
London (UK)	15 days	Gravimetric high flow personal sampler	4/day	44 personal samples	<2.5 µm	-	-	*Adams et al., 2001*
London (UK)	-	DustTrak, P-Trak monitor, cowl holders fitted with Nuclepore polycarbonate filters	-	-	<2.5 µm	Fe, Cr, Cu, Zn, Mn	-	*Seaton et al., 2005*
Los Angeles (USA)	99 days	Q-Trak 7565, DustTrak 8520, Sioutas™ Personal Cascade Impactor Sampler (Teflon and quartz microfibre filter)	-	-	10-2.5, <2.5 µm	Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, Na^+, NH_4^+, K^+, Mg, Al, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Cd, Ba, Eu, OC, EC	Frictional processes of the wheels, rails, and brakes of the system, sparking, resuspension from train and passenger movement	*Sioutas, 2011*
Los Angeles (USA)	99 days	Q-Trak 7565, DustTrak 8520, Sioutas™ Personal Cascade Impactor Sampler (Teflon and quartz microfibre filter)	-	-	10-2.5, <2.5 µm	Cl^-, NO_3^-, SO_4^{2-}, PO_4^{3-}, Na^+, NH_4^+, K^+, Mg, Al, K, Ca, Ti, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Cd, Ba, Eu, OC, EC	Frictional processes of the wheels, rails, and brakes of the system, sparking, resuspension from train and passenger movement	*Kam et al., 2011*
Mexico city (Mexico)	24 days	Casella Vortex Ultraflow mass flow, Langan Model T15, 6-l stainless-steel canisters (SUMMA)	6/week	35 personal samples	<2.5 µm	Si, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Se, Br, Pb, TC, OC, EC	Vehicle exhausts penetrate into the ventilation grids of the Metro, brakes, rubber tyres	*Gómez-Perales et al., 2004*

Table 1. Continued.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Mexico city (Mexico)	21 days	High-Vol (Tisch), Mini-Vol (Airmetrics)	1/day (each size)	42	<10, <2.5 µm	Al_2O_3, SiO_2, Ca, Fe, Ba, Mg, Cu, Co, Cr, Mn, Ni, Pb V, Zn, Na, K, S	Friction, brake system, sparking	*Mugica-Álvarez et al., 2012*
Milan (Italy)	33 days (11 at each station)	Low-volume TECORA Sky-post samplers, OPC, Grimm 1107, Con.Tec.DustMonit	3/day	-	<10 µm	Al, Si, S, Cl, K, Ca, Ti, Mn, Ni, Cu, Zn, Br, Rb, Pb, Fe, Ba, Sb , Sr, Sn	Crustal oxides, wheel and brake dust, electric cable dust	Colombi et al., 2013
Naples (Italy)	5 days	Portable photometric Aerocet 531 sampler	-	-	<10, <2.5 µm	-	-	Cartenì et al., 2015
New York (USA)	8 hours	Teflone membrane filters, Met-One 237B	-	1 personal sample	<2.5 µm	Be, Ag, Cd, Sn, Sb, Cs, La, Pt, Tl, Pb, Na, Mg, Al, S, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, K, As, Se	-	Chillrud et al., 2004
New York (USA)	4 months	Teflon membrane filters, Met-One 237B	Depending on work shifts	39 personal samples	<2.5 µm	Fe, Mn, Cr	Frictional abrasion	*Grass et al., 2010*
New York (USA)	-	AM510 SidePak	-	-	<2.5 µm	-	-	*Morabia et al., 2009*
Paris (France)	15 days	Sampler Partisol Plus (Pallflex filters)	-	-	<10 µm	Fe, Mn, Ca, Cu, S, Si	-	*Bachoual et al., 2007*
Perugia (Italy)	-	Optical particle counter	-	-	<1, <2.5, <10 µm	-	-	*Castellini et al., 2014*
Prague (Czech Republic)	One year?	DustTrak 8520	-	-	<10 µm	-	-	*Braniš et al., 2006*
Rome (Italy)	-	High Volume sampler (PVC and silver filters), DustTrak	-	-	<10 µm	Fe, Cu, Zn, Mn, Pb, Sb, Ni, Cr, rare earth, Sn, Th, Zr, Co, As, Y, Bi, Cd	-	Ripanucci et al., 2006
Rotterdam (The Netherlands)	3-4 days at each of the eight stations	Versatile Aerosol Concentration Enrichment System, chemiluminescence NO-NO_2- NOx analyzer 42, U.V. Photometric O_3 Analyzer 49, CPC 3022A	-	-	2.5-10, <2.5 µm	Al, Cu, Fe, Ni, V, Zn, NH_4^+, Cl^-, NO_3^-, SO_4^{2-}, EC, OC, PAH	-	*Steenhof et al., 2011*
Santiago de Chile (Chile)	-	DustTrak II 8532, P-Trak 8525, Personal Environmental Monitor 761-203A		18 personal samples	<2.5 µm	-	-	*Suárez et al., 2014*
São Paulo (Barazil)	-	-	-	-	-	-	-	*Silva et al., 2012*
Seoul (Korea)	-	MCC filter	-	-	10-2.5 and 2.5-1.0 µm	Fe, Cu, K, Ca, Ba, Pb, Zn, Ni, Na, Mn, Mg, Cr, Cd	Electrial wire, wheel, rail brake block	*Kim et al., 2010a*
Seoul (Korea)	3 days	Permanent magnets of 4000 Oe	-	4	<2.5 µm	Ca, Ti, Si, Fe, C, Na, Mg, Al, S	ballast tracks, rail–wheel–brake interfaces	*Jung et al., 2012a*
Seoul (Korea)	-	MINIVOL-TAS with quartz filters	1/day	-	<2.5, < 10µm	-	The deterioration of the internal facilities, rails, wheels	*Kim et al., 2012*

Table 1. Continued.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Seoul (Korea)	4 days	OPS 3330	-	-	<2.5, <10 µm	-	-	*Kim et al., 2013*
Seoul (Korea)	32 hours	Grimm 1180	-	-	<1, <2.5, < 10µm	-	-	*Son et al., 2014*
Seoul (Korea)	55600 min	High-volume sampler with a cascade impactor	-	-	<2.5, <10 µm (chemical composition only <10 µm)	Benzo(a)anthracene, Benzo(b)fluoranthrene, Benzo(k)fluoranthrene, Anthracene, Chrysene, Fluoranthrene, Phenanthrene, Pyrene, Acenaphthylene	-	*Jung et al., 2012b*
Seoul (Korea)	-	Polycarbonate membrane filters	-	90	-	-	-	*Cho et al., 2006*
Seoul (Korea)	-	17G9 GilAir Sampler	-	66	-	-	-	*Hwang and Park, 2014*
Seoul (Korea)	14 days	PM_{10} cyclone samplers URG-2000-30ENB (nuclepore polycarbonate filters)	3/7 days	6	<10 µm	Fe, Ca, Si, C	-	*Eom et al., 2013*
Seoul (Korea)	8 days	May cascade impactor (Ag foil)	-	-	>16, 16- 8, 8-4, 4-2 and 2-1 µm	Fe, C, N, Mg, Al, Si, S, Ca, Ti, Cr, Mn, Ni, Cu, Zn, Ba	-	*Kang et al., 2008*
Seoul (Korea)	6 days	3-stage Dekati PM_{10} sampler	1/day	6	<1, <2.5, <10 µm	Fe, C, N, Mg, Al, Si, S, Ca, Ti, Cr, Mn, Ni, Cu, Zn, Ba	Friction between the rail and the brake block of the wheel	*Kim et al., 2010b*
Seoul (Korea)	-	Sampler 17G9 GilAir (polycarbonate membrane filters)	-	66	Total suspended particulate	-	-	*Hwang et al., 2010*
Seoul (Korea)	30 days	Light scattering monitor LD-3B, mini volume air sampler PAS201 (PTFE Membrane Filter)	1/day	30	<10 µm	Mg, Al, Si, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ba, Pb, NO_3^-, SO_4^{-2} Cl^-,	Soil and road dust, abrasion of the railroad tracks, brakes, and power supply, secondary nitrate, Cl^- (cleaning) and secondary sulphates	*Park et al., 2012*
Seoul (Korea)	12 days	Mini-volume air sampler PAS 201	4/day	44	<10 µm	Mg, Al, Si, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Ba, Pb, Cl^-, NO_3^-, SO_4^{2-}	Oil combustion, soil and road dust, rail, wheel, and brake wear, abrasion of the power supply lines, secondary aerosols	Park et al., 2014
Shanghai (China)	1 day	2 L pre-evacuated stainless steel canisters	-	45	-	VOCs (Benzene, toluene, ethylbenzene, xylenes, tetrachloride, vinyl chloride, chloroethane, 1,2-dichloropropane, TrCE, TeCE, chlorobenzene and dichlorobenzenes)	Traffic-related emission through indoor/outdoor air exchange, solvent emissions	*Zhang et al., 2012*

Table 1. Continued.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Shanghai (China)	-	Personal-size Sioutas Impactor (Teflon filters), single-stage cascade impactor (300-mesh copper TEM grids), AM510 SidePak	-	4	<1, <2.5 µm	Mg, Al, Na, K, Ca, Ti, V, Cu, Cr, Mn, Fe, Ni, Zn, Sr, Mo Ba, Pb	-	*Guo et al., 2014*
Shanghai (China)	46 days	Portable sampler with a multi-sampling-head (Buck LP-20, polycarbonate filters), portable $PM_{2.5}$ sampler	-	-	<2.5 µm	Li, Be, Na,Mg, Al, K, Ca, V, Cr,Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Ag, Cd, Cs, Ba, Tl, Pb, Bi, Th, U	-	*Lu et al., 2015*
Shanghai (China)	-	Dust samples	-	29	Total dust	Al, Fe, Ca, Na, Ti, Mn, Cr, Cu, Ni	Rail friction, wheel-rail mechanical abrasion	Zhang et al., 2011
St. Petersburg (Russia)	-	Passive sedimentation on Petri dishes	-	200	-	-	-	*Bogomolova et al., 2009*
Stockholm (Sweden)	3 days	Grimm 1109; Milllipore filters (mounted in the Grimm), P-Trak 8525, DustTrak 8520	-	4	0.25-32 µm	Fe, Cu, Zn, Ca, Mg, Al, Sb, Na, Ni, Mn, Ba, Cr, K, Si, As, U, B, Be, Se, Cd, P, S, Th, Tl, Li, Ag, Bi, Co, Rb, Pb, V, Sn, Sr, Ti, Mo	Ballast, concrete sleepers, rails, wheels, brake discs, brake pads, electrical wire	*Abbasi et al., 2012*
Stockholm (Sweden)	-	High-volume sampler (glass fiber filter)	-	-	<10 µm	-	-	*Karlsson et al., 2008*
Stockholm (Sweden)	-	Harvard impactors, teflon filters, SMPS, AC 31M (NOx), DataRAM MIE pDR1000, P-Trak	-	11	<2.5 µm	Iron, Barium, Manganese, Copper	-	*Klepczyńska-Nyström et al., 2011*
Stockholm (Sweden)	35 days	TEOM instrument, non-dispersive IR	-	-	<10, <2.5 µm	-	-	*Johansson and Johansson, 2003*
Stockholm (Sweden)	56 days	TEOM, automated cartridge collection unit (ACCU), APS 3321, SMPS 3321 (DMA 3071, CPC 3022)	-	-	<10 µm	Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Cu, Zn, Mo, Sb, Ba, Pb,	Rail, wheel and brake wear	*Gustafsson et al., 2012*
Stockholm (Sweden)	-	SMPS (DMA 3071A, CPC 3022), µ-aethalometer, P-trak, Grimm 1190, PNS 16T (Zeflour filters)	8-11/day	-	<10, <2.5 µm	EC, OC, Fe, C, Ca, Al, Mg, Cl, Tl, Cu, Ag, Cr, Ni, Zr, Ce, Si, K, S, Na, P, toluene, styrene isomers, antracene, fluoranthene, alkyl benzenes, azulene, naphtalenes, chloroform, methylene chloride	Breaks, wheels, infiltration of vehicle exhaust emissions	Midander et al., 2012

Table 1. Continued.

City	Time duration	Measuring equipments	Frequency of samples	Number of samples	Size fraction	Species analyzed	Type of sources	Study
Taipei (Taiwan)	-	DustTrak 8520	-	-	<10, <2.5 µm	-	-	*Cheng et al., 2008*
Taipei (Taiwan)	84 days	Grimm 1108, CPC 3007, Q-Trak 7565	-	-	<10, <2.5 µm	-	-	*Cheng et al., 2011*
Tokyo (Japan)	4 days	Personal air sampler GilAir-5 (polycarbonate Nuclepore quartz filter filter), digital dust monitor Kanomax 3421, laser particle counter Kanomax TF-500,	-	-	0.5–5.0 µm	Fe, Si, Ba, Cl, Ca, S, K, Cu, Zn, Cr, Ni, Mg, P, pyrene, benzo-e-pyrene, benzo-ghi-pyrene, fluoranthene, benzo-a-anthracene, benzo-k-fluoranthene, benzo-a-pyrene	-	*Furuya et al., 2001*
Washington D.C. (USA)	6 days	Met One 6 size-bin 237A, single particle fluorescence analyzer, SASS-2000 wet cyclone air sampler, filter sampler	-	-	<1 µm	-	-	*Birenzvige et al., 2003*

Table 2. Parameters characterised in each subway system summarised by city.

City	Mass concentration	Inorganic chemical compositon	Organic chemical composition	Black Carbon	Number concentration	Number size distribution	Microscopy	Bioreactivity /Toxicity	Microorganisms	NO	NO_2	CO	CO_2	O_3	Source apportionment
Amsterdam (Netherlands)	●	●					●	●							
Barcelona (Spain)	●	●					●					●	●		●
Boston (USA)	●		●		●										
Budapest (Hungary)	●	●					●								
Buenos Aires (Argentina)	●	●					●								●
Cairo (Egypt)	●								●					●	
Fukuoka (Japan)	●	●			●	●	●								
Helsinki (Finland)	●	●		●	●	●									
Hong Kong (China)	●														
Istanbul (Turkey)	●	●			●	●									
London (UK)	●	●			●		●	●							
Los Angeles (USA)	●	●						●					●		
Mexico city (Mexico)	●	●					●					●			
Milan (Italy)	●	●													●
Naples (Italy)	●														
New York (USA)	●	●			●	●									
Paris (France)	●	●						●							
Perugia (Italy)	●				●	●									
Prague (Czech Republic)	●														
Rome (Italy)	●	●					●								
Rotterdam (The Netherlands)	●	●	●					●							
Santiago de Chile (Chile)	●				●										
São Paulo (Barazil)															
Seoul (Korea)	●	●	●		●	●	●	●	●						●
Shanghai (China)	●	●	●				●								
St. Petersburg (Russia)									●						
Stockholm (Sweden)	●	●	●	●	●	●	●	●		●	●				
Taipei (Taiwan)	●				●							●	●		
Tokyo (Japan)	●	●	●		●	●									
Washington D.C. (USA)	●				●	●			●						

6. CONCLUSIONS

As shown in Annex A, a total of 62 studies, carried out in 30 different cities, have been considered in this report. The key parameters examined by these research investigations have been as follows:

- particle mass concentrations,
- inorganic and organic chemical composition,
- black carbon concentrations,
- particle number concentrations and size distribution,
- microscopy (for size, shape and chemical composition of individual particles),
- toxicity,
- bioaerosol concentrations,
- concentration of gases such as NO, NO_2, CO, CO_2 and ozone concentrations,
- and identification of contaminant source (source apportionment).

However, most of the studies have focused on particle mass concentration (in 93% of the subways). Only 9 of them have measured air quality inside trains, usually PM levels, with very few (two) measuring particle numbers or presenting chemical composition data. In the more frequent measurements in subway platforms half of the studies have chemically characterised PM samples, although only four have analysed organic components. Also very rare is the register of gaseous components such as CO_2, CO or NO_2 (only in 3% of the cases). When studying PM in the subway platforms 39% of the studies present PM_{10} and/or $PM_{2.5}$ concentration data (most commonly using DustTrak equipment), less frequent is the concentration of number of particles (16% of the studies). Chemical analyses are done on PM collected in a wide variety of filters, including quartz-fibre, Teflon, nitrate cellulose or polycarbonate, and only very rarely were passive samplers used. The number of samples collected is very variable, most commonly in the 20-50 range, with very few having a number of samples above 50 (4 studies).

Although up to 27 scientific publications discuss the possible sources emitting airborne particles within the subway environment, there is only data on the contribution of each source to the total PM mass in four subway systems. The sources identified in these studies are in order of number of citations (in brackets):

- wheels abrasion (18),
- brake wear, both discs and pads (18),
- rails abrasion (17),
- wires, electrical supply (10),
- mineral dust (8),
- outdoor contamination including secondary inorganic compounds and traffic (6),

- ballast erosion (3),
- rubber tyres wear (1),
- oil combustions (1)
- solvent emissions (1)

The examination of this historical database has facilitated the determination of the main parameters on which to focus in IMPROVE LIFE, and revealed the existence of obvious gaps in knowledge. In order to obtain the most comprehensive database in IMPROVE we will need to monitor the maximum number of parameters, including not only those most commonly shown in other studies (i.e. particle concentrations and inorganic chemistry), but also others less frequently studied such as particle numbers, size distribution, organic chemistry, microscopy studies, bioreactivity, gaseous components, combined with a detailed source apportionment study based on a large number of samples. The selection and analysis of these parameters to be tested will then enable us to move on to the development of the implementation actions.

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ANNEX A

City	Study	Platform										Inside train						
		TSP	PM_{10} (μgm^{-3})	$PM_{2.5}$ (μgm^{-3})	PM_1 (μgm^{-3})	Particle number ($\#cm^{-3}$)	CO (ppm)	CO_2 (ppm)	NO_2 (μgm^{-3})	Inorganic chemical composition	Organic chemical composition	PM_{10}(μgm^{-3})	$PM_{2.5}$ (μgm^{-3})	PM_1 (μgm^{-3})	Particle number ($\#cm^{-3}$)	CO	CO_2 (ppm)	Inorganic chemical composition
Amsterdam (The Netherlands)	*Loxham et al., 2013*		287 ± 8	169 ± 6						●								
Barcelona (Spain)	*Querol et al., 2012*		145-346	46-125						●			11-32					
Barcelona (Spain)	*Moreno et al., 2014*		159-178	124-144[1]	50-59			371-569		●								
Barcelona (Spain)	*Moreno et al., 2015*			29-72						●								
Barcelona (Spain)	*Martins et al., 2015*			20-51 in summer 41-91 in winter									42 with air conditioning 62 without air conditioning					
Boston (USA)	*Levy et al., 2002*			67		25000 (0.02-1 µm)					●							
Budapest (Hungary)	*Salma et al., 2007*		155±55							●								
Budapest (Hungary)	*Salma et al., 2009*									●								
Buenos Aires (Argentina)	*Murtuni et al., 2009*	152-270								●								
Cairo (Egypt)	*Awad, 2002*	793.6-1096																
Fukuoka (Japan)	*Ma et al., 2012*		115,8			108-145 (0.3->5µm)				●								
Helsinki (Finland)	*Aarnio et al., 2005*			47-60		31000±14 000 (<500 nm)				●								
Hong Kong (China)	*Chan et al., 2002*												23-85	21-48				
Istanbul (Turkey)	*Şahin et al., 2012*		58-213							●								
Istanbul (Turkey)	*Onat and Stakkeva., 2013*			11-178		54-209 Rush hours 49-184 Non-rush hours (0.3->0.5 µm)												
London (UK)	*Adams et al., 2001*												238,7					
London (UK)	*Seaton et al., 2005*			270-480		14000-29000 (0.02 - 1 µm)							130-200		17000-23000 (0.02-1 µm)			
Los Angeles (USA)	*Sioutas, 2011*		78	57						●		31,5	24				350-1200[2]	
Los Angeles (USA)	*Kam et al., 2011*		78	57								31,5	24				350-1200[2]	
Mexico city (Mexico)	*Gómez-Perales et al., 2004*												61[2]			7[2]		●
Mexico city (Mexico)	*Mugica-Álvarez et al., 2012*		88-145	60-93						●								
Milan (Italy)	*Colombi et al., 2013*		105-283			124-220 (0.3->5 µm)				●								
Naples (Italy)	*Carteni et al., 2015*		172-262	45-60								58-138	18-36					
New York (USA)	*Chillrud et al., 2004*			62						●								
New York (USA)	*Morabia et al., 2009*												30.6[2]					
New York (USA)	*Grass et al., 2010*												56[3]					
Paris (France)	*Bachoual et al., 2007*									●								
Perugia (Italy)[4]	*Castellini et al., 2014*																	
Prague (Czech Republic)	*Braniš et al., 2006*											113,7						
Rome (Italy)	*Ripanucci et al., 2006*		348-479							●								
Rotterdam (The Netherlands)	*Steenhof et al., 2011*		96	38[5]						●								
Santiago de Chile (Chile)	*Suárez et al., 2014*												62,4		42500			
São Paulo (Brazil)[6]	*Silva et al., 2012*																	
Seoul (Korea)	*Kim et al., 2010a*									●								
Seoul (Korea)	*Jung et al., 2012a*[7]									●								
Seoul (Korea)	*Kim et al., 2012*		116±25.4 before PSD[8] 97.2±44.7 after PSD[8]	66.2±22.9 before PSD[8] 58.1±29.2 after PSD[8]														
Seoul (Korea)	*Kim et al., 2013* [10]											132.8±21.7 before SCAP[9] 112.2±17.0 after SCAP[9]	81.4±9.0 before SCAP[9] 73.9±8.4 after SCAP[9]					
Seoul (Korea)	*Son et al., 2014*		245.6±43.9 before filters[11] 130.7±26.8 after filters[11]	219.1±40.2 before filters[11] 128.6±27.3 after filters[11]	159.7±38.4 before filters[11] 104.8±28.8 after filters[11]													
Seoul (Korea)	*Jung et al., 2012b* [10]		34															
Seoul (Korea)	*Cho et al., 2006* [12]																	
Seoul (Korea)	*Hwang and Park, 2014* [12]																	
Seoul (Korea)	*Eom et al., 2013* [10]									●								
Seoul (Korea)	*Kang et al., 2008*									●								
Seoul (Korea)	*Kim et al., 2010b*									●								
Seoul (Korea)	*Hwang et al., 2010* [12]																	
Seoul (Korea)	*Park et al., 2012*											88.1±43.1 Rush hours 68.4±23.1 Non-rush hours						●
Seoul (Korea)	*Park et al., 2014* [10]		200.8 ±22.0							●								
Shanghai (China)	*Zhang et al., 2012*										●							
Shanghai (China)	*Gua et al., 2014*			121.9±13.64	88.7±7.45					●								
Shanghai (China)	*Lu et al., 2015*			49.17±19.7-66.15±25.2						●								
Shanghai (China)	*Zhang et al., 2011* [13]									●								
St. Petersburg (Russia)	*Bogomolova et al., 2009* [12]																	
Stockholm (Sweden)	*Abbasi et al., 2012* [14]									●								
Stockholm (Sweden)	*Karlsson et al., 2008* [15]																	
Stockholm (Sweden)	*Klepczyńska-Nyström et al., 2011*		232±51	71±13		8960±660 (10-100nm)			20±3	●								
Stockholm (Sweden)	*Johansson and Johansson, 2003*		470	260														
Stockholm (Sweden)	*Gustafsson et al., 2012*		88-247			900-6000 (0.01-0.7 µm)				●								
Stockholm (Sweden)	*Midander et al., 2012*		160	60		7500-20000 (14-330nm)				●	●							
Taipei (Taiwan)	*Cheng et al., 2008*		11-137	7-100								10-97	8-68					
Taipei (Taiwan)	*Cheng and Yan, 2011* [16]		51-65	25-40	9500-17000 (0.23-20 µm)		0.30-0.48	574-1051										
Tokyo (Japan)	*Furuya et al., 2001*		85-120 in winter 30-85 in summer							●	●							
Washington DC (USA)	*Birenzvige et al., 2003* [12]					*100-1000 (>1 µm)*												

Notes:

[1] PM_3
[2] Commuting
[3] Subway workers' mean time-weighted $PM_{2.5}$ exposure
[4] Methodological approach
[5] $PM_{2.5-0.18}$
[6] Effect on outdoor levels of a subway strike
[7] Airborne magnetic particles
[8] Platform screen door
[9] Subway cabin air purifier
[10] In tunnels
[11] removal of PM using magnetic filters
[12] Investigate on airborne fungi/bacteria concentrations
[13] Dust samples
[14] Two sampling points: one near a pad–rotor disc brake contact and a second under the frame. Concentrations on PM mass and number not clearly indicated
[15] Focused on genotoxicity. No information about concentrations
[16] Underground ticket hall and platform

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