Environmental Research 146 (2016) 35–46

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Factors controlling air quality in different European subway systems

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ARTICLE INFO

Article history:
Received 26 October 2015
Received in revised form
2 December 2015
Accepted 8 December 2015

Keywords:
Exposure
Subway stations
Trains
$PM_{2.5}$
Commuting

ABSTRACT

Sampling campaigns using the same equipment and methodology were conducted to assess and compare the air quality at three South European subway systems (Barcelona, Athens and Oporto), focusing on concentrations and chemical composition of $PM_{2.5}$ on subway platforms, as well as $PM_{2.5}$ concentrations inside trains. Experimental results showed that the mean $PM_{2.5}$ concentrations widely varied among the European subway systems, and even among different platforms within the same underground system, which might be associated to distinct station and tunnel designs and ventilation systems. In all cases $PM_{2.5}$ concentrations on the platforms were higher than those in the urban ambient air, evidencing that there is generation of $PM_{2.5}$ associated with the subway systems operation. Subway $PM_{2.5}$ consisted of elemental iron, total carbon, crustal matter, secondary inorganic compounds, insoluble sulphate, halite and trace elements. Of all metals, Fe was the most abundant, accounting for 29–43% of the total $PM_{2.5}$ mass (41–61% if Fe_2O_3 is considered), indicating the existence of an Fe source in the subway system, which could have its origin in mechanical friction and wear processes between rails, wheels and brakes. The trace elements with the highest enrichment in the subway $PM_{2.5}$ were Ba, Cu, Mn, Zn, Cr, Sb, Sr, Ni, Sn, Co, Zr and Mo. Similar $PM_{2.5}$ diurnal trends were observed on platforms from different subway systems, with higher concentrations during subway operating hours than during the transport service interruption, and lower levels on weekends than on weekdays. $PM_{2.5}$ concentrations depended largely on the operation and frequency of the trains and the ventilation system, and were lower inside the trains, when air conditioning system was operating properly, than on the platforms. However, the $PM_{2.5}$ concentrations increased considerably when the train windows were open. The $PM_{2.5}$ levels inside the trains decreased with the trains passage in aboveground sections.

1. Introduction

Underground subway is one of the major transportation modes in most metropolitan areas worldwide, due to its convenience, safety, efficiency, high speed, large transport capacity (in terms of number of commuters) and low emission system (electrical). Furthermore the shift from private transportation mode to subway system allows reducing road traffic congestion. It is also a distinctive microenvironment since it is a confined space poorly ventilated that may promote the concentration of pollutants both from the outside atmosphere and also generated internally (Nieuwenhuijsen et al., 2007).

Particulate matter (PM) in the underground subway microenvironments are of great concern since many people spend considerable time commuting on a daily basis, and the exposure to this pollutant in the subway systems has been linked to adverse human health effects (e.g. Bachoual et al., 2007; Bigert et al., 2008; Salma et al., 2009). Exposure studies in subways from different countries have reported concentrations of PM in subway systems usually several times higher than in the outdoor environments (see Martins et al., 2015b and references therein). Furthermore, there are some evidences that the PM of subway air is substantially different from the above outdoor air or other transport

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http://dx.doi.org/10.1016/j.envres.2015.12.007

air, in terms of number, mass, size, concentration and chemical composition (e.g. Adams et al., 2001; Furuya et al., 2001; Martins et al., 2016; Moreno et al., 2015b; Querol et al., 2012; Salma et al., 2007).

Particles in the subway system are mainly generated by mechanical wear and friction processes at the rail–wheel–brake interfaces, and at the interface between power conductive materials providing electricity and the current collectors attached to trains, as well as by the erosion of construction material and resuspension (Jung et al., 2010; Loxham et al., 2013; Sundh et al., 2009). A railway is generally powered either by an overhead catenary with the current drawn through the contact material of the pantograph or by a third rail with the current drawn through the current-collecting component (contact shoe) on the train. Since PM emission sources in the underground subway systems are very different from those in the aboveground environment, the chemical composition of PM is also distinct. To know the chemical composition of PM on a subway platform is an essential prerequisite for understanding the indoor air quality of the subway system and subsequently to access on remediation measures. The air quality measurements at these microenvironments can also provide relevant information to evaluate the potential for health effects from exposures to PM as well as the effectiveness of ventilation systems (Martins et al., 2015a, 2015b and references therein). Several studies have reported Fe as the major chemical element constituting underground subway PM, while significant amounts of Mn, Si, Cr, Cu, Ba, Ca, Zn, Ni and K have been also observed (Aarnio et al., 2005; Chillrud et al., 2004; Martins et al., 2016; Murruni et al., 2009; Nieuwenhuijsen et al., 2007; Querol et al., 2012; Salma et al., 2009, 2007). Wear and friction processes initially produce iron-metal particles that react with oxygen in the air resulting in the formation of iron oxides (Guo et al., 2014; Jung et al., 2010; Moreno et al., 2015b). Moreover, the chemical composition of PM derived by sample analysis can be further utilised for the assessment of its source inventory (Martins et al., 2016; Park et al., 2014). The determination of the concentration of trace metals (Ba, Mn, Cr, Cu, Ni, Zn, etc.) is indispensable for risk assessment and although the trace metals represent only about 1% of the total PM, they can play a critical role in the source identification (Lim et al., 2010).

Concentration and chemical composition of subway particles depend on various factors, such as: outdoor air quality; differences in the depth and design of the stations and tunnels; system age; composition of wheels, rail tracks, brake pads and current supply materials; power system; braking mechanisms; train speed and frequency; passenger densities; ventilation and air conditioning systems; cleaning frequency; and other operational conditions (Johansson and Johansson, 2003; Kwon et al., 2015; Martins et al., 2016, 2015b; Moreno et al., 2014; Park and Ha, 2008; Ripanucci et al., 2006; Salma et al., 2007). Furthermore, results are not always directly comparable because of differences in sampling and measurement methods, data and sample analyses and the type of environment studied (Kim et al., 2008; Nieuwenhuijsen et al., 2007).

Starting from this consideration, the aim of this study was to assess the exposure concentrations and chemical composition of $PM_{2.5}$ (particulate matter with an aerodynamic diameter less than 2.5 μm) in the subway systems of three South European cities, including Barcelona (Spain), Athens (Greece) and Oporto (Portugal), to better understand the main factors controlling air quality in this environment. The study was based on air quality campaigns following the same sampling, measurement and analysis methods, and data treatment. Specific objectives of the study included: (1) determining concentrations of $PM_{2.5}$ and their chemical composition in selected subway stations; (2) comparing the levels of $PM_{2.5}$ and chemical elements among subway systems; (3) comparing $PM_{2.5}$ exposure levels on the subway platforms with outdoor levels; (4) studying the spatial and temporal variations in $PM_{2.5}$ in the subway stations; and (5) evaluating real-time variations in $PM_{2.5}$ levels inside trains.

2. Experimental section

2.1. Sampling methodology

The Barcelona subway system is one of the oldest underground transport systems in Europe, with its first line beginning operation in 1924. It comprises 8 lines, numbered L1 to L5 and L9 to L11, covering 102 km of route and 139 stations. The system carries around 376 million passengers a year and about 50% of people choose it as their mode of public transport in the city. The Athens Metro is a rapid-transit system in Greece. Line 1 was a conventional steam railway constructed in 1869, which was converted to electrical railway in 1904, and runs almost entirely aboveground. Lines 2 and 3 opened in 2000 and are underground. The entire system is 82.7 km long, with 61 stations (new stations are added continually) and is used by about 494 million passengers per year. The Oporto subway system is a light rail network with its first line opened in 2002. The network has 6 lines (LA, LB, LC, LD, LE and LF) and currently has a total of 81 operational stations across 67 km of double track commercial line. The system is underground in central Oporto (8 km of the network) and aboveground into the city's suburbs, carrying about 57 million passengers per year.

In the three South European subway systems (Barcelona, Athens and Oporto), aerosol measurements were performed both on the subway platforms and inside the trains. One station platform was selected from each of the subway systems to determine the exposure concentrations and chemical composition of $PM_{2.5}$. Additional real-time measurements were carried out on the platforms of 24 stations from Barcelona subway, and 5 stations from both Athens and Oporto subways. Inside the trains the samplings were performed in 5 lines in Barcelona, and 2 lines both in Athens and Oporto. Whereas the measurements performed in the Barcelona subway system have been published previously (Martins et al., 2016, 2015b), the measurement campaigns in Athens and Oporto were carried out exclusively for this study, as well as the simultaneous outdoor aerosol measurements performed at these two cities. Information on the subway systems, selected stations as well as the characteristics of the measurements carried out are summarised in Table 1.

2.1.1. Subway platforms

Continuous aerosol sampling and monitoring was performed on one station platform selected from each of the subway systems (Barcelona, Athens and Oporto). For comparison purposes, the measurements were performed on the platform of stations with the same architectural design: wide tunnel with two rail tracks in the middle with lateral platforms.

For the collection of $PM_{2.5}$ samples on the subway platforms different instruments were used among subway systems. In Barcelona and Athens campaigns the samplings were conducted using a High Volume Sampler (HVS, Model CAV-A/MSb, MCV S.A.) with a $PM_{2.5}$ head operating at an airflow rate of 30 $m^3\ h^{-1}$. In Oporto campaign a high volume sampler (TE-5200, Tisch Environmental Inc.) operating at 67.8 $m^3\ h^{-1}$ was used to collect coarse ($PM_{2.5-10}$) and fine ($PM_{2.5}$) particles. However, for purposes of comparison among the three subway systems only the $PM_{2.5}$ data were used in this study. A comparison of $PM_{2.5}$ concentrations measured with both high volume samplers presented a squared Pearson correlation (R^2) equal to 0.91 and a linear regression with a slope close to unity. The particles were collected daily on quartz microfibre