Atmospheric Environment 156 (2017) 169–181

Contents lists available at ScienceDirect

Atmospheric Environment

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

Factors controlling particle number concentration and size at metro stations

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HIGHLIGHTS

- Particle number size distribution recorded at 9 different metro platforms.
- Mean $N_{0.3-10}$ correlate with the depth of the platforms in the old metro lines.
- UFP may be partly governed by outdoor emissions through mechanical ventilation.
- At operating hours, coarse particles less abated than UFP by tunnel ventilation.
- The control of coarse particles should be a priority at the metro system.

ARTICLE INFO

Article history:
Received 24 November 2016
Received in revised form
27 February 2017
Accepted 3 March 2017
Available online 6 March 2017

Keywords:
Metro system
UFP
Size distribution
Forced ventilation

ABSTRACT

An extensive air quality campaign was performed at differently designed station platforms in the Barcelona metro system, aiming to investigate the factors governing airborne particle number (N) concentrations and their size distributions. The study of the daily trends of N concentrations by different size ranges shows that concentrations of $N_{0.3-10}$ are closely related with the schedule of the metro service. Conversely, the hourly variation of $N_{0.007-10}$ (mainly composed of ultrafine particles) could be partly governed by the entrance of particles from outdoor emissions through mechanical ventilation. Measurements under different ventilation settings at three metro platforms reveal that the effect on air quality linked to changes in the tunnel ventilation depends on the station design. Night-time maintenance works in tunnels are frequent activities in the metro system; and after intense prolonged works, these can result in higher N concentrations at platforms during the following metro operating hours (by up to 30%), this being especially evident for N_{1-10}. Due to the complex mixture of factors controlling N, together with the differences in trends recorded for particles within different size ranges, developing an air quality strategy at metro systems is a great challenge. When compared to street-level urban particles concentrations, the priority in metro air quality should be dealing with particles coarser than 0.3 μm. In fact, the results suggest that at narrow platforms served by single-track tunnels the current forced tunnel ventilation during operating hours is less efficient in reducing coarse particles compared to fine.

1. Introduction

Metro systems are main transportation modes and typically serve billions of commuters annually in metropolitan areas worldwide. In major cities, metro can be viewed as a transport lifeline, relieving road traffic congestion (Vasconcellos, 2001). They also reduce air pollution above ground, thus Silva et al. (2012) concluded that a metro strike in São Paulo led to a significant increase in daily mean particulate matter (PM) mass concentrations due to extra road traffic. However, the underground system is a confined space that may cause a concentration of contaminants, either infiltrating from the outside atmosphere or generated internally. In this context, a number of studies have been conducted

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http://dx.doi.org/10.1016/j.atmosenv.2017.03.002
1352-2310/

to assess the levels of air pollutants and their chemical compositions. Generally, PM mass concentrations in metro systems, whether on platforms or inside trains, have been found to be higher when compared to those in adjacent outdoor air (Martins et al., 2015a and references therein).

It has been argued that current levels of PM in metro systems are unlikely to lead to any significant excess health effects in commuters (Nieuwenhuijsen et al., 2007 and references therein). Moreno et al. (2017) reported a low oxidative potential in metro samples from Barcelona compared with outdoor air. Conversely, some studies have shown evidences of a significant toxicity. For example, Steenhof et al. (2011) concluded that the underground PM samples caused the largest decrease of metabolic activity compared to traffic and urban background PM. Karlsson et al. (2008) also reported that, compared to outdoor PM, metro PM is more genotoxic and induces oxidative stress in cultured human lung cells. In the Paris metro system, Bachoual et al. (2007) concluded that lung inflammatory and structural cells could be targets of metro PM exposure. Consequently, it is reasonable to conclude that PM concentrations at metro systems should be controlled and reduced where possible.

The first comprehensive metro air quality study was conducted in Boston at the end of the 1980s (Chan et al., 1991) and focused on exposure to gasoline-related volatile organic compounds (VOCs). This work was followed by further studies assessing levels of different air pollutants in metro systems. After more than a decade of research, different air pollutants such as different size modes of PM mass (Furuya et al., 2001; Seaton et al., 2005; Park et al., 2012; Querol et al., 2012), PAHs (Furuya et al., 2001), CO (Cheng and Yan, 2011), NO_2 (Klepczyńska-Nyström et al., 2012), O_3 (Wad, 2002), metals (Kang et al., 2008; Karlsson et al., 2008; Park et al., 2012; Querol et al., 2012; Moreno et al., 2014; Martins et al., 2016a,b), and different biological pollutants (Wad, 2002; Hwang and Park, 2014; Triadó-Margarit et al., 2016) have all been measured using off-line samplers and/or real-time monitors. A search on SCOPUS using the combined keywords "air quality", "metro system", and "exposure" results in more than 65 publications in the past 10 years. However, publications on particle number (N) concentrations in metro systems both at platforms and inside trains are more limited (Levy et al., 2002; Birenzvige et al., 2003; Aarnio et al., 2005; Seaton et al., 2005; Cheng et al., 2009; Ma et al., 2012; Klepczyńska-Nyström et al., 2012; Gustafsson et al., 2012; Midander et al., 2012; Onat and Stakeeva, 2013; Colombi et al., 2013; Suárez et al., 2014; Cusack et al., 2015). Commuting studies have reported a higher particle size mode in metro systems compared with other transport modes and with those reported for urban backgrounds (Moreno et al., 2015).

Several studies have concluded on a lack of correlation of PM mass and N concentrations, which implies different sources and/or formation processes for particles in different size ranges (Morawska et al., 1998; Mejía et al., 2008). PM mass is dominated by coarse particles (>1 μm) and provides little information about ultrafine particles (UFP; <0.1 μm). UFP often contribute only a few percentage to the mass, at the same time contributing to over 80% of N. Therefore, the focus of a study differs widely when measuring one or another parameter.

The main goal of this study is the characterization of N concentrations in different size ranges in the metro system of Barcelona (Spain) in order to assess the influence of key parameters, mainly station design, ventilation settings, number and location of ventilation grills and train frequency. Thus, intensive monitoring campaigns have been carried out at 9 different platforms and different seasonal periods, accounting for specific features.

2. Methodology

2.1. Instrumentation

Different particulate matter size distribution instruments are often used to extend the measured size range within a single study, thus implying that the values they provide are comparable and complementary (Price et al., 2014). For this study, an Optical Particle Sizer (OPS 3330; TSI) and an Electrical Low Pressure Impactor (ELPI; Dekati) were used. Specifications on each instrument are summarized in Table 1. Maintenance services were routinely performed, including the cleaning of the charger and the impactor of the ELPI, in order to avoid changes in the cut points and particle bouncing effects. It is important to note that while OPS is based on the optical diameter, ELPI classifies particles according to their aerodynamic diameter. Different types of particles have distinct relationships between optical and aerodynamic diameters (Chien et al., 2016), which could result in important differences between instruments which are necessary to be characterized and taken into account when interpreting measurements.

The linear regression shows poor agreement between both pieces of equipment OPS and ELPI for N concentrations calculated over similar size ranges (0.374–10 μm as reported by OPS, and 0.384–10 μm as reported by ELPI; Figure S1). The study of the relationships by size ranges reveals that temporal trends between OPS and ELPI are more similar when each range of the OPS is compared with the immediately higher one of the ELPI. The R^2 of the linear regression between equipments increases by 25% and the slope is closer to one when the selected size range for ELPI is 0.616–10 μm (the lower selected stage being 0.616–0.953 μm instead of 0.384–0.616 μm; Figure S1). As the aerodynamic diameter is highly affected by density, one possible reason for this is that ELPI could slightly overestimate particle sizes due to the high density of metro particles, which ranges from 2.3 to 3.1 g cm^{-3}, based on their chemical composition (Martins et al., 2015b). On the other hand, the occurrence of particle re-entrainment (bounce), as the surface was not coated during sampling, could also lead to certain errors in the size classification in spite of the routine maintenance. Accordingly, regarding data reported by the ELPI, the interpretation will mainly focus on total

Table 1
Specifications of the instruments deployed for this study.

	ELPI	OPS
Measurement principle	Impactor technology with particle charging and electrical detection	120° light scatter and filter sampling
Particle size range	0.007–10 μm	0.3–10 μm
Size uncertainty	4% in cut-off diameter[a]	5% at 0.5 μm
Size channels	12 (0.007–0.056; 0.056–0.094; 0.094–0.156; 0.156–0.263; 0.263–0.384; 0.384–0.616; 0.616–0.953; 0.953–1.61; 1.61–2.4; 2.4–4.01; 4.01–6.62; 6.62–10)	16 (0.300–0.374; 0.374–0.465; 0.465–0.579; 0.579–0.721; 0.721–1; 1–1.2; 1.2–1.4; 1.4–1.732; 1.732–2.156; 2.156–2.5; 2.5–3.343; 3.343–4.162; 4.162–5.182; 5.182–6.451; 6.451–8.031; 8.031–10)
Flow rate	30 L min^{-1}	1.0 L min^{-1}; ±5% accuracy

[a] Pagels et al., 2007.