Atmospheric Environment 70 (2013) 166–178

Contents lists available at SciVerse ScienceDirect

Atmospheric Environment

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

Particulate matter concentrations, physical characteristics and elemental composition in the Milan underground transport system

C. Colombi*, S. Angius, V. Gianelle, M. Lazzarini

ARPA Lombardia, Settore Monitoraggi Ambientali, via Rosellini, 17 Milano 20124, Italy

HIGHLIGHTS

► PM10 levels in subway stations were studied and its elemental composition determined.
► OPC's were used to determine size distributions.
► PM10 concentrations were greater than in ambient air by up to a factor of 8.
► Source contributions were estimated on the platform and mezzanine levels.
► PM10 levels were largely due to local sources such as brake, wheel and cable wear.

ARTICLE INFO

Article history:
Received 11 October 2012
Received in revised form
4 January 2013
Accepted 18 January 2013

Keywords:
Subway
Transport microenvironment
PM10
Size distribution
Elemental composition
Source contribution

ABSTRACT

An extensive measurement campaign was conducted in the Milan subway system in order to investigate PM10 concentrations, to determine its physical and elemental composition, its origins, and to attempt to quantify source contributions. The Milan subway system includes three lines and stations typically consist of two underground levels: an intermediate floor (mezzanine) where the turnstiles for accessing the platform are located, and a platform level, one floor down. Measurements were performed in two stations for each line, and both microenvironments (platform and mezzanine) were investigated in all cases. PM10 samples were collected at all twelve sites over three daily periods for nine consecutive days at each site. Particle number concentrations were also measured with Optical Particle Counters (OPC) and size-number distributions were determined. X-ray fluorescence analysis was also performed on the samples to determine element concentrations. The results indicate PM sources related with train operations as the dominant impact on particulate concentrations. Average weekday PM10 concentrations between 105 and 283 $\mu g\ m^{-3}$ were observed at the platform level, while average ambient concentrations of 36 $\mu g\ m^{-3}$ were observed. Fe, Ba, Sb, Mn and Cu were found to be significantly enriched. Metal particles, occurring mostly in the range of diameters between 1 and 5 μm, and therefore likely originating from mechanical processes, account for most of the PM10 mass at the platform level. Wheel, brake and track wear are found to contribute 40–73% of total PM10 mass and electric cable wear (Cu and Zn oxides) 2%–3%. Concentrations measured on the mezzanine levels are intermediate between those found in ambient air and on the platform level, with average daytime PM10 values ranging from 50 to 80 $\mu g\ m^{-3}$. The situation observed on the mezzanine can well be described through an appropriate mixing of ambient and platform level air. A decreasing, albeit still significant, impact from internal sources is observed, with particulate from wheel, brake and track wear contributing an average of 2–25%, and electric cable wear 0.5–1.2%, to total PM10 mass.

1. Introduction

Ambient PM10 concentrations exceeding the limits set by the European air quality Directive (European Commission, 2008) are a major concern in the Milan metropolitan area, but individual exposure to particulate matter can be strongly influenced by indoor levels, as most people spend 80–90% of their time in a variety of indoor environments. In urban areas, transport-related microenvironments can be of concern when evaluating population exposure to particulate matter (Adams et al., 2001; Gómez-Perales et al., 2007).

Prior studies in the subway lines of several cities throughout the world indicate, with few exceptions, that particulate matter (PM)

* Corresponding author. ARPA Lombardia, via Juvara, 22, Milano 20129, Italy. Tel.: +39 0274872244, +39 3472930152 (mobile); fax: +39 0276110170.
E-mail address: c.colombi@arpalombardia.it (C. Colombi).

1352-2310/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.atmosenv.2013.01.035

concentrations significantly higher than those measured in ambient air are generally found in these environments. Elevated PM concentrations have been found in the subway systems of Barcelona (Querol et al., 2012), Berlin (Fromme et al., 1998), Boston (Levy et al., 2000), Budapest (Salma et al., 2007, 2009), Buenos Aires (Murruni et al., 2009) Helsinki (Aarnio et al., 2005), London (Adams et al., 2001), Los Angeles (Kam et al., 2011), Mexico City (Gómez-Perales et al., 2004, 2007), Rome (Ripanucci et al., 2006), New York (Chillrud et al., 2004, 2005), Paris (Raut et al., 2009), Prague (Braniš, 2006), Seoul (Kim et al., 2008; Jung et al., 2010), Shanghai (Xiaojiang et al., 2010), Stockholm (Johansson and Johansson, 2003), and Tokyo (Furuya et al., 2001). However, results are not always directly comparable because of differences in measurement methods, time averages, chemical and size characterization of particulate matter, the type of environment investigated and duration of the measurements (Nieuwenhuijsen et al., 2007). Some of these studies have also investigated particulate matter composition (Aarnio et al., 2005; Salma et al., 2007; Murruni et al., 2009; Chillrud et al., 2004, 2005), and metals such as Fe, Cu, Ba, and Mn, were found to be significantly enriched in comparison with typical outdoor levels. It has been suggested that these elements originate from the mechanical wear of rails, electric cables, brake pads, and wheels, but the contribution of such sources has not been quantified. A pedestrian exposure study performed in Milan also gives indications of elevated particle mass concentrations in subway stations (Lonati et al., 2011).

Based on the information available, measurements of particulate levels in the Milan subway system were performed to provide data and information for a possible exposure study and to determine the contributing sources for the purpose of identifying possible abatement measures.

Milan is served by three subway lines, at different depths, with different tunnel sizes, and different train frequencies. The underground system is a heavily used mode of transportation, carrying almost one million passengers on a weekday. In all three subway lines, two main types of environments are connected with the subway system: a first underground level (mezzanine), where cafes, newspaper kiosks, sometimes small shops, and the station controller (transport company employee) are located; and the track-level station (platform level), one floor down. Both types of locations were investigated in two different stations for each of the three subway lines. In order to gather information on the relationship between pollutant levels and the characteristics of the sites investigated, the measurements were extended to all three subway lines and to different stations and microenvironments with different characteristics (amount of mixing with external air, depth, connections with the upper level, size and shape of the station itself and the tunnels, number of trains in transit).

A comprehensive study of PM10 levels, and its physical and chemical characteristics was performed with continuous measurements over a significant length of time (nine days at each site); local particulate sources were identified and their contributions quantified. A simple method was also applied to estimate the respective contributions of outdoor and platform level air to the mezzanine floor air quality.

Since airborne particulate matter is an heterogeneous mixture with chemical and physical characteristics dependent on the originating sources and other environmental factors, particulate matter in a closed underground environment with local particulate emission sources is likely to be qualitatively different from that typically found in ambient air. As a consequence, mass concentrations might not correlate with possible health effects in the same way as in the case of urban particulate matter. Number and size distribution and chemical composition (Harrison and Yin, 2000; Riley et al., 2002; Davidson et al., 2005; Valavanidis et al., 2008) can therefore be useful metrics for an evaluation of personal exposure in such microenvironments. Particle number and size distributions were therefore also measured in each site and elemental composition of the samples was determined.

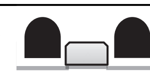
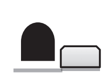
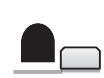
2. Experimental methodology

2.1. Sampling sites

The Milan subway system is a heavily used mode of transportation within the city and between the city and nearby towns. The M1 (Red) line was inaugurated in 1964 and extends over a total length of 28 km and 38 stations; the M2 (Green) line was inaugurated in 1969, and is 35 km long with 33 stations; the M3 (Yellow) line was inaugurated in 1990, and is 13 km long with 17 stations.

All three lines were investigated in this work. Two stations in the urban area were selected for each line, based on their different characteristics: Duomo and Porta Venezia on the Red line (R), Piola and Cadorna on the Green line (G) and Duomo and Crocetta on the Yellow line (Y). In all cases, measurements were performed both on the mezzanine level and on the platform at the track-level. The architecture of the stations and tunnels is different for each station: two separate tunnels with a central platform in Piola, one wide tunnel with two tracks in Duomo-R, Porta Venezia and Cadorna, a single narrow tunnel with one track in Duomo-Y and Crocetta. The mezzanine at Duomo is large and several shops are located there, as in Cadorna where it is also connected to a railway station; the others are smaller. Duomo and Cadorna are connecting stations between the Red and the Yellow Lines and the Red and the Green Lines, respectively. In all stations an air exchange system guarantees at least eight air changes per hour, through natural ventilation and forced extraction. The characteristics of the stations and the measurement periods are summarized in Table 1 and train operations are summarized in Table 2.

Table 1
Characteristics of the subway stations where measurements were performed and of the external area by the station entrance according to Directive 2008/50/CE.

Subway line/ station	Measurement period	Tunnel type	Plaform depth	Ambient station classification
Green Line – Piola	23 Mar–2 Apr		–13 m	Urban traffic
Green Line – Cadorna			–8 m	Urban traffic
Red line – Duomo	8–19 Apr		–10 m	Urban background
Red line – Porta Venezia			–9 m	Urban traffic
Yellow line – Duomo	19–30 Apr		–23 m	Urban background
Yellow line – Crocetta			–20 m	Urban traffic