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Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design

T. Moreno [a,*], N. Pérez [a], C. Reche [a], V. Martins [a], E. de Miguel [b], M. Capdevila [b], S. Centelles [b], M.C. Minguillón [a], F. Amato [a], A. Alastuey [a], X. Querol [a], W. Gibbons [c]

[a] Institute for Environmental Assessment and Water Research (IDÆA-CSIC), C/Jordi Girona 18-24, 08034 Barcelona, Spain
[b] Transports Metropolitans de Barcelona, TMB Santa Eulalia, Av. del Metro s/n L'Hospitalet de Llobregat, 08902, Spain
[c] WPS, C/Major 13, 08870 Sitges, Spain

HIGHLIGHTS

- Subway platform air quality varies depending on ventilation and station design.
- In some stations PM levels can double if tunnel ventilation is switched off.
- Accumulation of PM occurs at one end of the platform rather than in the middle.
- CO levels are low and controlled by traffic-contaminated air from street level.
- CO_2 variations depend on passenger numbers and train frequency.

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ABSTRACT

A high resolution air quality monitoring campaign (PM, CO_2 and CO) was conducted on differently designed station platforms in the Barcelona subway system under: (a) normal forced tunnel ventilation, and (b) with daytime tunnel ventilation systems shut down. PM concentrations are highly variable (6–128 μgPM_1 m^{-3}, 16–314 μgPM_3 m^{-3}, and 33–332 μgPM_{10} m^{-3}, 15-min averages) depending on ventilation conditions and station design. Narrow platforms served by single-track tunnels are heavily dependent on forced tunnel ventilation and cannot rely on the train piston effect alone to reduce platform PM concentrations. In contrast PM levels in stations with spacious double-track tunnels are not greatly affected when tunnel ventilation is switched off, offering the possibility of significant energy savings without damaging air quality. Sampling at different positions along the platform reveals considerable lateral variation, with the greatest accumulation of particulates occurring at one end of the platform. Passenger accesses can dilute PM concentrations by introducing cleaner outside air, although lateral down-platform accesses are less effective than those positioned at the train entry point. CO concentrations on the platform are very low ($\leq$1 ppm) and probably controlled by ingress of traffic-contaminated street-level air. CO_2 averages range from 371 to 569 ppm, changing during the build-up and exchange of passengers with each passing train.

1. Introduction

Commuting by underground rail is a transport mode pioneered in London 150 years ago and now used daily by over one hundred million people worldwide (Nieuwenhuijsen et al., 2007). Subway systems reduce road traffic congestion above ground and provide efficient transit that is generally viewed as environmentally friendly, offering what has been described as "the lifeline of urban development" (Pan et al., 2013). Despite the obvious benefits, however, it has become increasingly clear that many subway systems have a problem with regard to underground air quality and, as such, present a potential health risk to regular commuters and working staff (e.g. Karlsson et al., 2006), especially those already compromised by respiratory or cardiovascular disease. Inhalable particulate matter (PM) levels are typically much higher than those above ground, with published studies in subway systems from cities as varied as Los Angeles, Barcelona, Milan, Paris, Prague, Rome, Stockholm, Seoul, Shanghai and Taipei consistently reporting

* Corresponding author.
E-mail address: teresa.moreno@idaea.csic.es (T. Moreno).

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average PM_{10} levels on platforms that exceed 50 μg m^{-3} and in some cases reach 300 μg m^{-3} (Fromme et al., 1998; Johansson and Johansson, 2003; Seaton et al., 2005; Braniš, 2006; Ripanucci et al., 2006; Salma et al., 2007; Kim et al., 2008; Park and Ha, 2008; Raut et al., 2009; Ye et al., 2010; Cheng and Yan, 2011; Kam et al., 2011; Colombi et al., 2013).

The air quality of a given subway platform will depend on a complex interplay of factors such as the ventilation system, train speed and frequency, wheel materials and braking mechanisms, and station depth and design (Querol et al., 2012 and references therein). Air movements on the platform are influenced by periodic cycles involving three-dimensional turbulent flow through mechanically forced ventilation systems, draught relief outlets ("blast shafts"), and platform access points, driven to a large extent by the "piston effect" of the trains moving through the tunnels (e.g. Lin et al., 2008; Jia et al., 2009; Pan et al., 2013; López-González et al., 2014). In the latter process, the train passing through the tunnel has a dual effect by pushing the air in front of it and sucking the air behind into a negative pressure vortex in its wake, generating air currents of greater or lesser intensity depending on the speed of the train and the dimensions of the tunnel. A perceived virtue of these piston winds lies in their ability to ventilate the tunnels and platforms, thus possibly reducing the need for additional mechanically forced ventilation. Thus optimal use of the piston effect offers the possibility of making significant energy savings (Pan et al., 2013). In the city of Barcelona, for example, the subway system energy consumption can exceed 268 million kW h^{-1}, with ventilation systems consuming most of the 79 million kW h^{-1} related to non-traction electricity use (TMB, 2010 own data). However, another aspect of the interplay between the piston effect and mechanically forced ventilation in underground transport systems is the possible influence on platform air quality, although this aspect has been largely overlooked (Pan et al., 2013). With this in mind, we report on the results of a recent experiment conducted on platforms in the Barcelona metro system in which air quality was monitored across a range of station designs under (i) normal ventilation conditions, with mechanical forced ventilation running in the tunnels, and (ii) experimental ventilation conditions, when the forced ventilation of the tunnel was turned off during daytime so that the train piston effect was emphasized. During the two sampling periods we monitored ambient PM concentrations in different size fractions at high time resolution (every 6 s) and at different platform locations, along with coeval concentrations of CO and CO_2. The primary aim of the study was to analyze the degree to which station design and the train piston effect influence air quality on underground train station platforms and thus potentially impact on energy consumption and passenger health.

2. Methodology

Line 2 (L2) in the Barcelona Metro system was selected as our study target for the experiment because it has a wide variety of station designs and was constructed in different stages, culminating in the opening of the latest extension to the nearby municipality of Badalona in 2010 (Fig. 1). The line is 13.1 km long and has 18 stations, with trains circulating at an average speed of 27.6 km h^{-1} and crossing the city in a NE–SW direction almost parallel to the coastline and therefore with no major topographical gradients. The entire line runs underground, typically at depths of 10–20 m below the surface, with tracks built on concrete (with the exception of one station where ballast is used), and it operates using a rigid overhead catenary electric power supply. Measurements were carried out at 10 platforms from 14 to 27 January 2013, with stations being carefully selected to ensure that include different designs with regard to tunnel, railtrack and platform access points. As stated above, two different conditions were studied: from 14 to 20 January the ventilation system of the tunnels in L2 during working hours was normal (forced mechanical tunnel ventilation: FMTV), whereas it changed to experimental (no FMTV during daytime) from 21 to 27 January. The change was done during the weekend to allow conditions to stabilise before sampling. Ventilation in the platforms was kept the same during both periods. Measurements under these two contrasting conditions were performed at each selected station for 1 h, sub-divided into 15-min periods each at four positions approximately equidistant along the platform (numbered P1–P4, with P1 being the train entry point and P2–4 being progressively further away down-platform). Although it is clear that PM varies spatially along the platform (Querol et al., 2012), this protocol was adopted in order to investigate the possible reasons for these PM concentration variations at the 10 platforms. All measurements were carried out on subway platforms with trains travelling towards Badalona (NE direction) and only on weekday (Monday to Friday) mornings after the rush hour and prior to the lunchtime travel period.

Most of the monitored stations are served either by single track tunnels (Universitat, Monumental, and Sant Antoni) or by a wider double track tunnel with lateral platforms (La Pau, Verneda, Artigues, Gorg and Clot), as depicted on Fig. 1. Separated single track tunnels characterise much of the southwestern section of L2, especially the four contiguous stations between Universitat and Monumental (Fig. 1). Both Universitat and Monumental were inaugurated in 1995, have narrow platforms with only one end-access point and, in the case of Universitat, five spaced gaps connecting the two platforms. In the case of the double-railtrack stations, three of these (La Pau, Verneda, Gorg) have lateral access points on each platform, Artigues station has one single access located at one end of the platform, and Clot has two end accesses and a dividing wall separating the railtracks (Fig. 1). Whereas Verneda, Artigues and Gorg are the oldest stations on the line (opened in 1985), La Pau and Clot were opened in 1997 (Fig. 1). With regard to the end-of-line stations, Paral-lel has two end exits as well as lateral connections to an adjacent platform (Line 3), whereas the spacious, well-ventilated station of Badalona has two end access points and a third parking railtrack (Fig. 1).

The measuring equipment comprised: i) An optical particle counter Model 1108 (Grimm Labortechnik GmbH & Co. KG) measuring atmospheric PM concentrations (μg m^{-3}) in 15 different sizes of particles between 0.3 and 20 microns in diameter. For better visualization, the 15 channels results have been grouped into three, namely PM_{10}, PM_3 and PM_1, corresponding to particles smaller than 10, 3 and 1 micron in diameter respectively; ii) An indoor air quality analyzer IAQ-CALC, Model 7525 (TSI), which allows simultaneous measurement of continuous levels of carbon dioxide and carbon monoxide (CO_2 and CO) in parts per million (ppm).

Measurements were carried out simultaneously with a data collection interval of 6 s, the minimum time resolution offered by the equipment used, in order to test the effect of each train as it passes through each station. Levels of PM provided by the Grimm monitor were corrected after intercomparison with a reference high volume PM sampler after the study applying two factors, one for the PM_{10} size fraction ($y = 0.36x - 2$, $R^2 = 0.87$) and another one for both PM_3 and PM_1 ($y = 0.28x + 0.08$, $R^2 = 0.73$) data. Both factors were obtained by comparing PM automatic values with gravimetric data (14 and 7 PM_{10} and $PM_{2.5}$ filter samples respectively) from a referenced high volume sampler (MCV) collecting samples during the two weeks after the campaign. Measurements represent a total of over 1100 PM data per station. Also at each station a manual control of the exact time of arrival and departure of each train was registered, to check *a posteriori* correlations