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Exposure to airborne particulate matter in the subway system

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HIGHLIGHTS

- Higher PM concentrations were found on platforms compared to outdoor.
- Air quality was better in the new lines with PSDs.
- PM concentrations were higher in the colder than in the warmer period.
- Ventilation and air conditioning systems improve air quality in the subway system.
- Time commuting in the subway contributes substantially to the personal exposure.

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ABSTRACT

The Barcelona subway system comprises eight subway lines, at different depths, with different tunnel dimensions, station designs and train frequencies. An extensive measurement campaign was performed in this subway system in order to characterise the airborne particulate matter (PM) measuring its concentration and investigating its variability, both inside trains and on platforms, in two different seasonal periods (warmer and colder), to better understand the main factors controlling it, and therefore the way to improve air quality. The majority of PM in the underground stations is generated within the subway system, due to abrasion and wear of rail tracks, wheels and braking pads caused during the motion of the trains. Substantial variation in average PM concentrations between underground stations was observed, which might be associated to different ventilation and air conditioning systems, characteristics/design of each station and variations in the train frequency. Average $PM_{2.5}$ concentrations on the platforms in the subway operating hours ranged from 20 to 51 and from 41 to 91 μg m^{-3} in the warmer and colder period, respectively, mainly related to the seasonal changes in the subway ventilation systems. The new subway lines with platform screen doors showed $PM_{2.5}$ concentrations lower than those in the conventional system, which is probably attributable not only to the more advanced ventilation setup, but also to the lower train frequency and the design of the stations. PM concentrations inside the trains were generally lower than those on the platforms, which is attributable to the air conditioning systems operating inside the trains, which are equipped with air filters. This study allows the analysis and quantification of the impact of different ventilation settings on air quality, which provides an improvement on the knowledge for the general understanding and good management of air quality in the subway system.

1. Introduction

Citizens usually spend a considerable amount of their daily time commuting. Considering that in urban areas road traffic is a major emission source of air particles (Viana et al., 2008), travelling by public transportation saves energy and produces less pollution than travelling in private vehicles. The subway, being an electrical system and one of the cleanest public transport systems in large urban agglomerations, is considered to be the most appropriate public transport since it diverts the burdens of superficial traffic congestion. Its high capacity in terms of number of daily commuters makes it an environmentally friendly alternative. The energy efficiency and reduced urban atmospheric emissions make this kind of public transport a powerful tool to reduce energy demands and improve air quality in urban environments.

However, prior studies in subway systems of several cities worldwide indicate, with few exceptions, that particulate matter (PM)

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concentrations are generally higher in these environments than those measured in ambient air (Nieuwenhuijsen et al., 2007). The underground subway system is a confined space that promotes the concentration of contaminants entering from the outside atmosphere in addition to those generated inside. The subway aerosol particles are mainly generated by the abrasion of rail tracks, wheels, catenary and brake pads produced by the motion of the trains, and the movement of passengers which promotes the mixing and suspension of PM (Querol et al., 2012). PM levels have been reported in many subway systems, such as in Milan (Colombi et al., 2013), Barcelona (Querol et al., 2012; Moreno et al., 2014), Taipei (Cheng et al., 2008, 2012; Cheng and Lin, 2010), Seoul (Kim et al., 2008, 2012; Park and Ha, 2008; Jung et al., 2010), Mexico City (Mugica-Álvarez et al., 2012; Gómez-Perales et al., 2004), Los Angeles (Kam et al., 2011a,b), New York (Wang and Gao, 2011; Chillrud et al., 2004, 2005), Shanghai (Ye et al., 2010), Sydney (Knibbs and de Dear, 2010), Buenos Aires (Murruni et al., 2009), Paris (Raut et al., 2009), Budapest (Salma et al., 2007), Beijing (Li et al., 2006, 2007), Prague (Braniš, 2006), Rome (Ripanucci et al., 2006), Helsinki (Aarnio et al., 2005), London (Seaton et al., 2005; Adams et al., 2001), Stockholm (Johansson and Johansson, 2003), Hong Kong (Chan et al., 2002a), Guangzhou (Chan et al., 2002b), Tokyo (Furuya et al., 2001), Boston (Levy et al., 2000), and Berlin (Fromme et al., 1998). However, results are not always directly comparable because of differences in sampling and measurement methods, data analysis, duration of the measurements and the type of environment studied (Nieuwenhuijsen et al., 2007). There are important factors influencing PM concentrations in underground railway systems around the world, which include differences in the length and design of the stations and tunnels, system age, wheel and rail-track materials and braking mechanisms, train speed and frequency, passenger densities, ventilation and air conditioning systems, cleaning frequencies, among other factors (Moreno et al., 2014 and references therein).

Despite the number of studies on PM in underground subway systems, the main focus of most of them has been to monitor variations in mass concentration of PM on platforms and in a reduced number of stations. Therefore, there is a need for extensive studies of entire subway systems, covering the vast diversity of lines, trains and stations and providing an overview of the overall exposure to PM in this environment.

With this in mind, this work is the first study that presents a large dataset from an extensive campaign, able to characterise 24 stations in the Barcelona subway system and providing valuable information for human PM exposure studies in such environment, considering its possible adverse health effects (Pope et al., 2004; Seaton et al., 2005; Karlsson et al., 2006, 2008; Gustavsson et al., 2008). For this, continuous PM measurements were carried out in 4 underground subway stations in Barcelona, on a daily basis during two months and supplementary samplings were also performed in a total of 20 additional stations. Measurements inside the trains were also carried out in 6 subway lines.

In order to gather information on the relationship between pollutant levels and the characteristics of the sampling sites, the measurements were obtained in several subway lines, including stations with different characteristics (design and ventilation of the station and tunnels, number and location of connections with the outdoor level, and train frequency). This monitoring scheme was designed to characterise the temporal and spatial variation of particles at each site and to identify their possible sources. Therefore, the four subway stations studied on daily basis have different characteristics; in particular, one of the stations is equipped with platform screen doors (PSDs) for commuters' safety but also resulting in less mixing of air between the platform and tunnels. The influence of the installed PSDs on aerosol characteristics is also investigated in this work.

2. Methodology

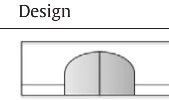
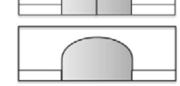
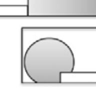
2.1. Field study

The subway system in the city of Barcelona (managed by Transports Metropolitans de Barcelona, TMB) is one of the oldest underground transport systems in Europe, with its first line beginning operation in 1924. By the present decade, the Barcelona subway system comprises 8 lines (3 of them in operation over the last five years) with a total length of 102.6 km and including 140 train stations. The new stations have platforms separated from the tunnel by a wall with mechanical doors (PSDs) that are opened simultaneously with the train doors. Trains run from 5 a.m. until midnight every day, with additional services on Friday nights (finishing at 2 a.m. of Saturday) and Saturday nights (running all night long), with a frequency between 2 and 15 min, depending on the day (weekend or weekday), subway line and time of day. The Barcelona subway absorbs around 50% of the urban commuting load, transporting 1.25 million commuters on weekdays, with the most frequent average journey time being 35 min (Querol et al., 2012).

In all subway systems, two main types of environments are connected: the platform station and the inside of the train. Both types of environments were investigated in this study. Four underground stations with distinct designs belonging to different lines were selected for continuous monitoring in two one-month periods: Joanic on the yellow line (L4), Santa Coloma on the red line (L1), Tetuan on the purple line (L2), and Llefià on the new light blue line (L10). The architecture of the stations and tunnels is different for each station: one wide tunnel with two rail tracks separated by a middle wall in Joanic station and without middle wall in Santa Coloma, a single narrow tunnel with one rail track in Tetuan, and a single tunnel with one rail track separated from the platform by a wall with PSDs in Llefià (Table 1).

The study was conducted in the warmer (2 April–30 July 2013) and colder (28 October 2013–10 March 2014) periods (Table 1), according to TMB ventilation protocols to ascertain seasonal differences. In total, the air quality at each station was measured continuously for 30 days

Table 1
Features of the subway stations and measurement periods.

Subway station (line)	Measurement period		Station	
	Warmer	Colder	Depth	Design
Joanic (L4)	2 Apr–2 May 2013	28 Oct–25 Nov 2013	−7.6 m	
Santa Coloma (L1)	1 Jul–30 Jul 2013	10 Feb–10 Mar 2014	−12.3 m	
Tetuan (L2)	2 May–31 May 2013	25 Nov–20 Dec 2013	−14.8 m	
Llefià (L10)	31 May–1 Jul 2013	13 Jan–10 Feb 2014	−43.6 m	

per season to obtain statistically representative data. Both seasons were analysed using the same analytical methodology and monitoring instruments. For comparison purposes, outdoor ambient PM concentrations were measured concurrently at the urban background station of Palau Reial (41°23′14″ N, 02°06′56″ E) which was used during both campaigns as a reference site.

The platform ventilation conditions in the stations are regulated by introducing outdoor air into the tunnel and/or platform (impulsion) and removing indoor air towards the outdoor environment (extraction). The mechanical ventilation settings (Table 2), with strong or low impulsion and/or extraction of air between the platform stations and tunnels, were adjusted for this study according to different TMB protocols during the sampling periods in order to evaluate the influence in PM concentrations and to determine the best operating conditions for air quality on the platform. Each selected ventilation setting was maintained at least during one week, in order to better evidencing their effects on PM levels.

2.2. Measurements and sampling equipment

Air monitoring equipment included a light-scattering laser photometer (DustTrak, Model 8533, TSI) for PM_1, $PM_{2.5}$ and PM_{10} (particulate matter with aerodynamic diameter less than 1 μm, 2.5 μm and 10 μm, respectively) concentrations, a high volume sampler (HVS, Model CAV-A/MSb, MCV) with a $PM_{2.5}$ head, and an indoor air quality meter (IAQ-Calc, Model 7545, TSI) for CO, CO_2, T and RH values. The instruments were placed at the end of the platform corresponding to the train entry point, far from the passengers' access-to-platform point, and behind a light fence for safety protection. This location was chosen as a compromise between meeting conditions for undisturbed measurement and obstructing commuter's path as little as possible. The aerosol inlets were placed at roughly 1.5 m above the ground level. Two protocols were undertaken concurrently during the study for continuous PM_X measurements: 1) additional measurements of PM_X concentrations on platforms to characterise spatial variations along the platform, and 2) monitoring of air quality inside the trains (see Sections 2.3 and 2.4).

The high volume sampler, which permits the sequential sampling of 15 filters, was equipped with quartz microfiber filters and programmed to sample $PM_{2.5}$ over 19 h (from 5 a.m. to 12 p.m., subway operating hours) at a sampling flow rate of 30 m^3 h^{-1}. A field blank was taken at each station. $PM_{2.5}$ concentrations were determined gravimetrically using a microbalance (Model XP105DR, Mettler Toledo) with a sensitivity of ±10 μg. The sampled filters were pre-equilibrated before weighing for at least 48 h in a conditioned room (20 °C and 50% relative humidity). The quartz filters were used only for gravimetric purpose in this study, however, a detailed chemical analysis will be performed in subsequent studies.

Continuous measurements (24 h day^{-1}) with a 5-minute time resolution were performed using the DustTrak monitor for PM_1, $PM_{2.5}$ and PM_{10} concentrations and the IAQ-Calc for CO_2 and CO concentrations, T and RH. CO concentrations were always below the detection limit (3 ppm) and hence they will not be further mentioned in this study. $PM_{2.5}$ concentrations provided by DustTrak monitor were corrected against the in-situ and simultaneous gravimetric $PM_{2.5}$ for each station. Levels of PM_1 and PM_{10} were corrected using the same correction factors obtained for $PM_{2.5}$. However, previous HVS-DustTrak intercomparisons for PM_1 and PM_{10} concentrations were done for the ambient outdoor air and weak correlations were obtained. The PM_{10} and PM_1 concentrations provided for the DustTrak monitor were undervalued and overvalued, respectively. Since the aerosol properties in the subway are different from the outdoor aerosol, the previously determined correlations are not suitable to correct the measurements. Therefore, in this study only the $PM_{2.5}$ concentrations are used in absolute terms.

In the urban background station of Palau Reial, continuous measurements were performed by a Laser Aerosol Spectrometer (Environmental Dust Monitor, Model EDM180, Grimm), with a 30-minute time resolution, corrected with in-situ and simultaneous measurements obtained with a high volume sampler (HVS, Model CAV-A/MSb, MCV), working for 24 h every third day.

2.3. Additional platform measurements

Measurements at the 4 selected platforms and at 20 additional platforms with wide variety of designs, from 6 subway lines, were carried

Table 2
Operating conditions for tunnel and platform ventilations.

<table>
<tr><th rowspan="3">Mode</th><th rowspan="3">Stations</th><th rowspan="3">Experimental period (week of each month)</th><th colspan="4">Operating conditions</th></tr>
<tr><th colspan="2">Day</th><th colspan="2">Night</th></tr>
<tr><th>Platform</th><th>Tunnel</th><th>Platform</th><th>Tunnel</th></tr>
<tr><td>I.W</td><td>J, SC, T</td><td>1^{st} and 3^{rd}</td><td rowspan="2">St. Imp.</td><td rowspan="2">St. Ext.</td><td rowspan="2">No ventilation</td><td>Low Imp.</td></tr>
<tr><td>II.W</td><td>J, SC, T</td><td>2^{nd} and 4^{th}</td><td>Low Ext.</td></tr>
<tr><td>III.W</td><td>L</td><td>1^{st} and 3^{rd}</td><td>St. Imp. + Ext.</td><td rowspan="2">St. Imp. + Ext.</td><td>St. Imp. + Ext.</td><td rowspan="2">St. Imp. + Ext.</td></tr>
<tr><td>IV.W</td><td>L</td><td>2^{nd}</td><td>Low Imp. + Ext.</td><td rowspan="2">Low Imp. + Ext.</td></tr>
<tr><td>V.W</td><td>L</td><td>4^{th}</td><td>St. Imp. + Ext.</td><td>Low Imp. + Ext.</td><td>Low Imp. + Ext.</td></tr>
<tr><td>I.C</td><td>J, SC, T</td><td>1^{st} and 4^{th}</td><td rowspan="3">Low Imp.</td><td>Low Extr.</td><td rowspan="3">No ventilation</td><td rowspan="2">Low Imp.</td></tr>
<tr><td>II.C</td><td>J, SC, T</td><td>2^{nd}</td><td>No ventilation</td></tr>
<tr><td>III.C</td><td>J, SC, T</td><td>3^{rd}</td><td>Low Extr.</td><td>Low Ext.</td></tr>
<tr><td>IV.C</td><td>L</td><td>1^{st} and 2^{nd}</td><td>St. Imp. + Ext.</td><td rowspan="2">St. Imp. + Ext.</td><td>St. Imp. + Ext. (*)</td><td rowspan="2">St. Imp. + Ext.</td></tr>
<tr><td>V.C</td><td>L</td><td>3^{rd}</td><td>Low Imp. + Ext.</td><td>Low Imp. + Ext. (*)</td></tr>
<tr><td>VI.C</td><td>L</td><td>4^{th}</td><td>St. Imp. + Ext.</td><td>Low Imp. + Ext.</td><td>St. Imp. + Ext. (*)</td><td>Low Imp. + Ext.</td></tr>
</table>

W: warmer period; C: colder period; J: Joanic station; SC: Santa Coloma station; T: Tetuan station; L: Llefià station; St: strong; Imp: impulsion; Ext: extraction; and (*): some fans switched off. Normal ventilation conditions marked in shadow.

out using a DustTrak monitor to obtain PM_1, $PM_{2.5}$ and PM_{10} concentrations with 5-second time resolution, enabling us to see the effect of trains and commuters movements. Out of the 24 stations, 4 were new stations (line 10) and the remaining were old stations (lines 1–5). The sampling protocol was as follows: the measurements at each station lasted for 1 h, divided into periods of 15 min in 4 positions approximately equidistant along the platform; the first measurement point was located at the sampling site (placed at the far end of the platform corresponding to the train entry point) for comparison with the average PM_X concentrations measured across the platform; additionally, in the colder period, the sampling in the first point was repeated during 5 min after the 4 positions as a control; a manual record of the exact arrival and departure times of the trains was kept; sampling was performed during weekdays between 9 a.m. and 2 p.m. Sampling was conducted twice in each season campaign (colder and warmer periods), resulting in 96 total sampling studies. In addition, in 12 old stations, in the colder period, measurements were performed once more to study the influence of the piston effect (with the ventilation mode II.C, Table 2) on the air quality of the platforms.

The PM_X concentrations reported in this study for the 4 selected stations are those corrected for spatial variation determined at each platform based on the aforementioned measurements (Table S1). The $PM_{2.5}$ correction factors for spatial variation obtained for the light-scattering laser photometer (DustTrak) data at Joanic, Santa Coloma, Tetuan and Llefià were 1.05, 0.71, 0.92 and 0.71 in the warmer period and 0.96, 1.06, 1.02 and 0.95 in the colder period, respectively. These values were obtained by dividing the average $PM_{2.5}$ concentrations in all station by the average $PM_{2.5}$ concentrations in the first point, located at the sampling site. In general, the factors indicate that levels measured at the sampling sites were very similar to the exposure levels of commuters waiting elsewhere along the platform, as factors were very close to 1, with the exceptions of Santa Coloma and Llefià, in the warmer period, in which exposure levels were around 40% higher in the far end of each platform.

2.4. Measurements inside the trains

Measurements inside the trains from 6 subway lines (L1, L2, L3, L4, L5 and L10) were carried out during a return trip along the whole subway line. PM_1, $PM_{2.5}$ and PM_{10} concentrations were measured using a DustTrak monitor. During the colder period, CO_2 concentrations were also monitored using an Indoor Air Quality meter (IAQ-Calc). The logging interval for all measurements was set at 5 s.

The measurements were performed from 10 a.m. on weekdays in duplicate at each route and were carried out in the middle of the central car of the train, with instrumentation being transported in a bag with the air uptake inlet placed at shoulder height when sitting. A manual record of the time when train doors open and close was performed. During the colder period of the campaign, measurements were carried out along the whole length of the line with and without air conditioning (not possible during warmer period due to passengers comfort requirements).

3. Results and discussion

3.1. PM_X concentrations on platforms

3.1.1. Influence of outdoor environment

The PM_X mass concentrations discussed in this section are those determined by the DustTrak instrument and corrected against gravimetric measurements. Fig. 1 shows a comparison between the average $PM_{2.5}$ concentrations on the subway platforms and outdoor, considering all day data and only operating hours data. Some outliers in the DustTrak time series were identified and associated with occasional, mostly night-time, maintenance or cleaning operations, and were included in the analysis of daily concentrations. In any case the most relevant data are those measured during subway operating hours, due to the commuters' exposure to PM.

$PM_{2.5}$ concentrations on the platforms were significantly higher than those in the outdoor environment. The average concentrations were 1.3–6.1 and 1.3–6.7 times higher on the platforms than outdoors for all day period and in the operating hours period, respectively. The outdoor PM concentrations do not seem to influence significantly the air quality in the subway stations, since most of the PM load in the underground stations is generated within the subway system, due to the abrasion and wear of rail tracks and wheels caused by the motion of the trains as well as to the braking systems (Querol et al., 2012). In Stockholm the exposure levels for $PM_{2.5}$ were 5–10 times higher than the corresponding values measured on the busiest streets in that city (Johansson and Johansson, 2003).

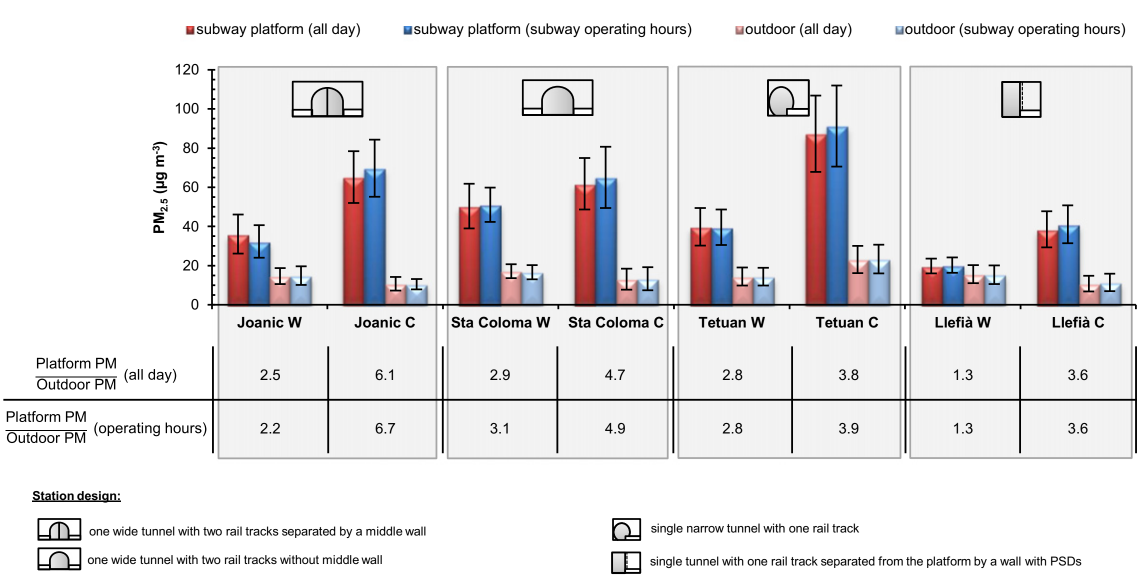


Fig. 1. Average $PM_{2.5}$ concentrations and standard deviations on the subway platforms and outdoor in both periods, and the ratios of $PM_{2.5}$ concentrations with respect to the outdoor levels (W — warmer period; C — colder period).

3.1.2. Comparison at different periods

Average $PM_{2.5}$ concentrations during operating hours were generally higher than those corresponding to the all day, which indicates the importance of $PM_{2.5}$ sources related to the subway operation activities. The opposite trend was only observed during the warmer period in Joanic when night-time maintenance or cleaning operations were more intense, generating larger amounts of $PM_{2.5}$ during non-operating hours (Fig. 1). Average $PM_{2.5}$ concentrations for operating hours on Joanic, Santa Coloma, Tetuan and Llefià subway platforms were 32, 51, 40 and 20 μg m^{-3} in the warmer period, and 70, 65, 91 and 41 μg m^{-3} in the colder period, respectively. Highest concentrations occurred thus during the colder period, mainly due to platform ventilation differences between seasons. The new station (Llefià) showed on average $PM_{2.5}$ concentrations lower (around 50%) than the old stations (Joanic, Santa Coloma and Tetuan), which is probably attributable to the design of the stations, but also due to the less train frequency and more advanced ventilation setup. Nieuwenhuijsen et al. (2007) mentioned that the high levels of PM could be observed in underground environments resulting from the generation or accumulation of PM in a confined space, particularly in old subway systems.

3.1.3. Daily patterns

Average intra-day variations of PM_X and CO_2 concentrations are plotted versus the train traffic frequency separately for weekdays, Saturdays and Sundays on the Joanic and Llefià platforms in Fig. 2, for both warmer and colder periods. Similar daily trends of PM_X and CO_2 concentrations were observed among the conventional stations (Joanic, Santa Coloma and Tetuan), only Joanic is shown as example in Fig. 2.

The PM_X daily pattern during weekdays of the warmer period presents a concentration increase in the morning with the arrival of the first trains until the maximum concentration at around 6 a.m., when the ventilation rate increased. From then the PM_X concentration decreased towards a rather stable concentration throughout the day. With the reduction of the ventilation rate at around 9 p.m. the PM_X levels rise again until midnight (when the trains operation stops) and tends to decrease during the night. In the conventional stations, increases in PM_X concentration up to a factor of 2 were observed around 3 a.m., and they were associated with occasional night-time maintenance or cleaning operations. However, for Joanic W (Fig. 2) there were higher average concentrations during the night than during subway operating hours, mainly due to the intense maintenance works or cleaning operations, as previously discussed. The CO_2 concentrations can also have a slight peak caused by the workers' exhalation and by the use of machinery. The highest peak of CO_2 concentrations on weekdays was found in the morning rush hour between 7 and 9 a.m., due to the higher influx of commuters. The commuters generate CO_2 through exhalation and at the same time they lead to the re-suspension of the PM_X created by walking. On weekends it is possible to observe the same pattern in relation to the ventilation rate. On Saturday, the PM_X levels only decrease after 2 a.m., when the trains stop operating, and on the night of Saturday to Sunday the PM_X concentration decreases gradually as the train frequency also decreases, which shows the train frequency influence in the absence of strong ventilation. Hence, the daily pattern of PM_X and CO_2 concentrations was primarily influenced by the ventilation settings and secondarily by the train frequency. The PM_X concentrations on the platforms are the result of a dynamic system controlled by the train frequency (source) and ventilation settings (removal), however, it is evident that the impact of train frequency on PM_X levels only becomes relevant when lower ventilation rates occur (Fig. 2).

In the colder period it is possible to observe that the stable and relatively low concentration registered in the warmer period (with stronger ventilation) is replaced by higher concentrations that tend to increase during the day, especially during weekend, reflecting the increasing number of trains, and probably enhanced by the accumulation of particles in the station caused by the weaker ventilation during this time of the year. During night-time however the pattern was very similar to the one described above for the warmer period.

The results in Llefià station (equipped with PSDs) for the warmer period showed that its stronger ventilation systems can achieve much lower and stable PM_X concentrations on the platforms, with only a slighter increase of PM levels between 6 and 9 a.m. especially during weekdays. Again, in the colder period, the daily pattern of PM_X concentrations presents higher and less stable values during the whole week due to the lower ventilation rates.

Regarding the three PM_X size fractions, the PM_1/PM_{10} and $PM_{2.5}/PM_{10}$ ratios were lower in the warmer period (Fig. 2), indicating that the ventilation of the subway system was more efficient removing coarser particles. Thus, the PM_1 were the principal size fraction composing the PM in the subway system, especially during the warmer period.

On the platforms, the PM_X concentrations were lower during weekends, probably due to the lower frequency of trains, as Aarnio et al. (2005) and Johansson and Johansson (2003) observed in the Helsinki and Stockholm subway systems, respectively. The average weekday values were between 1.2 and 1.5 times higher than those measured on weekends. Averages, maximum and minimum $PM_{2.5}$ concentrations for operating hours and standard deviations for the four stations are summarized in Table S2 for weekdays and weekends.

3.1.4. Influence of different ventilation settings

Regarding ventilation settings, several protocols (Table 2) were tested during weekly periods to detect PM_X concentration differences and determine the best operating conditions for optimizing the air quality on the platforms. The ventilation modes varying during day/night and platform/tunnel, were the same for the three old stations monitored, being Joanic (old) shown as example in Fig. 3, together with Llefià (new, with PSDs system).

Generally, on the old platforms, when comparing the I.W and II.W modes (Table 2, with different ventilation in tunnel at night) higher PM_X concentrations were recorded in the situation II during night-time hours (see shadow area in Fig. 3a, b), evidencing that the impulsion of outdoor air was more efficient than the extraction of indoor air for air quality purposes. The same effect of ventilation result was obtained during the I.C and III.C modes, also with different ventilation in tunnel at night (only I.C mode shown in Fig. 3c). Note that the general concentrations during the colder period were higher, attributed to the lower day-time ventilation than in the warmer period, as previously discussed. The ventilation mode II.C (Fig. 3d) was tested to observe if the piston effect (with no additional mechanical ventilation in the tunnel) produced by the movement of the trains was enough to reach a good air quality inside the subway system. On average the $PM_{2.5}$ concentrations were around 29% higher during this week compared to the levels observed with the normal ventilation in the colder period (I.C mode).

On Llefià platform, the ventilation III.W and IV.W modes resulted in similar diurnal patterns (only III.W mode shown in Fig. 3e) and the V.W mode resulted in higher PM_X concentrations during all day (Fig. 3f). These results revealed that changes in the ventilation settings on the platform did not influence the air quality in the station, while the opposite was observed for the tunnel ventilation, demonstrating that only the changes in the tunnel ventilation were relevant in the air quality within the new system.

There were no differences among the ventilation modes tested in the colder period (IV.C, V.C and VI.C), but the use of a lower number of fans on the platforms resulted in higher PM_X concentrations.

3.1.5. Spatial and temporal variations along platforms

Some clear spatial and temporal trends were obtained among all measurements, although in some platforms there were day-to-day fluctuations in PM_X concentrations. Representative cases are discussed below (Fig. 4), whereas all the results for $PM_{2.5}$ are displayed in Table S1. As mentioned before, the PM_X concentration on the platforms was generally lower in the warmer period, when compared with the

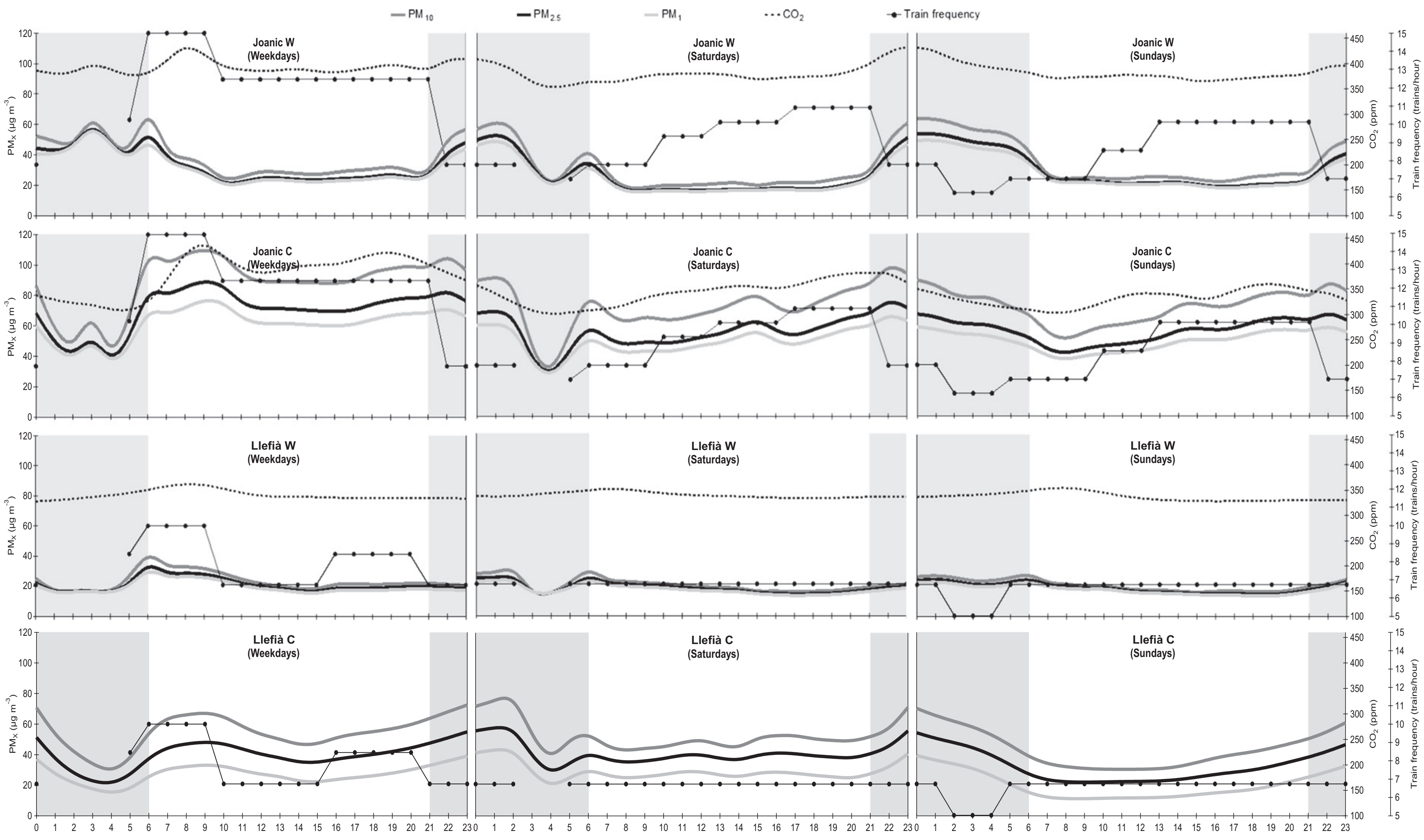


Fig. 2. Relation between the train frequency per hour and the hourly average PM_{10}, $PM_{2.5}$, PM_1 and CO_2 concentrations on the subway platforms of Joanic (old) and Llefià (new) stations, during weekdays, Saturdays and Sundays in both periods (W — warmer period; C — colder period). The (lower) night ventilation is highlighted in grey. See text for details.

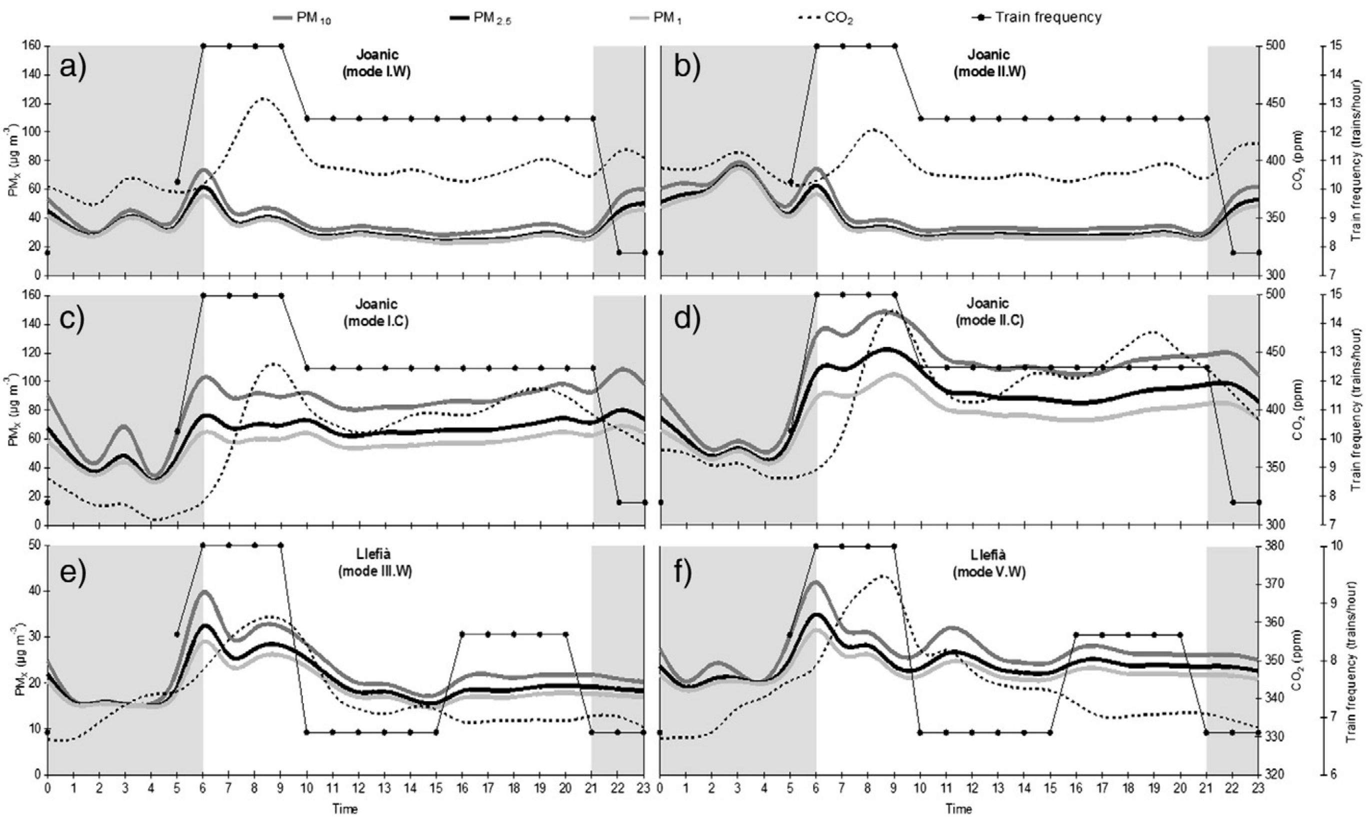


Fig. 3. Hourly average PM_{10}, $PM_{2.5}$, PM_1 and CO_2 concentrations and train frequency on the subway platforms of Joanic and Llefià stations with different ventilation settings. The night ventilation is highlighted in grey (W — warmer period; C — colder period).

colder period, due to the increased use of ventilation throughout the station diluting PM_X (Figs. 4a, b, 5). In addition in colder period, the PM_X concentrations on the platforms were generally more variable in shorter time scales (five second periods) ranging for example from 33 to 133 µg $PM_{2.5}$ m^{-3} in Joanic station.

High time resolution PM_X measurements evidenced that PM_X concentrations on the platform increased when the train entered the platform pushing in polluted air from the tunnel (by piston effect) and decreased when it departed. While the train was stopped in the station the PM_X concentration on the platform was kept stable, due to polluted air introduced by piston effect and PM_X generated by resuspension. The decrease of PM_X concentrations when the train left the station can also be explained by the reverse piston effect as the train moves polluted air from the station, renewing the air of the platform. The same PM_X time patterns were described by Salma et al. (2007) for the Budapest subway, although different patterns were found in other study (Ma et al., 2014). The passage of trains was a very important factor in the PM_X concentrations on some platforms, being especially strong in the new stations (Fig. 4c) and with single rail track (Fig. 4d). In some stations with two rail tracks without middle wall (Fig. 4e, f) this pattern was also observed but in general less frequently.

In some stations, higher PM_X mass concentrations, especially the coarse particles, were recorded at one end of the platform, coinciding with the train entry edge, and a clear decreasing trend for PM_X concentrations was observed along the platform (Fig. 4c). This variation can be attributed to the turbulence generated by the trains entry, due to the wind blasts caused by the trains when they pull into the stations.

The results obtained in the new lines equipped with PSDs showed that this system, despite being an effective security barrier, does not prevent completely air exchange between the railway and the platform. Therefore, the PM_X values were also influenced by the arrival and departure of trains similarly to older platforms.

Gorg station, which is located in the end of one of the new lines and has an uncommon design (directly connected with the street level in the P4 location), also shows high PM_X concentrations at the point of entry and exit of the train (P1, Fig. 4g) caused by the trains' motion. Smaller concentration peaks were observed along the rest of the platform related to the open PSDs while the train was stopped, allowing air exchanges between the tunnel and the platform. In any case the PM_X concentrations in the rest of the platform were lower than those measured in other stations, which can be strongly influenced by outdoor air that may enter the station, influencing the dilution of PM_X.

In the areas closer to the passengers' access to the platforms there is also a high probability of air turbulences, created by the commuters walking and the air flowing in and out of the station. This turbulence can cause PM_X resuspension, which explains the higher mass concentrations measured in these points at Llucmajor and Encants stations (Fig. 4e, f), as it has already been described by Moreno et al. (2014). However, due to the design of both stations (one wide tunnel with two rail tracks without middle wall) it is impossible to assure if the nearest point of entry of the train had also influence in these results. More specific measurements will be required in these cases.

Measurements carried out with normal ventilation used in the colder period (C1) and without ventilation in the tunnel (C2, as the II.C ventilation mode in Table 2), allowed evidencing different spatial variation of PM_X concentrations in some stations (Fig. 4d, h). When the ventilation of the tunnel was turned off (i.e. only piston effect ventilation, Table S1), average PM_X concentrations on the platform were 26% higher than those registered on a fully operational ventilation system, indicating an accumulation of PM_X in the tunnel. This percentage was very similar to the result obtained for the extensive campaigns on the four platforms studied on daily basis (29%).

Overall, a substantial variation in PM_X concentrations between distinct subway stations was observed (averages ranging from 13 to

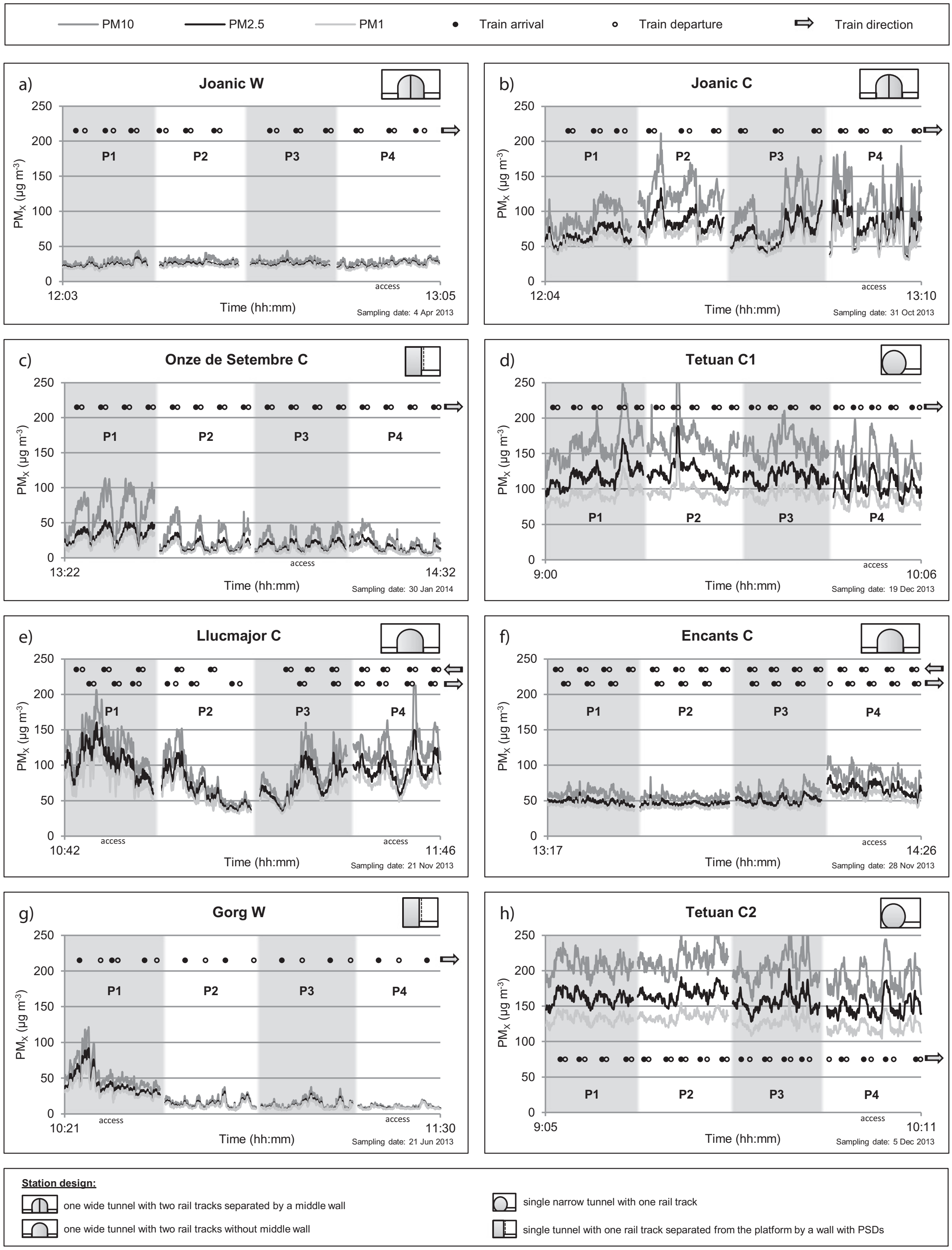


Fig. 4. Concentrations profiles of PM_{10}, $PM_{2.5}$ and PM_1 on selected platforms at 4 different sites (P1, P2, P3 and P4). Locations of accesses to platforms, train arrival/departure and direction are indicated (W — warmer period; C — colder period).

154 μg m^{-3} of $PM_{2.5}$, Table S1. — excluding the piston effect measurements) and this might be related to the differences in the length and design of the stations and tunnels, variations in the train frequency, passenger densities and ventilation systems, among other factors (Moreno et al., 2014 and references therein). In general, the stations composed by a single tunnel with one rail track separated from the platform by a wall with PSDs (new system) showed on average $PM_{2.5}$ concentrations lower (around 50%) than the conventional system (Fig. 5), as previously mentioned (Section 3.1.2). Among the conventional system, the stations with single narrow tunnel and one rail track showed on average $PM_{2.5}$ concentrations higher than those observed in stations with one wide tunnel and two rail tracks separated by a middle wall. The stations with one wide tunnel and two rail tracks without middle wall presented average PM_X concentrations much more variable (Fig. 5).

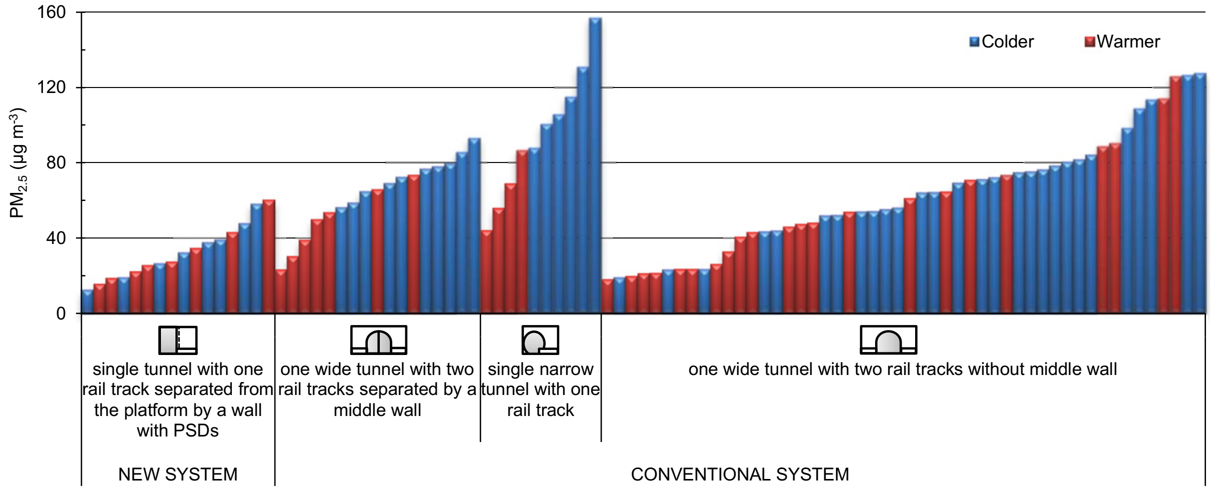


Fig. 5. Average $PM_{2.5}$ concentrations for colder and warmer periods of measurements sorted by subway station design categories.

3.2. PM_X concentrations inside the trains

All measurements carried out inside trains from 6 different lines are shown in Table 3. Lines 1–5 are the oldest ones whereas line 10 is one of the newest, most technologically advanced lines with more efficient mechanical ventilation system. $PM_{2.5}$ concentrations inside the trains in line 10 were on average 2.2 times lower than in the rest of the lines (Table 3). Repetition of measurements showed important variations in some cases (Table 3) indicating a possible dependency on variables such as the number of passengers (not counted in this campaign) although measurements were done at the same hours of the day. Regarding seasonal variations, there was not a regular variability among all results, perhaps influenced by changes of the air filters in the trains (the trains are fitted with air filters coupled to the air conditioning system that are changed monthly). A future study will be performed taking into account the changes of the filters and analysing their influence in the PM_X measurements to obtain a conclusive result.

From the measurements carried out with and without air conditioning, it is possible to conclude that the air conditioning had a clear effect on both concentration and variability of PM_X inside the trains. The results indicate that the ventilation system provides a clear abatement of PM concentrations inside the trains (Fig. 6), resulting in lower PM_X concentrations (by around 47% for $PM_{2.5}$) and finer particles (around 15% finer). Similarly, a study in Hong Kong also reported that the filter in the air-conditioning system was supposed to be capable of removing the larger portion of coarse particles (Chan et al., 2002a).

The PM_X and CO_2 concentration profiles during trips inside trains showed dissimilar behaviours (Fig. 6). Generally, the PM_X concentrations monitored along the lines presented temporary increases after the train doors close in a number of cases, possibly due to turbulence and consequent PM re-suspension produced by the movement of passengers inside the train. The CO_2 concentration profile was most probably proportional to the number of passengers inside the carriages of the trains. Hence the CO_2 concentrations presented always the maximum peak in the central part of each line, coinciding with the maximum influx of people.

3.3. Comparison with other studies

Table 4 shows a comparison of the average $PM_{2.5}$ concentrations on subway platforms worldwide with the results of this study. $PM_{2.5}$ levels measured in the conventional system were in the range of those measured in Budapest (Salma et al., 2007), Helsinki (Aarnio et al., 2005), Los Angeles (Kam et al., 2011a), New York (Wang and Gao, 2011), Mexico (Mugica-Álvarez et al., 2012) and Paris (Raut et al., 2009), and were lower than those from London (Seaton et al., 2005), Buenos Aires (Murruni et al., 2009) and Shanghai (Ye et al., 2010). The average $PM_{2.5}$ value referred by Kim et al. (2012) to the PSDs system present also in Seoul was relatively higher than the result obtained in the current study for a similar system (L10). The PM concentrations found in the present study were lower than those found in a previous study performed in July 2011 in 2 stations of Barcelona subway (Querol et al., 2012) for both conventional and new systems.

Given that the lowest PM_X concentrations were found in the new line both on the platforms and inside the trains, it is possible to conclude that PM_X levels inside the trains were affected by the surrounding

Table 3
Average $PM_{2.5}$ concentrations inside the trains in both periods of measurements.

	Warmer period		Colder period		
	Sampling date	$PM_{2.5}$ (µg m^{-3})	Sampling date	$PM_{2.5}$ (µg m^{-3})	
		With air conditioning		With air conditioning	Without air conditioning
Line 1	05 Jul 2013	74.8	11 Feb 2014	42.1	58.9
Line 1 repetition	19 Jul 2013	59.5	04 Mar 2014	38.9	56.6
Line 2	09 May 2013	34.4	26 Nov 2013	37.5	77.1
Line 2 repetition	16 May 2013	30.2	17 Dec 2013	46.4	98.8
Line 3	24 May 2013	43.8	11 Nov 2013	62.9	75.5
Line 3 repetition	29 May 2013	49.4	09 Dec 2013	71.6	90.9
Line 4	08 Apr 2013	29.3	29 Oct 2013	63.2	87.1
Line 4 repetition	19 Apr 2013	51.1	18 Nov 2013	43.9	72.9
Line 5	12 Jun 2013	43.3	20 Jan 2014	19.2	27.7
Line 5 repetition	28 Jun 2013	41.2	24 Feb 2014	39.1	47.1
Line 10	05 Jun 2013	30.7	14 Jan 2014	23.6	30.1
Line 10 repetition	20 Jun 2013	20.3	27 Jan 2014	18.6	21.2

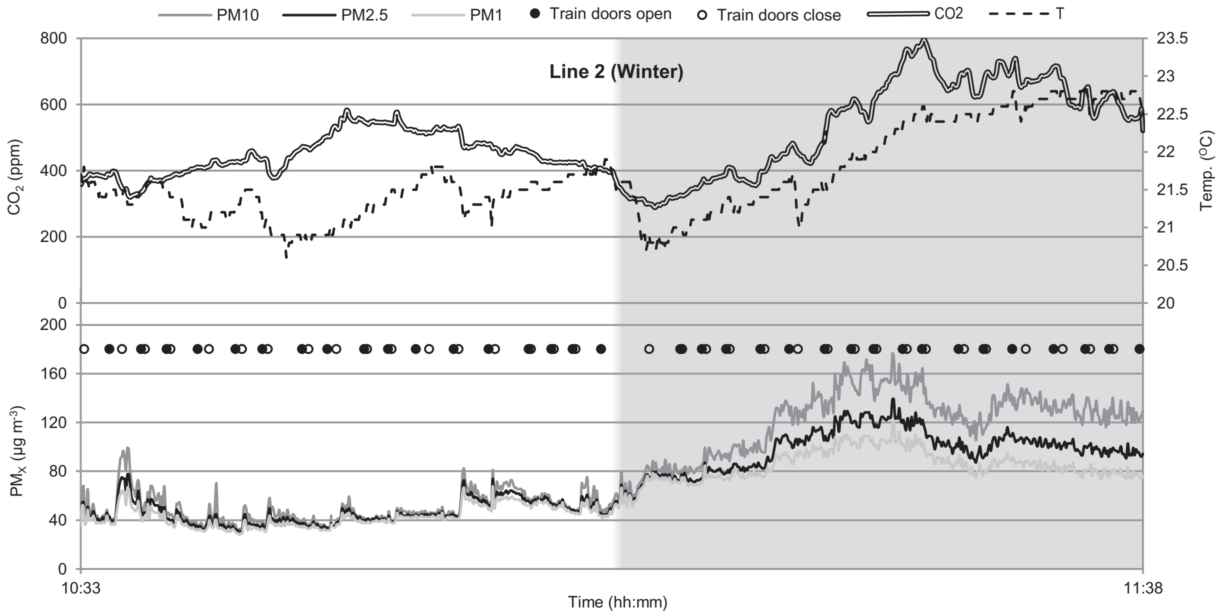


Fig. 6. PM_X, CO_2 concentrations and temperature measured inside the train of line 2, with and without (grey area) air conditioning.

conditions, such as those on the platforms. Hence, air exchange between platforms and the inside of the trains occurred when doors were open with the consequent exchange of air pollutants. Table 4 presents the $PM_{2.5}$ levels inside the trains for different subway systems worldwide. $PM_{2.5}$ levels inside the trains in the conventional Barcelona subway system are lower than those measured in Seoul (Kim et al., 2008; Park and Ha, 2008), Beijing (Li et al., 2007) and London (Seaton et al., 2005), and similar to those measured in Mexico (Gómez-Perales et al., 2004) and New York (Chillrud et al., 2004). The average $PM_{2.5}$ levels of the remaining subway systems referred in Table 4 are more similar to the value obtained for the new system. Both in the conventional and new systems the average concentrations inside the trains found in the present study were higher than those from the previous study in Barcelona (Querol et al., 2012).

Comparing the results with previous worldwide studies measuring the concentrations of PM_X on subway platforms and inside the trains, there is a remarkable variation among respective results. This could be explained by differences in the monitoring conditions such as the time, place, or season of the measurements, the differences in the length and design of the stations and tunnels, the system age, the wheels and rail-track materials, the type of brake mechanism, the train speed and frequency, the measurement equipment used, the ventilation systems, the passenger density, among other factors (Moreno et al., 2014 and references therein). Therefore, the results are not always directly comparable because of differences in sampling methods, data analysis, duration of the measurements and the type of environment studied (Nieuwenhuijsen et al., 2007).

The $PM_{2.5}$ concentrations inside the trains were lower (around 15%) than those on station platforms (Table 4). These measurements results can be explained by PM that was re-suspended on platforms due to train or commuter movement. Moreover, PM concentrations can also be diluted rapidly via the air conditioners inside the trains as the space is confined during operation. Nieuwenhuijsen et al. (2007) implicated the air conditioning in trains as a possible factor favouring low PM levels inside the trains.

3.4. $PM_{2.5}$ exposure during subway commuting

The $PM_{2.5}$ exposure was calculated taking into account all data obtained during both the intensive campaign on the 4 selected stations and the additional 20 platform measurements. Regarding the measurements inside the trains, the data used were obtained in the commuters normal conditions during the warmer period (with air conditioning) and without air conditioning in the colder period for the exposure calculations.

For a subway commuting travel of 30 min in the train and 5 min on the platform, the average $PM_{2.5}$ exposure would reach 53 µg m^{-3}. This value was reduced to 27 µg m^{-3} in the case of line 10, whereas for L1, L2, L3, L4 and L5 lines the exposures were 66, 62, 67, 59 and 40 µg m^{-3}, respectively. The average commuter exposure levels for the warmer and colder periods among all lines were 43 and 63 µg m^{-3} of $PM_{2.5}$, respectively, emphasizing that in the colder period the commuters are exposed to worse air quality when commuting. When air conditioning was switched on, a decrease of 32% of $PM_{2.5}$ exposure levels was reached, being an effective approach to reduce exposure levels.

It has been recognized in several studies that concentrations inside the trains are lower than in subway stations (Chillrud et al., 2004; Aarnio et al., 2005; Seaton et al., 2005; Braniš, 2006), suggesting that time spent in stations may be a better predictor of personal exposure than total time spent underground. The exposure is repeated almost every day for most commuters, which may cause cumulative or chronic health effects over time. Nevertheless, higher health risks for sensitive groups, such as children, the elderly, and individuals with pre-existing health conditions exacerbated by air pollution (many respiratory and cardiovascular diseases) may be significant, even for short periods spent in underground environment (Salma et al., 2007). Train drivers and other workers, who spend several hours a day within the underground subway are subject to higher exposure to PM_X levels than the commuting public and thus possibly greater health risks. In a study of PM exposure of pregnant women in Barcelona, a train/subway source contribution was identified, and its contribution was found not related to the time spent during commuting but only to the fact of using the subway, pointing to a maximum exposure on the platform, as opposed to inside the train (Minguillón et al., 2012).

The average $PM_{2.5}$ exposure during subway commuting in Barcelona obtained in the current study is higher than that reported (26 µg m^{-3}) by Querol et al. (2012), which might be related to the higher amount of measurements carried out in this study. Comparing to subway systems worldwide, the $PM_{2.5}$ exposure obtained in the current study was also higher than that reported in Mexico (33 µg m^{-3}; Gómez-Perales et al., 2007), Taipei (35 µg m^{-3}; Tsai et al., 2008), Hong Kong (33 µg m^{-3}; Chan et al., 2002a) and Guanzhou (44 µg m^{-3}; Chan et al., 2002b),

Table 4
Comparison of $PM_{2.5}$ concentrations measured on platforms and inside the trains at different subway systems worldwide.

Measurement environment	City	$PM_{2.5}$ (μg m^{-3})		Reference
		Range (min–max)	Average	
On the platform	Budapest	–	51	Salma et al. (2007)
	Helsinki	23–103	60	Aarnio et al. (2005)
	London	–	270–480	Seaton et al. (2005)
	Los Angeles	9–130	57	Kam et al. (2011a)
	New York	60–77	68	Wang and Gao (2011)
	New York	–	62	Chillrud et al. (2004)
	Buenos Aires	–	152–270	Murruni et al. (2009)
	Mexico	41–67	48	Mugica-Álvarez et al. (2012)
	Paris	–	61–93	Raut et al. (2009)
	Seoul	82–176	129	Kim et al. (2008)
	Seoul	–	105	Park and Ha (2008)
	Seoul	39–129	66	Kim et al. (2012)
	Seoul PSDs[a]	20–166	58	
	Shanghai	–	287	Ye et al. (2010)
	Stockholm WD[b]	105–388	258	Johansson and Johansson (2003)
	Stockholm WE[c]	24–334	185	
	Taipei	7–100	35	Cheng et al. (2008)
	Barcelona L3[d]	110–186	125	Querol et al. (2012)
	Barcelona L9[e]	12–99	46	
	Barcelona L1, L2, L3, L4 and L5[d]	18–154	66	Current study
	Barcelona L10[e]	13–61	32	
Inside the train	Beijing	–	113	Li et al. (2007)
	Beijing	13–111	37	Li et al. (2006)
	Guangzhou	–	44	Chan et al. (2002b)
	Helsinki	17–26	21	Aarnio et al. (2005)
	Hong Kong	21–48	33	Chan et al. (2002a)
	London	–	130–200	Seaton et al. (2005)
	Los Angeles	11–62	24	Kam et al. (2011b)
	Mexico	31–99	57	Gómez-Perales et al. (2004)
	Mexico	8–68	–	Gómez-Perales et al. (2007)
	New York	34–44	40	Wang and Gao (2011)
	New York	–	62	Chillrud et al. (2004)
	Seoul	115–136	126	Kim et al. (2008)
	Seoul	–	117	Park and Ha (2008)
	Sydney	–	36	Knibbs and de Dear (2010)
	Taipei	8–68	32	Cheng et al. (2008)
	Taipei	3–48	24	Cheng et al. (2012)
	Barcelona L3 and L5[d]	17–32	25	Querol et al. (2012)
	Barcelona L9[e]	11–18	15	
	Barcelona L1, L2, L3, L4 and L5[d]	28–99	57	Current study
	Barcelona L10[e]	20–31	26	

[a] PSDs—platform screen doors.
[b] WD—weekdays.
[c] WE—weekends.
[d] Conventional system.
[e] New system.

and lower than that referred for London (202 μg m^{-3}; Adams et al., 2001) and New York (62 μg m^{-3}; Chillrud et al., 2004).

In addition, an assessment on $PM_{2.5}$ exposure for different commuting modes reported in several studies worldwide (Querol et al., 2012 and references therein) was done to compare the data obtained in the present study. The $PM_{2.5}$ exposure while commuting by bus and passenger car reached values in the range of 33–75 μg m^{-3} and 22–83 μg m^{-3}, respectively, comparable to those reported for subway commuting in Barcelona during this study (27–67 μg m^{-3}). Cycling/motorbike and pedestrian commuting were reported with $PM_{2.5}$ exposure levels of 68–88 and 63 μg m^{-3}, respectively, being markedly higher than in the Barcelona subway.

4. Conclusions

Subway aerosol particles have been monitored in Barcelona on diverse platform stations and inside the trains, focusing on particulate matter mass concentration. The following main conclusions were drawn:

- PM_X concentrations on the platforms were higher than those in outdoor environment approximately 1.3–6.7 times, revealing the prevalence of PM sources on the platform and tunnel level.
- The new system (L10) with PSDs showed on average PM_X concentrations lower (around 50%) than the conventional system (L1–L5).
- The measured $PM_{2.5}$ concentrations on all types of platforms were lower or in the range of other reported subway systems worldwide.
- The measurements in the warmer period (strong ventilation) showed lower concentrations than in the colder period (weak ventilation). Variations in PM_X levels in different seasons were thus clearly influenced by the ventilation system. This suggests that an appropriate ventilation mode should be applied to the subway system to obtain both PM reduction and energy saving.
- The piston effect alone (with no additional mechanical ventilation in the tunnel) produced by the movement of the trains was not an effective approach to obtain a good air quality in the subway system.

- PM_X concentrations displayed a typical diurnal cycle during the weekdays, driven by the ventilation settings and secondarily by the train frequency.
- Both lower PM_X concentrations and less marked cycles were observed on Saturdays and Sundays.
- Real-time measurements of PM_X showed temporal and spatial variations along the platforms, related to the differences in the time, place, or season of the measurements, design of the stations and tunnels, variations in the train frequency, passenger densities and ventilation systems, among other factors.
- The use of air conditioning inside the trains was an effective approach to reduce exposure levels. The PM_X concentrations inside the trains were lower (around 15%) than those on station platforms.
- The ventilation and air conditioning systems were more efficient removing coarse particles, resulting in a relatively fine-dominated PM in the subway system.
- This study shows that the time spent commuting in the subway system can contribute substantially to total daily exposure to $PM_{2.5}$ and be associated with adverse health effects.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2014.12.013.

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