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The effect of ventilation protocols on airborne particulate matter in subway systems

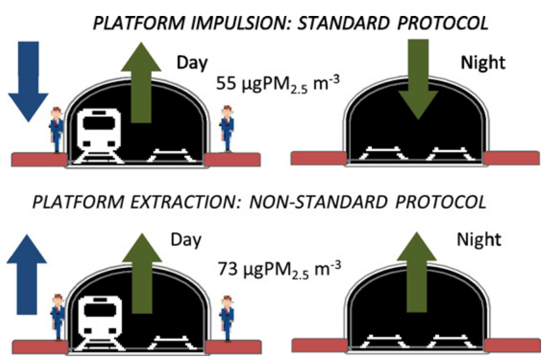
Teresa Moreno [a,*], Cristina Reche [a], Maria Cruz Minguillón [a], Marta Capdevila [b], Eladio de Miguel [b], Xavier Querol [a]

[a] Institute of 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

HIGHLIGHTS

- Tunnel ventilation plays a key role in maintaining cleaner subway platform air.
- Better platform air quality is achieved by combining fan impulsion with higher power.
- Reversing platform air flow to extraction immediately results in higher ambient PM.
- A/C filters in trains keep their PM improvement capability even when 3 months old.

GRAPHICAL ABSTRACT



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ABSTRACT

As part of the European-funded IMPROVE LIFE project work programme experiments were performed in the Barcelona Metro system with the objective of better understanding the relationship between ventilation and air quality. The results demonstrate that tunnel ventilation plays an extremely important role in maintaining cleaner air and is capable of reducing both inhalable particulate matter (PM) mass and particle number concentration (>0.3 μm) on platforms by over 50%, even in the presence of full-length platform screen doors. Another key influence on platform air quality is the chosen combination of fan power and forced air flow direction (impulsion of outdoor ambient air or extraction of subway indoor air): cleaner platform air was achieved using platform impulsion at higher power settings designed to ameliorate high summer temperatures underground. Reversing platform air flow from impulsion to extraction produced an immediate deterioration in PM air quality, most notably if the higher power setting was maintained, when an especially marked increase in numbers of very fine (submicron) particles was observed and attributed to tunnel air being drawn into the platform. At night, in the absence of trains and platform ventilation, platform air quality improves when tunnel fans are working at reduced power, whatever the flow direction (impulsion/extraction). Inside the air conditioned Barcelona Metro trains (where underground commuters spend most of their time) air quality is markedly better than on the platform, and unchanged A/C filters were observed capable of maintaining a similar reduction in inside train PM for at least three months.

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

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1. Introduction

The use of public rather than private transport to abate urban atmospheric emissions is to be encouraged, and, in this context, subway systems are especially desirable as they are based on electric trains, are energetically/environmentally efficient, and help diminish surface traffic congestion. However, in response to increasing scientific and public awareness of the importance of clean air to human health, a number of studies have revealed unacceptably high levels of inhalable particulate matter (PM) in some subway systems (e.g. Furuya et al., 2001; Johansson and Johansson, 2003; Aarnio et al., 2005; Seaton et al., 2005; Cheng et al., 2008; Kim et al., 2008; Park and Ha, 2008; Murruni et al., 2009; Salma, 2009; Ye et al., 2010; Cheng and Yan, 2011; Sioutas, 2011; Múgica-Alvarez et al., 2012; Park et al., 2012; Querol et al., 2012; Colombi et al., 2013; Cartenì et al., 2015; Perrino et al., 2015; Chen et al., 2016; Wang et al., 2016; Xu et al., 2016; Gong et al., 2017; Zheng et al., 2017). This realisation has in turn led to studies increasingly concerned with understanding the PM sources and controls on subway air quality, this being a major focus of the on-going European-funded IMPROVE LIFE project (http://improve-life.eu). This project involves close collaboration between the Barcelona subway operator TMB and the Spanish Research Council (CSIC) Air Quality Research Group based at IDAEA, these two partners together designing a series of experiments aimed at improving air quality underground and offering transport authorities scientific information to help them to reduce concentrations of PM in the subway environment.

It is by now clear that while there are several factors affecting PM concentrations in underground train systems, a key controlling influence common to subways worldwide is the type of ventilation operating in the tunnels and station platforms (e.g. Awad, 2002; Ripanucci et al., 2006; Moreno et al., 2014; Kim et al., 2015; Lee et al., 2015; Martins et al., 2015; Kwon et al., 2016). This has been demonstrated, for example, by observing differences in air quality due to seasonal changes in tunnel and platform ventilation: studies in both Prague (Braniš, 2006) and Barcelona (Martins et al., 2015, 2016) record a decrease in PM concentrations of 30–35% when summer air conditioning is operating. A similar percentage decrease in $PM_{2.5}$ concentration has been observed during experiments when the mechanical ventilation system was turned on after a period of inactivity when reliance was placed only on the train piston effect to move air through the tunnels and platforms (Moreno et al., 2014; Martins et al., 2015). Such subway ventilation systems are traditionally designed and installed with the primary purpose of ensuring energy efficiency and passenger comfort and safety, particularly in controlling temperature and reducing smoke hazard during emergency incidents (e.g. EC, 2001; Kim and Kim, 2009; Luo et al., 2014; Di Perna et al., 2014; Casals et al., 2016). Consideration of the effects of subway ventilation on underground air quality and specifically on PM inhalation by passengers is, in contrast, a relatively recent and untested development. In this paper we report on three new experiments designed under the IMPROVE LIFE work programme to study the influences of subway ventilation on PM air quality within the Barcelona Metro system. These involved investigations of the effects of: (1) changing forced underground air flow direction under differing ventilation power settings; (2) eliminating tunnel ventilation in a new station equipped with platform screen doors; (3) extending the user lifespan of air conditioning filters inside rail carriages.

2. Methodology

2.1. Reversing platform and tunnel forced ventilation air flow

This experiment was carried out at the metro station of Tarragona in line 3 (L3), which was built in 1975 at a depth of 14 m below ground level. The design of the station is characterised by one wide tunnel with two rail tracks and lateral platforms. The mechanical ventilation system utilized in this station during the subway working hours involves introducing outdoor air using fans (50 Hz) into the platform (impulsion) and removing indoor air back towards street level (extraction) through vertical shafts in the tunnel. During normal (weekday) night time hours there is no mechanical ventilation in the platforms and the fans in the tunnel are reversed to introduce outdoor air into the underground system. For this study, over a period of one week the normal ventilation conditions were changed from impulsion to extraction on the platform during daytime hours so that underground air was being removed simultaneously from both platform and tunnel ("Total Extraction"). During the non-operational night hours there was no ventilation operating on the platform (as normal), but in the tunnel the fans were maintained in extraction mode rather than reversing to the normal night time impulsion. The experiment was repeated in order to compare both warmer (June 2015) and colder (March 2016) conditions, as the forced ventilation in the tunnel operates at stronger levels during the summer heat (49 Hz versus 24 Hz in cooler seasons).

The ventilation conditions compared during the Tarragona study are illustrated in Fig. 1, which contrasts the standard air flow system (impulsion on platform) with the modified (extraction from platform) ventilation setting during "day" (operational hours) and night.

The measurement equipment was located at the platform end, corresponding to the train entry point, at around 1.5 m above the ground level and behind a light fence for safety protection. The specific monitoring equipment used comprised: i) a light-scattering laser photometer (DustTrak 8533, TSI) for PM_1, $PM_{2.5}$ and PM_{10} (particulate matter with aerodynamic diameter <1 μm, 2.5 μm and 10 μm, respectively) mass concentrations; ii) an optical particle sizer (OPS 3330, TSI) to measure number size distributions (N) in the size range 0.3–10 μm; this instrument measures the optical diameter of the particles by a 120° light scatter, and filter sampling, in 16 size channels at a 1 $L \cdot m^{-1}$ flow rate); iii) a high volume sampler (CAV-A/MSb, MCV) with a $PM_{2.5}$ head for gravimetric and chemical analysis. Continuous measurements (24 h/day) with a 5-min time resolution were performed using the OPS and the DustTrak equipments. $PM_{2.5}$ concentrations provided by DustTrak monitor were corrected against the in-situ and simultaneous gravimetric $PM_{2.5}$ measurements.

2.2. Platform air quality with and without tunnel ventilation

The air quality monitoring station (including the same equipment used in the Tarragona experiment detailed above, although with the OPS operating only during the first two weeks), was positioned at the platform end in the station of Collblanc. This platform belongs to the newest metro line of the city (L9S, the southern end of the future L9 still in progress), opened in February 2016 to connect the city centre

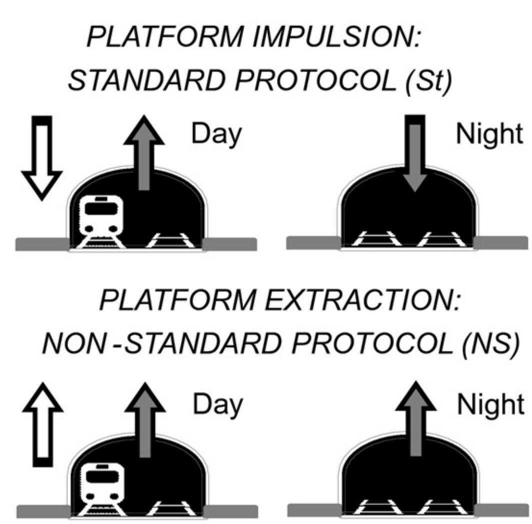

Fig. 1. Ventilation setting for platforms and tunnel in Tarragona station during the study.

with the airport. The design of the station is characterised by driverless trains running through a single tunnel with one rail track separated from a single platform by a wall with a full length platform screen door system (PSD). The organisation of L9S at Collblanc is unusual because at this end of the line the two railtracks run one above the other in vertically separated 12-metre-wide tunnels, rather than side by side. In Collblanc the situation is complicated by the fact that only the lower rail track and platform are currently open for public use, so that trains run in both directions using the same tunnel. The upper station is closed to the public until new future stations are opened, and is currently only used for maintenance works.

The L9S line runs from the airport towards the city initially at relatively shallow depths beneath the River Llobregat delta but in its final stretch tunnels deeper as it runs beneath the rapidly rising ground surface of the *Pla de Barcelona*, a peneplain that slopes down to the sea from the Collserola Hills (Gibbons and Moreno, 2012). This topography results in unusually deep stations at the "city" end of the line (Collblanc lies at 53 m below ground level), these being ventilated by stronger and more numerous fans than in the older conventional lines. A very strong air velocity is always felt on the platform at Collblanc when each train is approaching, with in some instances this enhanced piston effect being strong enough to trigger one of the station fire alarms. In the process of investigating the reasons for this unusual piston blast it was decided to monitor air quality while experimenting with air flow intensity driven by the tunnel mechanical ventilation settings. Air quality was therefore measured on the passenger in-use platform for five weeks (11th May to 27th June 2016). During the first, third and fifth weeks ventilation conditions were operating as normal, with platform air extraction fans operating at 30 Hz, and two tunnel air impulsion fans operating at 37.5 Hz. During the second and fourth weeks the tunnel ventilation was shut down completely while platform ventilation remained operating as normal. From 27th June to 11th July 2016, instruments were moved to the out-of-service platform located immediately above, to compare platform air quality in the absence of regular passenger movement but the presence of maintenance transport.

2.3. Train air conditioning filters

To measure the effect on $PM_{2.5}$ concentrations of using train air conditioning filters beyond their normal replacement date a DustTrak monitor was installed inside an intermediate driver cabin in two trains of line 3 (L3). The filters used are made of polyester fibres impregnated with synthetic resins (class EN779). These filters are not designed for cleaning the air (as is the case for cabin air filters inside vehicles) but to maintain the comfort temperature in the carriage. Data on $PM_{2.5}$ concentrations provided by DustTrak monitors were corrected against simultaneous gravimetric $PM_{2.5}$ measurements before and after the monitoring campaign, a widely accepted reference method. These cabins are not in use, so they were chosen as a compromise between meeting conditions for uninterrupted continuous measurement and not obstructing the commuters or driver during normal activity. The selected rolling stock form part of the old fleet of L3 (3000 series) which comprise two trains attached, so that an empty ("intermediate") driver cabin lies in the centre of the train. $PM_{2.5}$ levels were simultaneously measured in a passenger carriage during four 20–30 min trips, also using a DustTrak monitor. The linear correlation between $PM_{2.5}$ levels measured in the intermediate driver cabin and in the passenger carriage shows a coefficient (R^2) of 0.70 and a slope of 0.76, confirming that air inside these cabins is indeed representative of the passengers' exposure as they have the same ventilation system as the rest of the carriage. The A/C filters are normally regularly replaced every month according to current manufacturer protocol. Measurements in the train started when all air conditioner filters were replaced. Filters were changed again after one month (following the established TMB protocol) but then were left in place in order to evaluate any effects on air quality by doubling the service life of filters from one to two months. To test the reproducibility of the results, a second campaign was carried out in a different train of L3. In this case air conditioner filters in the selected train had been changed one month before the beginning of the sampling campaign, and were not replaced again for the whole campaign, allowing us to observe air quality up to three months after filter replacement.

3. Results

3.1. Platform air flow reversal

Table 1 summarises the data on $PM_{2.5}$ mass and particle number concentrations measured on the platform during normal operating hours (05:00–24:00). Comparison is made between normal levels under standard ventilation protocols, measured the previous week, and those during the non-standard ventilation experiment for the two campaigns at different seasons in June (Stronger Tunnel Ventilation: STV) and March (Weaker Tunnel Ventilation: WTV). One immediate result that emerges from the High Volume Sampler data is that under standard ventilation conditions average $PM_{2.5}$ concentrations are consistently and substantially (>35%) higher when the fans are operating at reduced levels (Table 1: compare platform impulsion STV with platform extraction WTV: 55 ± 18 vs. 76 ± 18 $\mu g \cdot m^{-3}$). Under experimental conditions, when platform ventilation was reversed from impulsion to extraction, air quality deteriorated sharply when the fans in the tunnel were operating at higher power (Table 1: compare 55 ± 18 with 73 ± 28 $\mu g \cdot m^{-3}$), bringing $PM_{2.5}$ mass concentrations back up almost to those under standard cooler weather/weaker ventilation conditions. The rise in PM levels produced by air flow reversal from impulsion to extraction was much less marked (5%) when the fans in the tunnel were operating under cooler weather/weaker ventilation settings (Table 1: 76 ± 18 to 80 ± 22 $\mu g \cdot m^{-3}$).

The reduction in PM air quality produced by reversing platform ventilation fans from impulsion to extraction during operating hours while the tunnel fans are running at higher-power in summer is also revealed by the DustTrak laser photometer and OPS data, as demonstrated by comparing the bar graphs a-d on Fig. 2. This drop in PM concentrations was not registered in the ambient PM concentrations measured outdoor during the same time period (data not shown) indicating a low influence of outdoor air in the platform as previously noted by Martins et al. (2015) in the Barcelona subway system. The data on Fig. 2 also allow comparison between operating hours (05:00–24:00 = "DAY") and non-operating hours (00:00–05:00 = "NIGHT") by selecting only weekday data and thus avoiding the confounding effects of the Barcelona Metro being open all night at weekends. The OPS data indicate that the rise in PM due to the switch from platform impulsion (PI) to extraction (PE) during operating hours with stronger ventilation in the tunnel is most marked in the finer particle sizes. Thus average numbers of

Table 1
Mean concentrations of selected air pollutants in the station of Tarragona during working hours (05:00–24:00 h). N values (particle number concentrations for 0.3–1, 1–3 and 3–10 μm in size) expressed as dN/dlogDp. PI/TE: Platform Impulsion/Tunnel extraction (Standard Ventilation Protocol); PE/TE: Platform Extraction/Tunnel Extraction (Non-Standard Ventilation Protocol); STV: Stronger Tunnel Ventilation (summer: 49 Hz); WTV: Weaker Tunnel Ventilation (colder season: 24 Hz).

Parameter	STV		WTV	
	PI/TE	PE/TE	PI/TE	PE/TE
$PM_{2.5}$ ($\mu g \cdot m^{-3}$)[a]	55 ± 18	73 ± 28	76 ± 18	80 ± 22
$N_{0.3-1}$ ($\# \cdot cm^{-3}$)	1293 ± 136	1876 ± 138	1726 ± 68	1749 ± 85
N_{1-3} ($\# \cdot cm^{-3}$)	68 ± 5	84 ± 8	89 ± 4	95 ± 4
N_{3-10} ($\# \cdot cm^{-3}$)	8 ± 0.9	10 ± 0.8	10 ± 0.5	11 ± 0.6

[a] Gravimetric data from sample collected in quartz fibre filter in HVS.

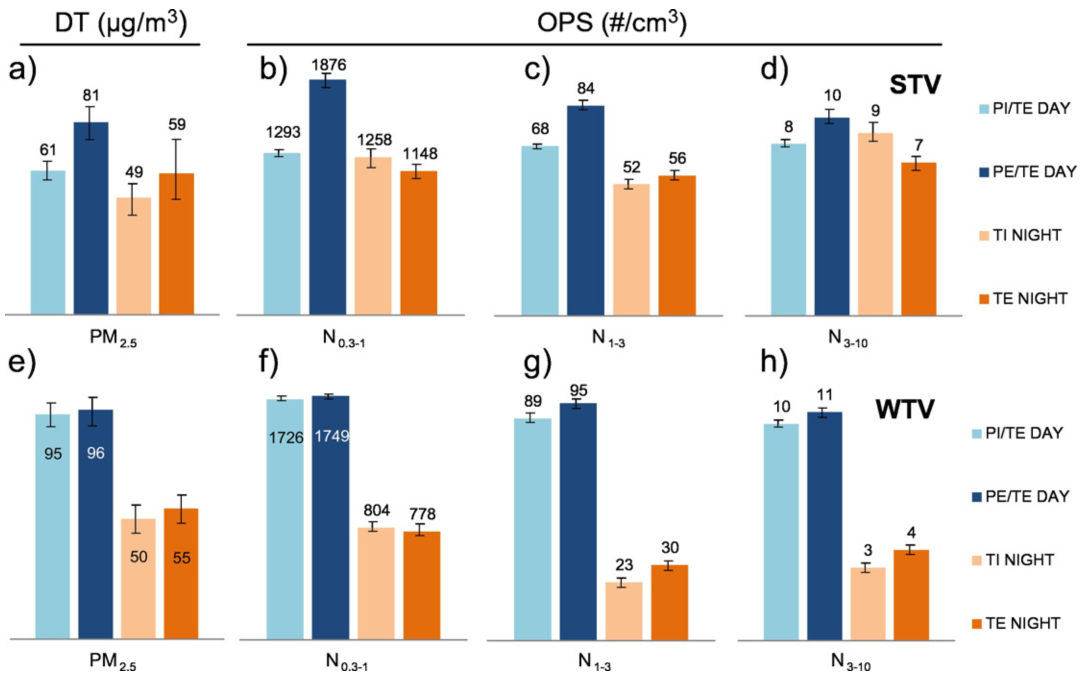

Fig. 2. DustTrak (DT, $PM_{2.5}$) and OPS ($N_{0.3-1}$, N_{1-3}, N_{3-10}) data for DAY (Operating hours (05:00–24:00)) and NIGHT (Non-operating hours, no platform ventilation) periods during stronger and weaker ventilation (SV/WV). PI = Platform Impulsion; PE = Platform Extraction; TI = Tunnel Impulsion; TE = Tunnel Extraction. STV: Stronger Tunnel Ventilation (summer: 49 Hz); WTV: Weaker Tunnel Ventilation (colder season: 24 Hz).

"daytime" submicron-sized number concentration rise by 45% as compared to only a 25% increase in coarser inhalable fractions (Fig. 2b–d). Under conditions when the tunnel ventilation fans are operating with less intensity, only a slight increase in particle number across all size ranges is induced by switching from platform impulsion to extraction (Fig. 2f–h). With regard to "night time" values, when the platform ventilation is switched off, here the enhanced tunnel ventilation air flow during the summer months has the effect of inhibiting gravitational settling and so maintaining high ambient PM and number particle concentrations in platform air, whether or not the tunnel fans are operating on impulsion or extraction (Fig. 2b–d). In striking contrast, when the night tunnel fans are working at lower power, both mass and numbers of inhalable PM on the platform drop by around half or more (Fig. 2f–h), producing unusually clean conditions if allowed to remain undisturbed by, for example, night time maintenance works. Judging from the night time data from both DustTrak and OPS monitoring systems, whether or not the tunnel fans are set at impulsion or extraction has little observable effect on platform air quality when compared to the impact of increasing fan power and therefore air flow rate in either direction.

The data therefore clearly demonstrate that reversing subway platform ventilation settings from impulsion to extraction during subway operational hours impacts negatively on air quality when tunnel fans are working at higher power to alleviate summer heat. It is interesting to highlight that this increase of platform PM levels and number concentrations under summer conditions was observed *immediately* after the change of the ventilation air flow from impulsion to extraction. Levels did not tend to increase during the subsequent week, but the percentage of increase over standard conditions was maintained.

3.2. Tunnel ventilation experiment

As demonstrated by the data in Table 2 there was an obvious and marked deterioration in platform PM air quality at Collblanc station in response to the shutdown of tunnel ventilation. Concentrations of $PM_{2.5}$ as measured during operational hours by the High Volume Sampler were initially very low for subway air (as previously reported in this station with its PSD system, Martins et al., 2015) but then more than doubled from $<25\ \mu g \cdot m^{-3}$ to $>50\ \mu g \cdot m^{-3}$ in the absence of operating tunnel fans (Table 2). Fig. 3 presents bar plots for the first two weeks of the experiment (when OPS data were available) and offers further insight into the distribution of ambient PM. Under normal ventilation conditions on the Collblanc platform the numbers of particulates are exceptionally low across each of the three size groupings ($N_{0.3-1/1-3/3-10} = 319/12/2$) when compared to, for example, conditions previously measured at Tarragona station ($N_{0.3-1/1-3/3-10} = 1293/68/8$). When tunnel ventilation is shut down the finest PM sizes over double in number whereas the coarser inhalable particles rise four- or fivefold ($N_{0.3-1/1-3/3-10} = 658/67/9$). This preferential increase in the coarser PM sizes has the effect of bringing PM_{1-10} numbers up to "Tarragona" levels (i.e. those more typical of the older lines not fitted with platform screen doors), whereas the numbers of finest particles ($N_{0.3-1}$) at Collblanc still remain relatively low.

3.3. Train air conditioning filters and PM levels

As has been demonstrated in previous publications, the use of air conditioning inside subway train carriages results in a clear drop in PM concentrations inside the train carriages, especially with regard to coarser inhalable particles (Chan et al., 2002; Querol et al., 2012; Martins et al., 2015). This was further confirmed during our A/C filter experiment, with the DustTrak equipment located inside the train

Table 2
Mean concentrations of selected air pollutants in the station of Collblanc during working hours (05:00–24:00 h). HVS: High Volume Sampler; DT: DustTrak. TV: Tunnel Ventilation.

Parameter	Operational platform		Nonoperational platform
	TV on	TV off	
$PM_{2.5}$ ($\mu g \cdot m^{-3}$) HVS	22 ± 6	53 ± 7	20 ± 5
$PM_{2.5}$ ($\mu g \cdot m^{-3}$) DT	22 ± 7	57 ± 16	26 ± 10
$N_{0.3-1}$ ($\# \cdot cm^{-3}$)	319 ± 23	658 ± 38	410 ± 22
N_{1-3} ($\# \cdot cm^{-3}$)	12 ± 0.9	67 ± 5.3	10 ± 1.7
N_{3-10} ($\# \cdot cm^{-3}$)	2 ± 0.1	9 ± 0.4	1 ± 0.4

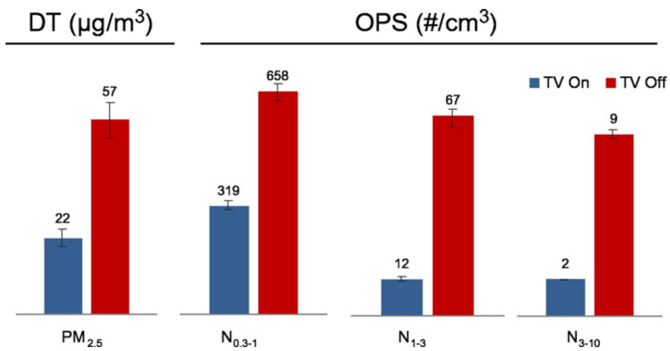

Fig. 3. DustTrak (DT) and OPS data in Collblanc station with tunnel ventilation (TV) on and off.

registering mean $PM_{2.5}$ levels of $36 \pm 13\ \mu g \cdot m^{-3}$ during subway operation hours, this being 30–50% lower than those recorded at platforms of L3 stations during the same period (a high linear correlation, $R^2 = 0.70$, was observed between daily levels recorded inside the train and those simultaneously measured at platforms of L3 stations). Table 3 shows average weekly $PM_{2.5}$ levels across the 3 month monitoring period (measured in three different periods). PM levels were highest (>40 $\mu g \cdot m^{-3}$) in the first weeks of the campaign (early to mid-July), decreasing to <35 $\mu g \cdot m^{-3}$ possibly influenced by Barcelona entering its summer holiday period when the number of trains on the L3 train decreased. A similar "weekend effect" decrease of up to 20% on weekday levels was also observed, presumably for the same underlying reason. The most important observation arising from collecting these data, however, is the fact that $PM_{2.5}$ concentrations appear unaffected by the same filter being used for over 90 days. Although current protocols operate on the understanding that these filters need to be replaced monthly, our results indicate that (at least in terms of air quality measured in inorganic particle mass) there is no obvious need for such frequent replacement, offering the possibility of considerable cost savings.

4. Discussion and conclusions

It is already clear from previous studies worldwide that concentrations of inhalable PM in the subway environment can be extremely variable (Martins et al., 2015 and references within). This is amply demonstrated by the IMPROVE LIFE results on the Barcelona Metro system, which provide one of the most detailed freely available published databases available on the range of average PM levels to be expected across a subway system (http://improve-life.eu). The new stations in Barcelona fitted with platform screen doors, such as those in line L9S at Collblanc, offer the best underground air quality under normal ventilation protocols (impulsion in both tunnel and platform). With $PM_{2.5}$ values commonly lying within the range 20–30 $\mu g \cdot m^{-3}$, air quality in these stations is comparable to, or even cleaner than, that inhaled when walking through the city streets above (Tsai et al., 2008; Moreno et al., 2015a). Levels of particulate matter inside air conditioned Metro train carriages (where commuters spend most of their travelling time) in our study were also relatively clean, being broadly comparable to commuting by tram in Barcelona (Moreno et al., 2015a). Switching off A/C in such trains, however, produces a steady deterioration in air quality, with ambient $PM_{2.5}$ concentrations in some cases more than doubling (Martins et al., 2015). Underground platform $PM_{2.5}$ average concentrations are typically substantially higher than those inside trains, commonly exceeding 50 $\mu g \cdot m^{-3}$ and in several published studies >100 $\mu g \cdot m^{-3}$ (Johansson and Johansson, 2003; Seaton et al., 2005; Kim et al., 2008; Park and Ha, 2008; Murruni et al., 2009; Ye et al., 2010; Querol et al., 2012).

Table 3
Mean concentrations of $PM_{2.5}$ measured inside a train across three monitoring periods with the same A/C filter.

$PM_{2.5}$ ($\mu g \cdot m^{-3}$)	Weeks after changing A/C filter												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Train 1 (1 month)	40	47	43	43									
Train 2 (2 months)	41	41	40	36	31	38	33	32	30				
Train 3 (3 months)				46	43	35	33	31	32	31	35	34	35

The majority of subway PM are locally sourced ferruginous particles derived from the wear of rails, train wheels and brakes (e.g., Chillrud et al., 2004; Aarnio et al., 2005; Kang et al., 2008; Salma et al., 2009; Jung et al., 2012; Midander et al., 2012; Eom et al., 2013; Moreno et al., 2015b; Cui et al., 2016). Many of these particles are extremely fine: the OPS data indicate the most common mean size at around 0.5 μm (data not presented here). These fine FePM materials are driven though the tunnels, ventilation shafts, and into station platforms by the piston effect of the trains, but their distribution is also influenced by the complex additional flows imposed by the presence and positioning of tunnel vent shafts and mechanical fans. Ventilation shafts in the tunnel will allow for the expulsion of air as the train approaches, thus ameliorating the blast of air directed towards the next station until the train passes the shaft, when air flow reverses in the shaft and an air blast peak is pushed into the station (e.g. Kim and Kim, 2009). In our study at Collblanc it is clear that the operational presence of a strong tunnel fan system does much to maintain relatively clean tunnel air and so lessen contamination of platform air by subway FePM. The importance of these fans to air quality is perhaps surprising considering the presence of brand new full-length platform screen doors which would be expected to inhibit air exchange between platform and tunnel. However recently published work has already indicated that such PSD systems do not prevent contamination of the platform by tunnel air (Martins et al., 2015; Kwon et al., 2016). Our data strongly reinforce this conclusion by demonstrating that such a PSD system will not prevent inhalable PM levels from doubling or even (for the coarser sizes resuspended by the strong train piston effect) quadrupling once the tunnel fans are shut down.

Another key point demonstrated by the data presented above is that with regard to platform ventilation, optimum air quality is best achieved by combining platform impulsion fans with tunnel extraction fans operating at high power to drive exterior air into the station and dilute the FePM. Switching from platform air impulsion to extraction under these well-ventilated conditions however fails to achieve this dilution, despite the high air flow, leading to a clear deterioration in air quality as measured by inhalable PM mass and number concentration. As demonstrated in Fig. 2, the finer FePM particles in particular are preferentially increased by this switch to platform extraction, indicating that more contaminated air is likely being sucked out of the tunnel into the platform. When fans in the tunnel are operating at lower power, thus reducing general air flow on the platform, air quality is correspondingly worse. Under these less well-ventilated conditions switching air flow from platform impulsion to extraction makes little difference to ambient PM during operational hours. Such less turbulent conditions, however, do lead to greatly reduced platform PM concentrations at night time, with the dust settling after trains cease running and tunnel fans are operating at lower power (Fig. 2).

In our studies presented in this paper we have focused on the effects of ventilation, not least because it has become increasingly clear during the IMPROVE LIFE project that the air flow patterns present in subway stations have an important, indeed dominant, influence on air quality. The primary concerns of subway design have traditionally focused on safety during emergency incidents underground, passenger comfort (temperature; piston air blast on the platforms) and energy efficiency. Given the greatly increased awareness these days of the benefits of clean air to human health, with current WHO Interim Targets for annual mean concentrations of outdoor $PM_{2.5}$ being 10 $\mu g \cdot m^{-3}$, improving air quality inside city vehicles and below ground should be an additional and equally important concern to design engineers involved in commuter transport. Many urban residents spend a significant amount of their lives commuting to work, and there is already more than enough epidemiological and toxicological evidence published to demonstrate the likely long term health benefits to such people of breathing cleaner air while travelling.

The main conclusions from this IMPROVE LIFE study on subway ventilation and air quality may be summarised as follows:

1. Subway platform air quality is markedly influenced by the power setting of tunnel ventilation fans and whether or not the platform air is being introduced by impulsion or removed by extraction.
2. In an “old-style” Metro station not fitted with platform screen doors the best subway platform air quality during operational hours was achieved by using platform fans operating on impulsion together with tunnel fans operating at higher power, and the worst when using platform fans set to extraction with tunnel fans at lower power.
3. Switching from platform impulsion to extraction with higher fan power in the tunnel results immediately in a marked increase in ambient inhalable PM, especially in the numbers of finest particles (submicron), which are presumably being drawn into the platform from the tunnel.
4. At night when neither trains nor platform ventilation fans are operational, platform air quality improves when tunnel fans are working at lower power, whether or not they are operating on impulsion or extraction. The resulting reduction in air movement from tunnel to platform, due to subdued fan power and no train piston effect, presumably allows particles to settle out of suspension.
5. Forced mechanical tunnel ventilation makes an important contribution to maintaining good air quality on subway platforms, even in the presence of full-length (floor to ceiling) platform screen doors. In our study at Collblanc (L9S), switching off tunnel fans (while maintaining platform ventilation) resulted in a four- to fivefold increase in platform PM_{1-10} number concentration.
6. The air quality benefits of operating air conditioning inside train carriages are maintained for at least three months without changing the filters. If energy efficiency and pathogens are similarly unaffected over this time span (or more), then there is a strong case for revising existing protocols requiring monthly replacement of such filters.

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