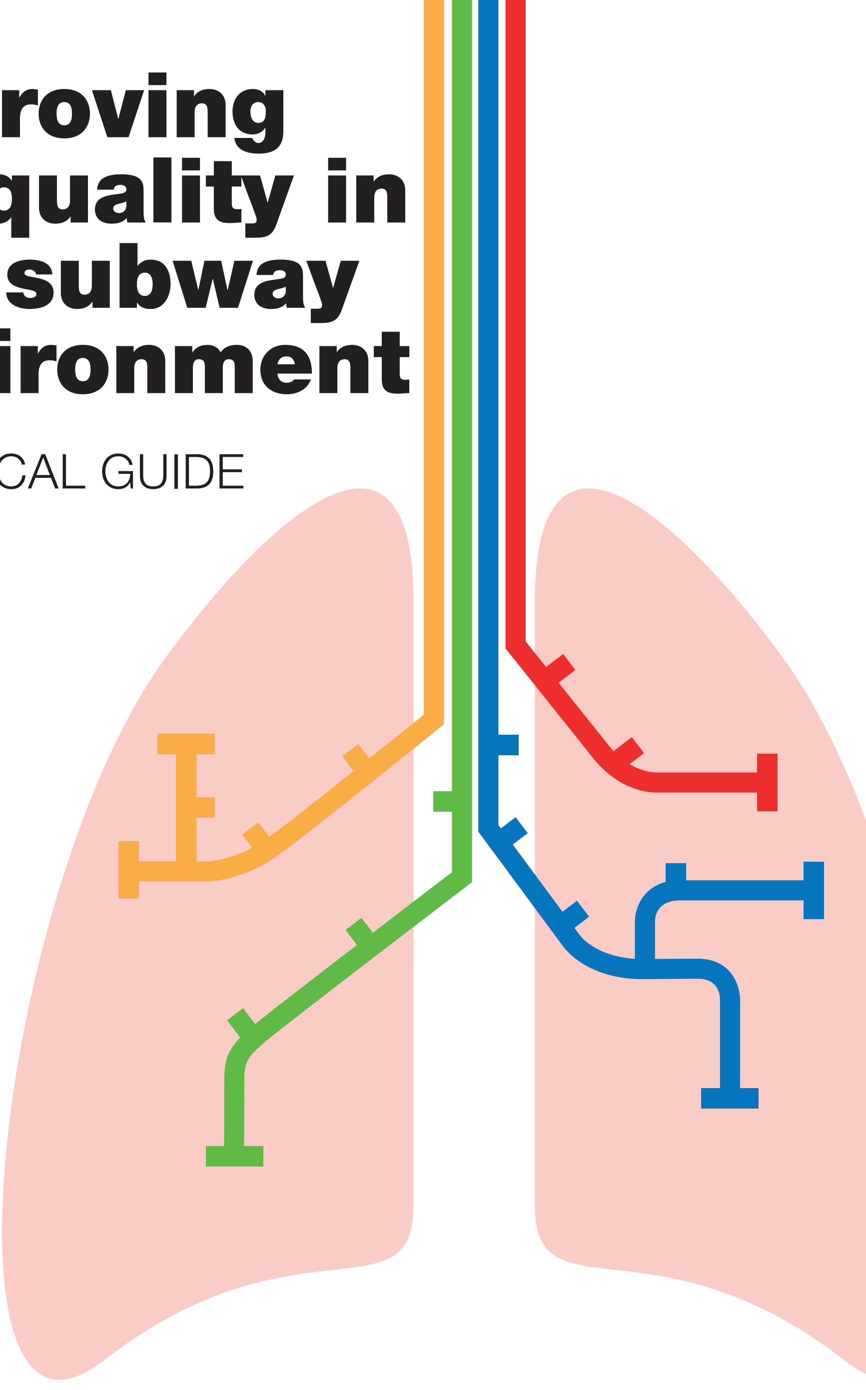
# Improving air quality in the subway environment

## TECHNICAL GUIDE



Edited by **Teresa Moreno**

LIFE13 ENV/ES/000263

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LIFE13 ENV/ES/000263
http://improve-life.eu/en/

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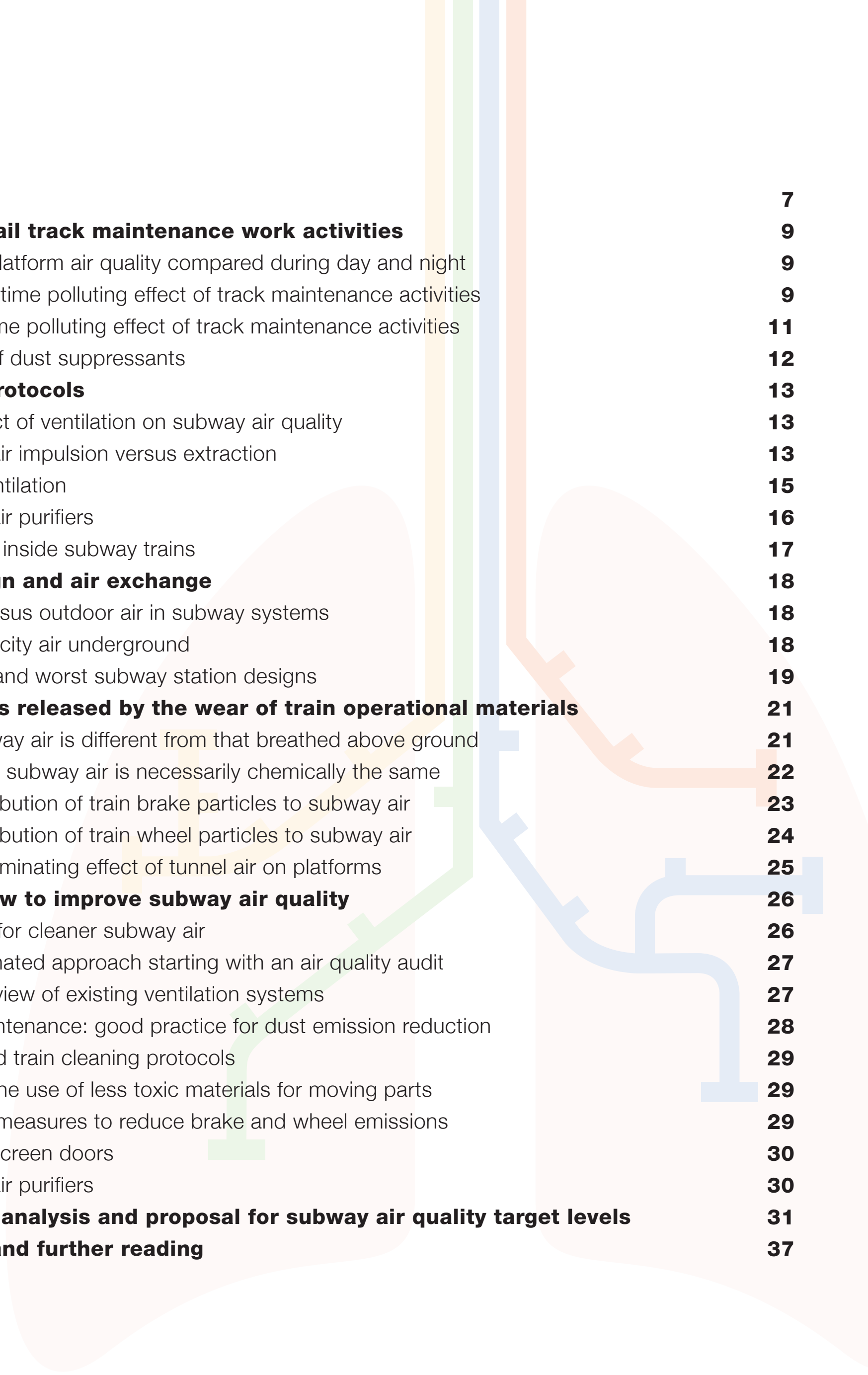
# Index



**1. Introduction** **7**
**2. Tunnel and rail track maintenance work activities** **9**
  2.1. Subway platform air quality compared during day and night **9**
  2.2. The night-time polluting effect of track maintenance activities **9**
  2.3. The daytime polluting effect of track maintenance activities **11**
  2.4. The use of dust suppressants **12**
**3. Ventilation protocols** **13**
  3.1. The impact of ventilation on subway air quality **13**
  3.2. Platform air impulsion versus extraction **13**
  3.3. Tunnel ventilation **15**
  3.4. Platform air purifiers **16**
  3.5. Air quality inside subway trains **17**
**4. Station design and air exchange** **18**
  4.1. Indoor versus outdoor air in subway systems **18**
  4.2. Impact of city air underground **18**
  4.3. The best and worst subway station designs **19**
**5. Contaminants released by the wear of train operational materials** **21**
  5.1. Why subway air is different from that breathed above ground **21**
  5.2. But not all subway air is necessarily chemically the same **22**
  5.3. The contribution of train brake particles to subway air **23**
  5.4. The contribution of train wheel particles to subway air **24**
  5.5. The contaminating effect of tunnel air on platforms **25**
**6. Overview: how to improve subway air quality** **26**
  6.1. The case for cleaner subway air **26**
  6.2. A co-ordinated approach starting with an air quality audit **27**
  6.3. Critical review of existing ventilation systems **27**
  6.4. Night maintenance: good practice for dust emission reduction **28**
  6.5. Tunnel and train cleaning protocols **29**
  6.6. Towards the use of less toxic materials for moving parts **29**
  6.7. Consider measures to reduce brake and wheel emissions **29**
  6.8. Platform screen doors **30**
  6.9. Platform air purifiers **30**
**7. Cost-benefit analysis and proposal for subway air quality target levels** **31**
**8. References and further reading** **37**

# 1. Introduction

The operation of deep-level underground electric railways began (in London) in the late 19th century and nowadays over 125 years later such systems can carry more passengers than any other city transport mode, so that many millions of commuters worldwide regularly spend a proportion of their daily time in subway trains. The numbers involved are impressive: over 160 subways (often called "metros") worldwide in more than 50 countries with something like 50 billion journeys being made every year, which is more than six times the current world human population.

The underground systems supporting such mass transit can be viewed as a transport lifeline, helping to improve the quality of urban infrastructure and relieve road traffic congestion. However, one disadvantage of any underground transport system is that it operates in a confined space that may permit the accumulation of unhealthy concentrations of airborne contaminants. Furthermore, much of the inhalable airborne particulate matter (PM) in subway air is actually produced underground and so is substantially different in nature from typical PM found outdoors.

This "subway source" PM is mostly generated by friction between moving train parts such as wheels and brake pads, as well as from the steel rails and power supply materials, giving the particles a peculiarly metalliferous character. Dominantly ferruginous and carbonaceous particles derived from these materials are mixed with PM from a range of other sources, including rock ballast from the track and infiltrating outdoor air, and driven through the tunnel system on turbulent air currents generated by train movement and ventilation systems.

**The main challenge with regard to improving air quality in subway systems is how to minimise the accumulation of inhalable particles generated by the moving trains**

Other air pollutants that have the potential to cause problems underground include $CO_2$ (in conditions of overcrowding), CO (when traffic-polluted air is drawn underground or hydrocarbon-powered work equipment is used in tunnels), bioaerosols, ozone (from electrical emissions), and a wide range of volatile organic compounds (VOCs). However, given the fact that underground trains are electric and so do not produce daytime hydrocarbon combustion emissions, the main challenge with regard to improving air quality in subway systems is how to minimise the accumulation of inhalable particles generated by the moving trains.

A key objective of the IMPROVE LIFE subway air quality project, based in Barcelona (Spain), has been to create the largest existing publicly available database on subway air quality. This database is designed to facilitate the development of realistic PM mitigation strategies in underground train systems that will result in cleaner air being breathed by commuters. In this short technical guide we summarise what the results obtained during the IMPROVE LIFE sampling and analysis programmes can teach us about how to improve air quality on subway platforms and in trains. Key points directly relevant to the problem of understanding air pollution underground are grouped into those related to the varying impacts of (i) tunnel and rail track maintenance work activities; (ii) applying different ventilation on protocols in tunnels, platforms and trains; (iii) station designs and outdoor air infiltration; and (iv) contaminants released by the wear of train operational materials. These key points are then brought together in an overview of measures most likely to achieve notable improvement in subway air quality, along with a tabulated consideration of the associated benefits and drawbacks for each measure.

We propose the introduction of a targeted, colour-coded approach to the problem, based on the methodology of the World Health Organisation (WHO) and designed to encourage transport authorities to aim for progressive PM reductions. The method defines for platforms a series of thresholds that cascade down through bands of decreasing PM concentrations towards the ideal WHO Air Quality Guideline of $PM_{2.5}$ levels of 10 µg $m^{-3}$, which is the lowest annual mean level at which negative health effects have been demonstrated. We are confident that application of the measures recommended in this document will reduce underground pollution levels and improve city commuter health.

# 2. Tunnel and rail track maintenance work activities

## 2.1. Subway platform air quality compared during day and night

The amount of inhalable dust particles present in subway air is normally highest during the daily peak transport hours and reduces to a minimum at night when the trains stop running. A typical example is offered by the results from our experiment in Sagrera station where median daytime platform $PM_{2.5}$ concentrations of 36 µg $m^{-3}$ dropped to 21 µg $m^{-3}$ between the weekday hours of 00:00-05:00. The higher daytime values result from repeated dust resuspension and transport by moving trains during operational hours, aided by tunnel and platform ventilation systems that commonly operate at lower power or are switched off altogether during the night. A common exception to this general rule is when underground air quality is influenced by track maintenance work taking place during the night.

**Subway air is normally cleaner when the trains are not operating**

## 2.2. The night-time polluting effect of track maintenance activities

Subway systems must be constantly inspected and maintained to ensure passenger safety, such work normally taking place during non-operational hours after midnight. Rolling campaigns involving work on rails, ballast, tunnel walls and electrical systems are part of the normal operation of any subway system, but a common unwanted side effect of such activity is the creation of air pollution episodes within the underground system during the night, raising levels of inhalable PM. Such polluting events can be due not only to dust generation at the worksite but also to the movement of tunnel work trains powered by diesel engines.

The contaminating effect of tunnel night work on platform air quality is clearly demonstrated by the several experiments designed to measure such events during the IMPROVE LIFE campaigns. On the platform of Sagrera station, for example, median night-time levels of $PM_{2.5}$ rose by >50% during most of a 7-week campaign of work involving rail track removal and replacement. However, such average values hide the fact that the additional pollution produced by night maintenance activities typically occurs as short-lived episodes of very high PM levels. Particulate levels ($PM_{2.5}$) during such episodes commonly exceed 200 µg $m^{-3}$ (Figure 1), and in extreme cases can peak above 1000 µg $m^{-3}$ (5-minute value) when adding new ballast, > 900 µg $m^{-3}$ when doing welding operations or > 800 µg $m^{-3}$ when heavy vehicles transporting material pass the measuring station.

**Subway night maintenance work affects platform air quality**

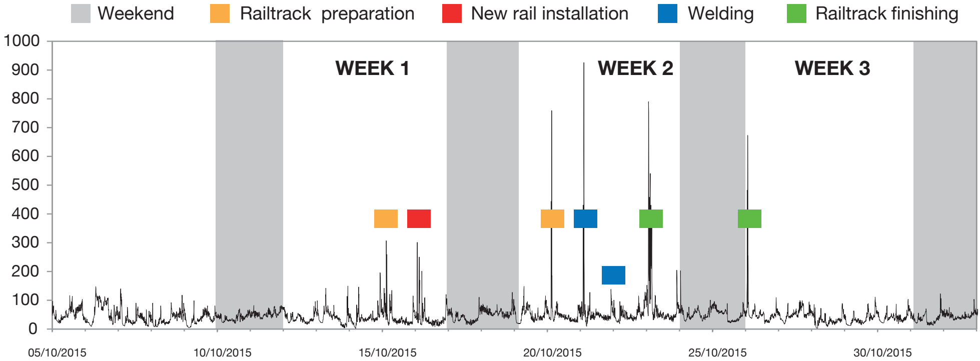


***Figure 1.*** Time series of $PM_{2.5}$ ($\mu g\ m^{-3}$) at Santa Coloma station demonstrating transient peaks produced during night maintenance works.

### 2.3. The daytime polluting effect of track maintenance activities

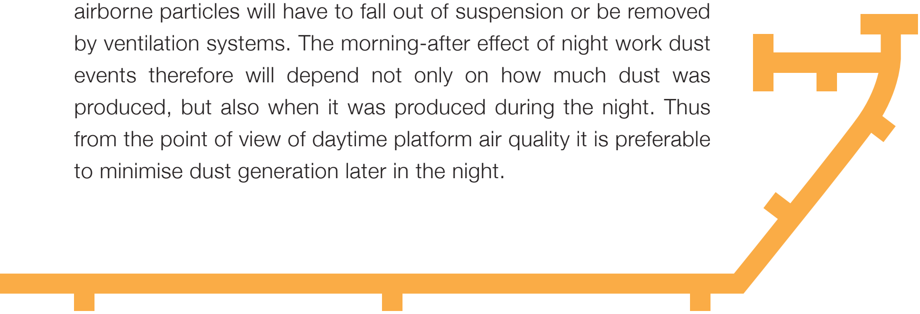
Any additional dust burden generated within the subway system during the night has the potential for damaging air quality for the commuters using the trains during operational hours. The data obtained during measurement campaigns conducted at several stations (Sagrera, Santa Coloma, Palau Reial, Maria Cristina and Poble Sec) all demonstrate that dust emissions from tunnel night work typically result in poorer platform air quality at the beginning of daytime train operations. This additional airborne PM loading declines over the working day as the extra dust burden is diluted and redistributed by train movement and ventilation. At Sagrera, for example, the additional works-related extra $PM_{2.5}$ loading on the platform at the beginning of the day was commonly around 10 µg $m^{-3}$. In some cases however, the extra early morning "works generated" dust burden can exceed 30 µg $m^{-3}$, as demonstrated by the data from Santa Coloma station shown in Table 1.

***Table 1.*** Median $PM_{2.5}$ concentrations (5-minute µg $m^{-3}$ values) on Santa Coloma platform calculated for 1, 4, 8 and 19 hours during the day after night tunnel works.

| | Median | | | |
|---|---|---|---|---|
| | 05-06:00 | 05-09:00 | 05-13:00 | 05-24:00 |
| 15/10/2015 Railtrack preparation | 75 | 42 | 32 | 28 |
| 16/10/2015 New rail installation | 50 | 39 | 28 | 28 |

The IMPROVE LIFE database also indicates that another factor influencing morning platform particulate levels during train operational hours is the timing of pollution peaks during the night. The closer the peaks are to subway opening hours, the less time airborne particles will have to fall out of suspension or be removed by ventilation systems. The morning-after effect of night work dust events therefore will depend not only on how much dust was produced, but also when it was produced during the night. Thus from the point of view of daytime platform air quality it is preferable to minimise dust generation later in the night.

**It is preferable to minimise dust generation later in the night**



## 2.4. The use of dust suppressants

Chemical dust suppressants have been used widely above ground on road surfaces and in the minerals industry, with mixed results. They are most efficient at reducing dust levels under conditions of high dust loading, low solar radiation, and low humidity. Within underground train systems, high levels of silicate rock dust can be generated during the laying of ballast (in Barcelona the rock used is granite), in a situation comparable to those processes involving non-exhaust fugitive dust emissions above ground (e.g. road dust and construction works). The increase in ambient PM mass produced during ballast-laying is particularly obvious in the coarser fraction of inhalable particles ($PM_{2.5-10}$) which we have demonstrated has a predictably “crustal” (silicate) chemical signature, strongly implicating ballast mineral dust as the likely source.

With the problem of night work emissions in mind the IMPROVE LIFE project pioneered the application of a polymer-based dust suppressant to ballast rock fragments prior to the material being laid on the rail track during subway night works. The effect on platform air quality was compared to a similar work programme in which the ballast was simply washed with water, with no application of chemical dust suppressant, which is the usual protocol followed in the Barcelona subway system. The results indicate that using the polymer-based suppressant produces an obvious reduction of 20-50% in night-time dust levels during ballast laying and tamping. This dust suppression during night work translates to a lowering of early daytime platform $PM_{2.5}$ concentrations by at least 10%, thus reducing the extra loading of coarser silicate rock dust available to be dispersed through the subway system during the operating day, although the effect was variable depending on factors including distance between the platform and work site.

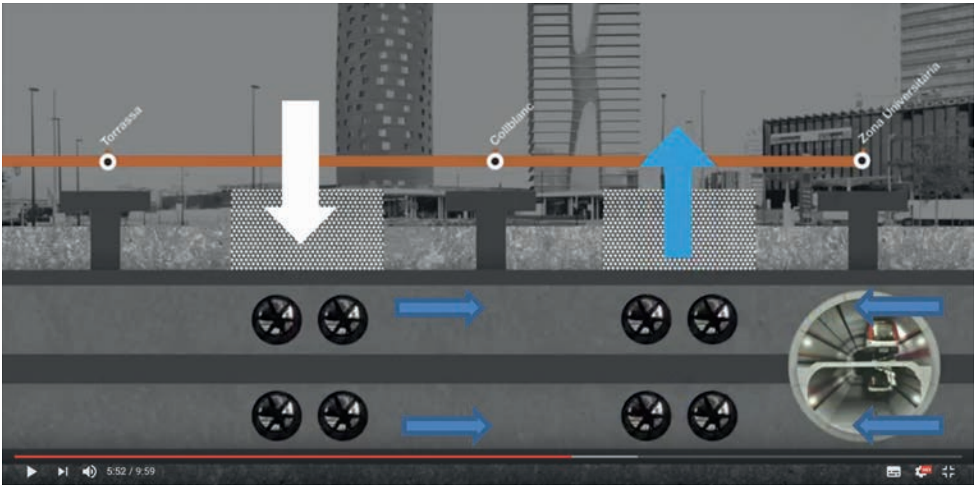
**Applying dust suppressants to ballast improves air quality underground**

# 3. Ventilation protocols

## 3.1. The impact of ventilation on subway air quality

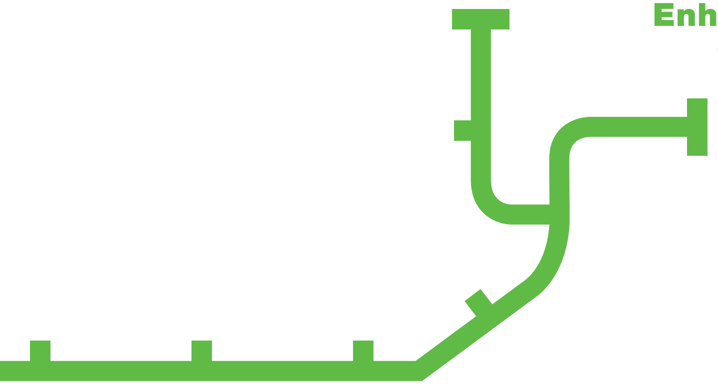
The type of ventilation system operating in the tunnels and station platforms is a key controlling influence on air quality common to subways worldwide. During our IMPROVE LIFE experimental measurement programme we demonstrated that the mass concentration of inhalable particles present on a platform can as much as quadruple in response to changing ventilation settings.

**The concentration of inhalable particles on platforms can increase dramatically under inappropriate ventilation settings**



## 3.2. Platform air impulsion versus extraction

Subway ventilation protocols can be designed to drive outdoor air into the platforms and tunnels by impulsion or suck air out of the system by extraction, and do this at different power settings. Our experiment in Tarragona station demonstrates that platform air quality can be significantly affected by both the direction and intensity of fan air flow. The ventilation intensity is higher in warmer periods than during colder periods, to maintain appropriate temperature conditions in the subway premises. Faster fan impulsion of outdoor air into the platform produces cleaner air by diluting ambient levels of subway particles, providing outdoor PM levels are not higher than those underground. Thus in our experiments on Tarragona station, with platform air impulsion average $PM_{2.5}$ concentrations were consistently and substantially (35%) higher when the fans were operating at reduced intensity in the colder period compared to the warmer period when fans were working harder (Table 2). In this case therefore any power-saving benefits of reducing fan speed were seriously offset by the fact that platform median $PM_{2.5}$ daytime concentrations changed from 61 to 82 µg $m^{-3}$.



**Enhanced impulsion of outside air into the platform can help improve air quality for commuters**

***Table 2.*** $PM_{2.5}$ concentrations (µg $m^{-3}$) at Tarragona station platform on the days under platform impulsion and platform extraction ventilation settings.

| **Stronger ventilation (Warmer period)** | **Night (00-05:00)** | | | **Day (05-24:00)** | | |
|---|---|---|---|---|---|---|
| | Mean | Median | SD | Mean | Median | SD |
| Platform impulsion | *49* | *48* | *23* | *61* | *61* | *21* |
| Platform extraction | 59 | 60 | 27 | 81 | 78 | 25 |
| **Weaker ventilation (Colder period)** | **Night (00-05:00)** | | | **Day (05-24:00)** | | |
| Platform impulsion | *50* | *54* | *23* | *95* | *82* | *18* |
| Platform extraction | 54 | 53 | 27 | 96 | 81 | 19 |

Reversing ventilation air flow from impulsion to extraction is not a strategy likely to improve air quality on the platform, especially under higher fan power settings when there can be a considerable worsening of air quality as compared to under impulsion conditions. The reason for this is revealed by the chemical data from Tarragona station which demonstrate how much of the extra PM loading comprises highly ferruginous particles of “subway” origin presumably sucked out of the tunnel by the higher fan extraction speed.

**Enhanced fan extraction can introduce contaminated tunnel air into the platform and thus worsen air quality**

### 3.3. Tunnel ventilation

Modern, powerful tunnel ventilation systems such as those operating on the newer Barcelona subway lines have a particularly strong influence on platform air quality, even in the presence of platform screen door systems. The modern ventilation system installed at the new, deep station of line L9S at Collblanc, for example, involves platform air extraction fans operating at 30 Hz and two tunnel air impulsion fans operating at 37.5 Hz. If these tunnel fans are switched off then ambient platform $PM_{2.5}$ mass concentrations more than double during train operating hours (26 vs. 61 µg $m^{-3}$). A similarly dramatic increase in particle number concentrations occurs immediately on the platform once the tunnel fans are turned off, especially in the case of the coarser particles, as demonstrated in Figure 2.

**Modern ventilation systems on new deep subway lines can be extremely effective in maintaining better platform air quality**

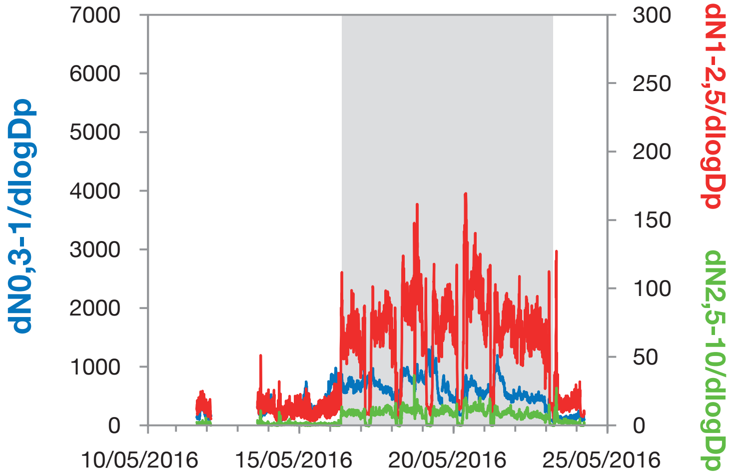


***Figure 2.*** Time series of particle number concentrations at Collblanc station (period without tunnel ventilation is highlighted in grey).

Our experiment at Collblanc clearly demonstrates the importance of a strong tunnel fan system in reducing contamination of tunnel and platform air by subway FePM. The impact of these fans on platform air quality is perhaps surprising considering the presence of brand new full-length platform screen doors (PSD) which might be expected strongly to inhibit air exchange between platform and tunnel. However, recently published work has already indicated that such PSD systems reduce but do not entirely prevent contamination of the platform by tunnel air (Martins et al., 2015; Kwon et al., 2016). Our data strongly reinforce this conclusion and further demonstrate that with platform fans operating on extraction such a PSD system will not stop inhalable PM levels from more than doubling if the tunnel fans are shut down.

### 3.4. Platform Air Purifiers

During the IMPROVE monitoring campaigns the opportunity arose to test a “state-of-the-art” air purifier currently in its research and development phase. The purifier comprises a set of six commercial air recirculation/filtration units (each 60 x 73 x 55 cm in size, using 178 W and 1.1 A of power) equipped with a F7 filter for particles with a diameter greater than 0.2 µm, a carbon adsorbtion filter for inorganic and organic gaseous pollutants and a HEPA H14 filter with a supposed > 99.9% efficiency for particles with a diameter between 0.1 and 0.3 micrometres. The internal recirculation/filtration flow is regulated with a potentiometer from 0 to 660 $m^3$ $h^{-1}$ for each unit.

The best result in terms of air quality improvement occurred during train operational hours when $PM_{2.5}$ mass concentrations at the end of the platform fell by over 30% (61 vs. 88 µg $m^{-3}$) when the purifier was placed close to the measuring equipment (end of the platform). The effectiveness of the purifier can also be demonstrated by measuring particle number concentrations, as revealed in the graph below (Figure 3).

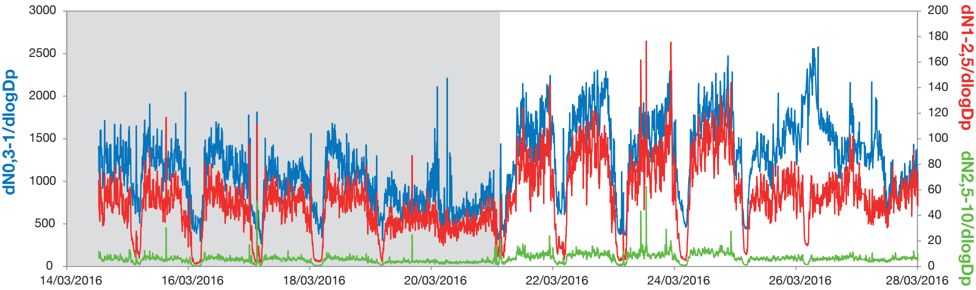


***Figure 3.*** Time series of particle number concentrations at Tarragona subway station, with purifier adjacent to measuring equipment. Note the reduction in all three PM size ranges (grey area with purifier on).

However, this benefit was limited in spatial extent: when the measuring equipment was placed in mid-platform, away from the purifier, a much lower improvement (10%) in air quality was seen. The experiment therefore demonstrates that air purifiers have the potential to improve subway platform air quality, but they need to be sufficiently powerful or numerous to make a substantial difference that would justify the extra expenditure on equipment and energy.

Given the dominance of the ferruginous “subway metal” component in platform air, air purifiers designed to focus more on removing this metallic fraction underground have the potential for greater success compared to those unable to fractionate different chemical components, as shown in a study in the Seoul subway system (Son et al., 2014).

**Platform and train air purifiers have the potential for improving subway air quality but they are still in R&D phase**

### 3.5. Air quality inside subway trains

Air quality inside trains in the Barcelona subway system is always better than on platforms. During one IMPROVE LIFE experiment (on the L3 line) for example, mean $PM_{2.5}$ levels during subway operation hours were 30–50% lower than those recorded on platforms of L3 stations during the same period. One reason for this is that Barcelona subway trains travel using air conditioning within a closed system that does not allow open windows. The effect of air conditioning on carriage air quality can be observed in the Figure 4 below.

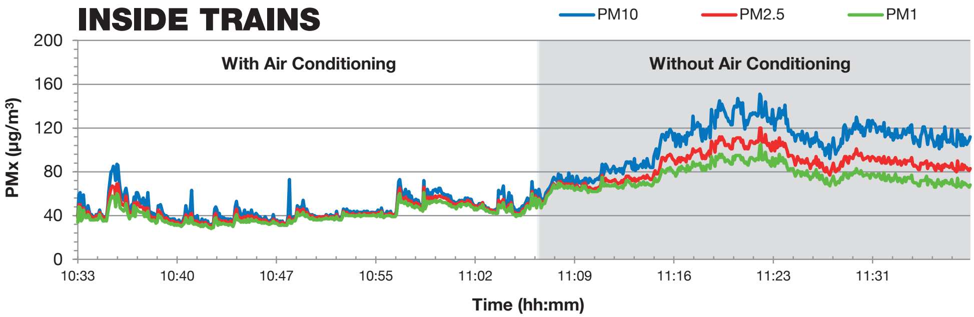


***Figure 4.*** PM concentrations measured inside a train during a return trip with and without (grey) air conditioning on (adapted from Martins et al., 2015a).

From the measurements carried out with and without air conditioning, one can conclude that the air conditioning produces a notable improvement on both concentration and variability of PMx inside the trains, especially for the coarser particles.

**Air conditioning can reduce $PM_{2.5}$ concentrations by 50% inside trains**

# 4. Station design and air exchange

## 4.1. Indoor versus outdoor air in subway systems

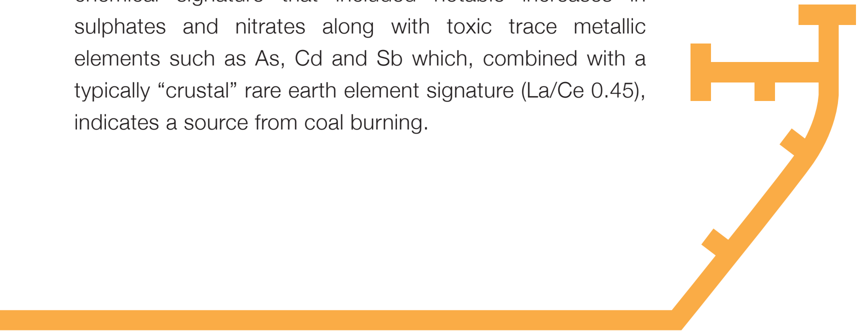
The air pollutants breathed by commuters whilst in the subway are a mix of particles and gases sourced both from within the underground system and from outside. The relative contributions of these two sources will depend on the amount of air interchange between street level, station concourse, and the platforms beneath, as well as on the quality of outdoor city air at any given time.

## 4.2. Impact of city air underground

The quality of outdoor air in the city at any given hour is dependent on a range of factors that include meteorological conditions, traffic flow, proximal pollutant sources such as industrial chimneys or port emissions, and the arrival of "exotic" air masses containing far-travelled pollutants such as desert dust or sulphates. We have consistently demonstrated during the IMPROVE LIFE sampling programmes that outdoor pollutants can be identified in the air present on subway platforms, adding to the locally-sourced PM mass as well as altering the chemistry of the air being breathed.

The effect of contaminated city air on subway air quality is elegantly demonstrated by our sampling programme at Sagrera station, which coincided in part with the arrival of a sulphatic pollutant cloud derived from Eastern Europe. Not only was this "exotic" particulate intrusion into city air capable of increasing underground platform $PM_{2.5}$ mass by over 10 µg $m^{-3}$, but it was accompanied by a distinctive chemical signature that included notable increases in sulphates and nitrates along with toxic trace metallic elements such as As, Cd and Sb which, combined with a typically "crustal" rare earth element signature (La/Ce 0.45), indicates a source from coal burning.

**The quality of outside city air can greatly influence conditions in the subway**



The above example offers an exception to the general rule that air in the city above ground away from traffic hot spots is usually less contaminated by PM than in the subway. Thus if outdoor air can be introduced underground it is likely to improve platform air quality by diluting the ambient burden of subway-sourced pollutants. The difference between the two environments is most marked after the arrival in the city of a clean atmospheric advection event such as, in the case of Barcelona, air blown northwest to southeast from the Atlantic. Such cleansing events can have a considerable impact on subway air, as demonstrated by data from Palau Reial station where one such cleansing arrival above ground caused a decrease in ambient subway platform $PM_{2.5}$ levels of over 20 µg $m^{-3}$.

A particularly graphic example of how atmospheric contamination in the city can impact subway air is provided by the infiltration of firework pollutants during the festival of San Juan in Barcelona (23-24th June). On 23rd June, with tunnel fans working as normal, levels of barium (Ba) in Collblanc station suddenly rose from 18 to 338 ng m$^{-3}$, strontium (Sr) from 3 to 59 ng m$^{-3}$, and potassium (K) from 0.2 to 3.9 µg m$^{-3}$. This impressive rise in these three classic firework tracers was accompanied by notable increases in Mg, Rb, As, Pb, Bi and Cu, all also known to be characteristic of firework emissions (Moreno et al., 2007). Given these levels, it is likely that increases occurred in most or all other stations and that the entire subway network was affected. The exceptional nature of this pollution event can be appreciated in the light of the fact that normal background levels of the three main firework tracers in Barcelona are 5.2 ng m$^{-3}$ for Ba, 0.8 ng m$^{-3}$ for Sr, and 0.1 µg m$^{-3}$ for K.

**Outdoor pollution events such as firework displays can be detected underground**

Any attempt at improving underground subway air, especially in the case of ultrafine particles (UFP), NO$_2$ or polyaromatic hydrocarbons (PAHs) concentrations, would therefore benefit from a constant awareness of outside air quality and ideally be able to respond by controlling and varying the exchange between the outdoor and underground air masses using intelligent ventilation systems.

### 4.3. The best and worst subway station designs

The IMPROVE LIFE campaigns have sampled widely from a range of subway lines and station types (Figure 5) and conclusions can be reached concerning which kind of subway stations are likely to have the best and worst air quality in any given system.

The subway stations likely to have the worst air quality will be those with limited air volume (such as single tube lines with one narrow platform), weak or inappropriately designed ventilation systems (especially in deeper stations), a lack of platform screen doors protecting the commuter from the free ingress of contaminated tunnel air, a topography that involves elevation changes and therefore requires harder braking, and old enough to have generated years of particulate pollutants available for repeated resuspension throughout the system.

In contrast, those subway stations with the best air quality are likely to be larger and/or newer, with good air interchange between outdoor street air (although not sourcing from traffic hotspots in the city), with full length screen doors fitted to all platforms, and with a straight, horizontal trajectory that minimises brake and wheel wear.

**There is great variation in air quality between different stations and lines**

The differences outlined above translate to notable differences in the quality of air breathed by commuters, depending on which stations they visit and which line they travel on. In Barcelona the worst lines typically have platform PM$_{2.5}$ levels above 80 µg m$^{-3}$, whereas the newer lines with platform screen doors have ambient levels below 35 µg m$^{-3}$.

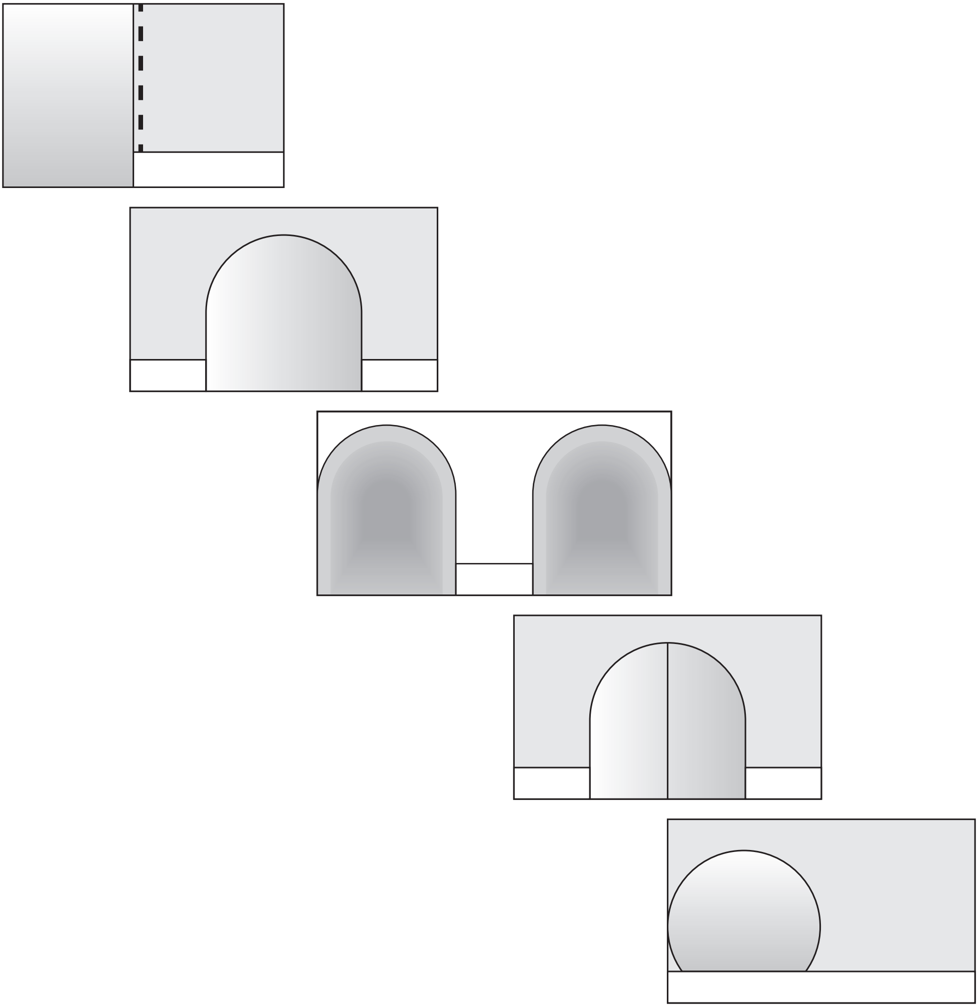


***Figure 5.*** Contrasting designs for subway stations can have a major effect on air quality. In this figure the cleanest design results from well-ventilated platforms fitted with full length platform screen doors (top left). The design most likely to be associated with poor air quality will involve inadequate ventilation of narrow single platform stations strongly contaminated by tunnel air (lower right).

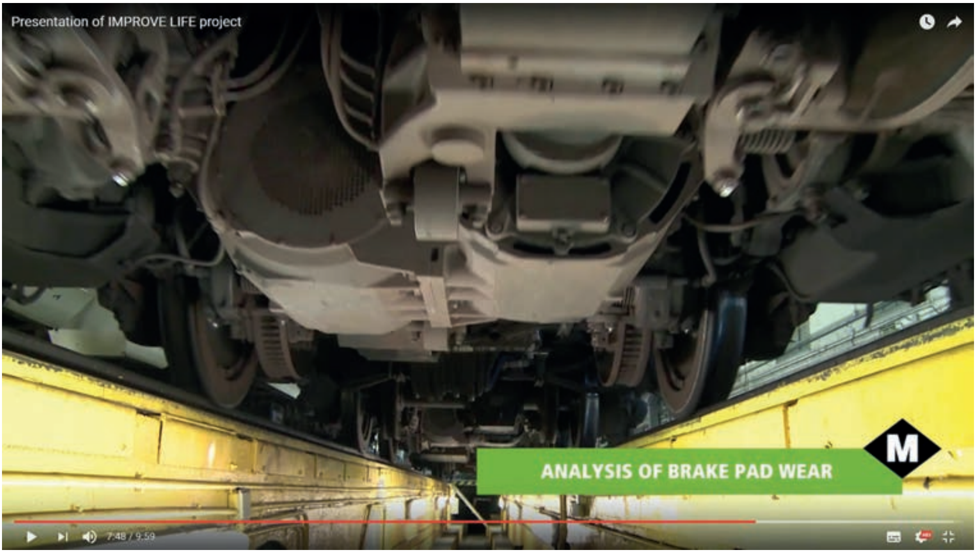
# 5. Contaminants released by the wear of train operational materials

## 5.1. Why subway air is different from that breathed above ground

One of the most innovative aspects of the IMPROVE LIFE programme has been the gathering of a detailed chemical database comprising > 500 analyses not just of the breathable PM present in subway platform air, but also of the train parts and other subway materials likely to be contributing to these inhalable particles. This database includes full chemical analyses of rock ballast, catenary materials, electric brushes, and different types of pantographs, brake pads, rails and train wheels. The release of particles from these source materials by friction processes induced during train movement is what makes subway air pollutants so chemically distinctive.

As a result of these “subway emissions”, most particles breathed in the subway are rich in iron (ferruginous: $\text{FePM}_{2.5}$) and/or carbon (carbonaceous: $\text{CPM}_{2.5}$). The third most common particle type (although much less abundant than Fe and C) is silicate mineral dust, followed by secondary inorganic compounds (SIC) mostly sourced from outdoor air. The SIC particles have a distinctive chemical signature rich in sulphate and ammonium ions, sometimes with additional nitrate and chloride, and usually accompanied by tracer metals such as V, Se and Cd.

**Subway particles are unusually rich in iron and carbon released by friction between moving train parts**



Our studies indicate that daily concentration ranges at subway underground platforms for each of the four dominant chemical components comprising subway $PM_{2.5}$ are as follows: ferruginous ($Fe_2O_3$) 4-52 µg $m^{-3}$; carbonaceous 7-24 µg $m^{-3}$; mineral dust 3-9 µg $m^{-3}$; SIC 1-5 µg $m^{-3}$. Iron particles in the subway derive mostly from the wear of steel wheels and rails, and ferruginous brake pads. Carbon particles generated in the subway are sourced mostly from pantographs, brakes and electric brushes.

### 5.2. But not all subway air is necessarily chemically the same

Not only are subway PM chemically distinctive when compared to outdoor city air, but the IMPROVE LIFE sampling campaigns have discovered that different subway lines can have their own distinctive chemical signatures. Thus, for example, platform air breathed in stations along Barcelona subway line 3 has barium (Ba) concentrations of around 1400-1500 ng $m^{-3}$, whereas platform air along lines 2, 4 and 5 contains Ba levels <150 ng $m^{-3}$. By comparison, average concentrations of Ba measured in the Barcelona outdoor city background station are 5 ng $m^{-3}$, so that subway Ba levels in L3 are around 300 times higher than above ground.

The reason for such a tremendous increase in Ba is attributed to the fact that 80% of the brakes used on that line contain exceptional amounts of this element (Ba 33,000 ppm). The darker, more carbonaceous component present in these chemically heterogeneous brakes contains nearly 5% Ba. No other subway PM source is Ba-rich so that most ambient Ba breathed on platforms along this line (around 1 µg $m^{-3}$) can be confidently attributed to particles released during brake wear.

**The air in a given subway line can have its own distinctive chemical signature**

Another important influence on the chemistry and mass of particles present in ambient subway air is the topographic trajectory of the train route. The PM in air samples collected along line 1 in Barcelona, for example, contains around half as much Ba than those from line 3, despite the fact that both lines use Ba-rich brake pads. This difference is likely to be due to the fact that L3 trains need to brake much more than those of L1. The L3 route descends from the higher ground around 100 m above sea level at the western entrance to the city to the coast then immediately climbs back up the piedmont to the base of the hills behind Barcelona. In contrast L1 runs through the city centre parallel to the coast and is essentially horizontal.

**The trace metal chemistry of moving train parts can be detected in the air breathed on platforms**

Thus chemical differences between air particles breathed on different platforms in some cases can be traced both to the use of chemically different materials as well as to variations in the amount of wear of moving train parts.

### 5.3. The contribution of train brake particles to subway air

The example given above clearly implicates the abundant presence of train brake particles in subway air. We estimate broadly that in some stations brake PM can form up to 40% of $PM_{2.5}$ mass present in the platform air. Such particles can be viewed under the electron microscope and are typically flakes measuring a few microns in size and with a strongly heterogeneous chemical structure. These brake flakes will be swept through and settle in the station under the diminishing influence of each train arrival piston effect, and therefore expected to be more common on the platform than in the tunnel or outdoors (Moreno et al., 2015). Four different types of brake-pads, and both lateral and frontal braking systems, are used in the Barcelona subway and they show distinctive trace element chemistries, with varying enrichments in amounts of Ba, Fe, Cu, Zn, Ca, Mg, S, Mn, Sr, Mo, and Sb all contributing to the chemistry of Barcelona subway air.

**Train brake pad chemistry influences the composition of ambient $PM_{2.5}$ present in subway air**

In some cases the different brake-pad chemistries can be specifically identified as the sources of inhalable particles present on subway platforms. Thus Ba-rich brakes preferentially contaminate subway air with Ba, Sr, Zr and Ti, whereas Sb-rich brakes produce enrichments in ambient Sb that can be 40 times higher than in stations of other lines and 100 times higher than in outdoor city air. Both Mg and Cu contents of platform $PM_{2.5}$ can also be traced to brake emissions, although other sources are also implicated, namely pantographs for Cu and ballast for Mg. Copper concentrations in platform $PM_{2.5}$ are highest in the subway line using brake-pads with the highest Cu content (L4) and with a steeper “hill-to-sea” route, and with Cu-containing pantographs, with source apportionment calculations suggesting that around 15 ng $m^{-3}$ of $CuPM_{2.5}$ can be sourced from the pantographs and 250 ng $m^{-3}$ of $CuPM_{2.5}$ from the brakes.

**Levels of train brake tracer elements such as Ba or Sb can be over 100 times higher in the subway than outdoors**

**Train brakes contribute abundant carbon-rich particles to the subway atmosphere**

The second most common element in brakes after iron is carbon (all brakes contain >25% C) and their wear makes a considerable contribution to the amount of ambient carbon in the subway atmosphere. We estimate that in some cases this contribution may be up to 15 µg $m^{-3}$, although given the multiple sources involved (notably pantographs, electric brushes, infiltration of C in outdoor air) more exact apportionment cannot be calculated with any confidence.

### 5.4. The contribution of train wheel particles to subway air

We identify the abrasion of train wheels as another source of particles within the subway, broadly similar to the inhalable PM mass burden contributed by brake wear. The steel wheels are made mostly of iron (Fe = 99%), with minor amounts of manganese (Mn = 0.7%) and traces of chromium, nickel and cobalt. These minor and trace elements usefully enable us to detect the presence of wheel particles in subway air. Levels of these elements are much higher in the subway than in outdoor city air which often contains for example 30 or even 40 times less Mn and Cr than on subway platforms. No consistent link between brake emissions and Mn, Cr, Ni or Co enhancements is discernible in our database, but instead the highest concentrations of this group of elements in the subway environment are found in train wheels.

**Train wheels contribute inhalable Fe particles containing Mn, Cr, Ni and Co to subway air**

Iron is the classic "subway metal", present throughout the Barcelona metro in average concentrations normally lying within the range 3-36 µg m$^{-3}$ FePM$_{2.5}$ (4-52 µg m$^{-3}$ $Fe_2O_3$). This metal is present in every subway component, but is by far most abundant in the steel of wheels and rails (98-99% Fe, 0.7% Mn, 0.1% Cr, 0.1% Cu). In brakes Fe is present in concentrations of 19-42%, whereas all other potential sources are much less ferruginous: ballast (3%), carbon brushes (0.3%), and pantographs (up to 0.14%). Chemical analysis reveals ratios of Cr/Fe = 0.0012 for train wheels and Cr/Fe = 0.0010-0.0015 for the ambient air in all subway lines. This similarity in Cr/Fe of both steel wheels and ambient PM$_{2.5}$ is particularly striking, especially given that steel rails contain much less Cr (Cr/Fe = 0.0002) and brakes are also Cr-depleted. Chromium is in fact much less common in any other subway component, suggesting that much of the Cr, and therefore also Fe, present in platform PM$_{2.5}$ is sourced from train wheels. The equivalent figures for the ratio Mn/Fe are 0.007 for steel wheels and 0.009-0.011 for subway air. The fact that the Mn/Fe ratio is somewhat higher in subway air than in steel wheels is attributed to contributions from other relatively Mn-richer sources such as ballast (Mn/Fe = 0.02), Mn-richer components such as certain types of brakes (Mn/Fe = 0.04), and/or infiltration of outdoor city air (Mn/Fe = 0.02, Moreno et al., 2015).

**Iron is the classic "subway metal", present throughout the Barcelona metro in average concentrations that can exceed 25 µg m$^{-3}$ FePM$_{2.5}$**

### 5.5. The contaminating effect of tunnel air on platforms

The considerable differences in measured subway $FePM_{2.5}$ between stations is strongly related to how much tunnel air contaminated with rail FePM is entering the platform. The most obvious example of this is provided by the L9S Collblanc station which is brand new and equipped with platform screen doors and powerful modern ventilation systems. On this station platform $FePM_{2.5}$ levels are only 3 µg $m^{-3}$, which is twelve times less than measured on Tetuan station which has a similar design but is older, has less advanced ventilation and lacks PSD. It is clear that in some subway stations it is theoretically possible to reduce ambient levels of platform FePMµg $m^{-3}$ by several tens of micrograms.

**In some subway stations cleaner air could reduce ambient levels of platform FePMµg $m^{-3}$ by several tens of micrograms**

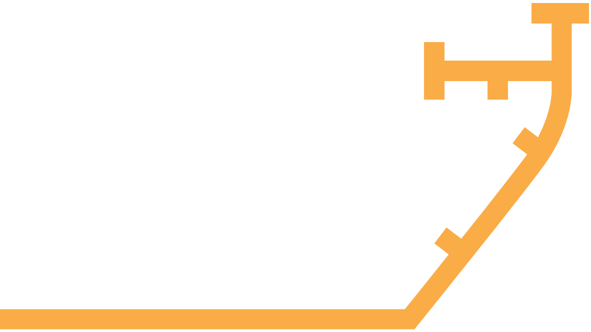
# 6. Overview: how to improve subway air quality

## 6.1. The case for cleaner subway air

Air quality inside underground rail systems is not yet included in legislation designed to clean up city air. Current European Commission rules require authorities to maintain ambient PM$_{2.5}$ levels in outdoor air below an annual average of 25 µg m$^{-3}$ (2008/50/EC). World Health Organisation (WHO) recommendations are more ambitious, calling for a tiered approach to reducing PM levels that starts with 35 µg m$^{-3}$ and works progressively towards an ideal level of just 10 µg m$^{-3}$.

In Barcelona average background mass concentration levels of PM$_{2.5}$ outdoors are currently (2016) 11-12 µg m$^{-3}$, although there is considerable variation within the city, and much higher values can be recorded in the central urban areas more contaminated with traffic emissions. A recent study comparing air quality exposure to commuters journeying into central Barcelona using different modes of transport showed that relative average PM$_{2.5}$ concentrations were lowest while travelling in the tram, and highest inside the bus. In terms of average numbers of fine particles inhaled the following hierarchy of increasingly compromised air quality was established: urban background < metro < tram < suburban main road walking < city centre walking < bus, with number of particles for the metro being 2-3 times less than those outdoors in the city centre (Moreno et al., 2015).

**Many subway stations have ambient levels of PM$_{2.5}$ higher than the legislated limits demanded for outdoor air**



Our IMPROVE LIFE measurement campaigns have demonstrated that a majority of subway stations have ambient levels of PM$_{2.5}$ higher than the legislated limits demanded for outdoor air. In some cases PM$_{2.5}$ concentrations on a given platform can exceed 100 µg m$^{-3}$, as a daily mean, demonstrating a clear need for improving air quality underground in some stations. On the other hand, subway stations can be remarkably clean. Levels of PM$_{2.5}$ on the Collblanc L9S platform (26 µg m$^{-3}$), for example, are close to the European limits for outdoor air, proving that it is perfectly possible to breathe relatively clean air even in the confined space of an underground train network.

### 6.2. A co-ordinated approach starting with an air quality audit

Given the complicated nature of the problem, with pollutants being emitted from different sources then mixing and moving through tunnels, platforms, passenger walkways, station concourses, ventilation systems and inside trains, we recommend a co-ordinated approach that recognises the different issues and influences involved. Once the decision has been made to launch a programme aimed at improving air quality in a given subway system, the first step should be an initial air quality audit designed to assess the nature of the existing air quality in stations and trains. This need not be overly expensive or time-consuming. The assessment will group stations by their design and ventilation systems, noting such features as station depth, location and nature of airflow outlets (e.g. at street level or elevated; close to traffic hot spots), air volume (e.g. larger stations serving two lines with central or side platforms versus narrow "tube" stations with side platform serving a single line), whether mechanical ventilation is used (impulsion vs. extraction; tunnel vs. platform fans; use of air purifiers), whether air is filtered inside trains, whether platform screen doors are installed (and, if so, whether they are full length), and any other factors pertinent to the system being examined.

**An initial air quality audit will demonstrate current $PM_{2.5}$ levels on platforms and in trains**

The audit should also compare the various lines in the subway system, noting those involving large numbers of curves and significant gradients likely to have an effect on brake emissions, and gather data on the chemistry of brake pads fitted to the trains. Most importantly, this initial study will need to obtain measurements of inhalable PM mass concentrations on station platforms (mid- and end-platform) and inside trains. Ideally on platforms this should include the use of static, officially calibrated reference equipment such as high volume air samplers. However, a good idea of relative PM concentrations can be obtained rapidly using less expensive and more mobile types of measuring equipment that are becoming increasingly available and reliable, so that not every station needs necessarily to use static measuring units (provided that that all equipment is properly calibrated and corrected against reference methods). Given the frequent infiltration of outdoor air into subway systems, note will need to be taken of fluctuating outdoor pollution levels in the city above ground as the air quality results are being collected underground.

The detailed chemical database obtained by the IMPROVE LIFE project need not be repeated: we can assume that for subway systems operating trains with steel wheels then FePM will be the dominant particulate pollutant, followed by CPM in those systems using carbonaceous brakes and pantographs. Some need for chemical analysis however may emerge for those subway lines that exhibit unusual characteristics, such as the use of rubber tyres, if no chemical data are already available.

### 6.3. Critical review of existing ventilation systems

Once the patterns of platform ventilation have been established and problem areas identified, we recommend a period of experimentation measuring platform air quality under different airflow speeds and directions. The IMPROVE LIFE experience is that platform impulsion produces cleaner air than extraction in terms of particles larger than 0.3 µm, assuming that outdoor air is not more polluted than tunnel air.

Outdated fan ventilation systems should be replaced by new, more efficient designs. The beneficial dilution effect of introducing clean air underground from outside would be maximised by the fitting of purifying filters to the inflow system. Ideally ventilation inlets should be raised above ground to lessen the inflow of traffic-contaminated air, although practical difficulties with any social impacts induced by installing raised towers or chimneys blocking the street view will need to be addressed.

**Smart ventilation systems need to be responsive to air quality changes outdoors and underground**

The operating system needs to be designed to minimise the movement of air from the tunnels into the platform. A combination of balanced extraction through tunnel ventilation shafts and impulsion from outside into the platform is most likely to favour platform air quality.

There should be a constant awareness of city air quality above ground, as reported from local government monitoring stations. During outdoor pollution episodes such as desert dust arrival, anticyclonic atmospheric stagnation, accumulating heavy industrial emissions, or transient but highly contaminating events such as firework displays or peak hour traffic emissions, it may be better to reduce, turn off, or reverse platform airflow impulsion. Fan systems equipped with PM sensors could do this automatically. Ideally, the whole subway ventilation system could be linked in to a “smart neural network” monitoring atmospheric conditions below and above ground in the city and capable of predicting changes in air quality as the day progresses. Such advanced systems are currently being developed in the Seoul subway network in South Korea.

### 6.4. Night maintenance: good practice for dust emission reduction

We identify the maintenance work that necessarily takes place regularly in the tunnels as an important source of dust generated in the subway system. In addition to the consideration of occupational exposure potentially affecting night workers underground, there is the wider issue of higher residual contamination on platforms the next morning, as well as the general increase in the background burden of dust circulating through the subway system.

**Create less dust underground**

The first step to improve this situation is generating an awareness of the problem. Work teams need to be instructed to minimise dust emissions, and best practice guidelines established. The laying and tamping of rock ballast typically results in considerable fugitive dust generation in the tunnels, and we recommend the application of mitigation measures, such as moistening the material or, even better, adding dust suppressants to the ballast material, prior to it being transported to the worksite. From a purely air quality perspective the use of rock ballast on the track would be better discouraged in favour of using concrete, although this is likely to generate noise issues. Finally, the use of diesel engines underground should be phased out in favour of heavy duty electric vehicles, thus removing a significant source of night-time emissions.

## Regular cleaning of tunnels and platforms

### 6.5. Tunnel and train cleaning protocols

The problem of subway PM is potentially aggravated by the fact that it may be cumulative, with the older lines likely to become dirtier with time if left untouched. Therefore we recommend an aggressive clean-up programme, especially in older lines, moving gradually and repeatedly through the entire tunnel and platform system and being maintained by regular high pressure cleaning of trains to remove adhering tunnel dust, concentrating on the moving parts where Fe-C particles are newly generated by wheel and brake friction.

### 6.6. Towards the use of less toxic materials for moving parts

## Remove toxic metals from train parts generating particles

Our observation that the trace metal components of moving train parts can be recognised in subway air prompts the question: are these materials as least toxic as possible? The current answer is no: some of these contaminating metals, such as Mn, Cu, Sb and Cr, are known to produce toxic effects in humans. Admittedly, airborne concentrations of these metals are always much lower than officially accepted occupational exposure limits. However in these situations the precautionary principle is always the wisest approach and we would urge further research into the toxicity of inhalable friction-generated polymetallic particles, particularly from brakes and copper-bearing catenary systems, released into subway air. Similarly further research and development to produce materials that emit fewer and potentially less toxic particles would be another positive way forward. Meanwhile we recommend a phasing out of Cu-rich catenary materials and of brake pads containing enrichments in more toxic metals and metalloids such as Sb. Subway workers and commuters need to be made more aware of the fact that the wear of materials used in brakes, wheels and catenary translates directly to the particles they are breathing underground.

### 6.7. Consider measures to reduce brake and wheel emissions

Subway operators are well aware of the fact that trains on certain lines need brake replacement much more frequently than others, due to the gradients involved in the trajectory of the route. As previously mentioned a good example in Barcelona is provided by comparing lines 1 and 3. L3 trains run down to the sea then back up to the hills behind the city and brake harder than the essentially horizontal L1. Both lines use brakes with high Ba content (only 11% difference) but whereas average levels of Ba in the station measured in L1 are 817 ng $m^{-3}$, those in L3 are 1466 ng $m^{-3}$. This coincides with the fact that stations on L3 have some of the highest PM concentrations measured in the Barcelona system.

## Minimise brake and wheel emissions

We argue that there is a good air quality case for reducing FeCPM emissions by slowing down the speed of trains in places on lines where there are sharp curves and high gradients. Furthermore, the source of these particles is highly specific: the brake-wheel interaction. Thus extraction systems attached to the underside of the train and designed specifically to collect PM emitted from the brakes have the potential to greatly enhance air quality. Such systems are currently being tested in the Seoul subway system.

### 6.8. Platform screen doors

Modern subway lines are increasingly being fitted with platform screen doors, primarily for passenger safety reasons. The additional benefit to passenger health by reducing the ingress of contaminated tunnel air into the platform is a welcome extra effect of such installations, as demonstrated by the remarkably clean air in the new L9S line connecting Barcelona with its airport.

We view the health benefit of breathing cleaner air on the platforms to be at least as important as the extra safety offered to the passenger by preventing access to the line prior to train arrival. The platform screen door system however must be full length; otherwise any air quality benefit is likely to be minimal or zero. It is also the case that even with PSDs in place, air quality is likely to deteriorate without powerful tunnel ventilation systems that serve to extract FeCPM that are prevented from escaping via the station platform.

**Install full length platform screen doors**

### 6.9. Platform air purifiers

Our experimentation with platform purifiers suggests that these provide a promising line of research that is likely to offer improvement in subway air, but that in Europe at least they are still in their developmental stage (they are currently being introduced in Seoul). Given the peculiarly ferruginous nature of particles generated within the subway environment, we would suggest a prioritisation on machines capable of selectively extracting the metallic component of subway air. The installation of air purifiers within trains is also likely to achieve benefits in air quality, given our experience with train carriage air conditioning filters. Such purifier units can be attached to the roof of trains.

**Install air purifiers in trains and on platforms**

# 7. Cost-benefit analysis and proposal for subway air quality target levels

In Table 3 we list various pollutants measured in the Barcelona subway project. As the table confirms, in all but the most modern and well ventilated subway lines it is the mass concentration level of inhalable particles that is most likely to give cause for concern with respect to air pollution underground. Therefore, as we have stated in 6.1, the primary objective of any air quality improvement campaign within a subway system must be to reduce the number of inhalable particles breathed by passengers on platforms and trains. Unlike above ground in the city, where particulate pollutants are joined by volatile organic compounds and toxic gases related to hydrocarbon combustion, in the subway system the main problem is FeCPM: ferruginous and carbonaceous particles generated by train movement.

**Commit to an air quality audit and targeted reductions**

***Table 3.*** Concentrations at all stations measured in Barcelona subway of i) $PM_{2.5}$, $NO_2$, $Fe_2O_3$, Mineral components, CA (carbonaceous aerosols) and SIC (secondary inorganic compounds) (in µg $m^{-3}$); ii) N (number of particles $cm^{-3}$ in 0.3-10 µm range); iii) $CO_2$ and CO (ppm); iv) Sb, Cr, Mn, Cu, Zn and Ba (ng $m^{-3}$).

| Platform | Line | $PM_{2.5}$ | #N | $CO_2$ | CO | $NO_2$ | $Fe_2O_3$ | Min | CA | SIC | Sb | Cr | Mn | Cu | Zn | Ba |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **St. Coloma** | **L1** | **65** | 126 | 475 | 0,3 | 62 | 24,4 | 7,5 | 24 | 2,5 | 3 | 22 | 193 | 103 | 195 | 817 |
| **Tetuan** | **L2** | **93** | 148 | 392 | 0,3 | -- | 51,5 | 8,1 | 23 | 5,0 | 36 | 45 | 358 | 228 | 191 | 72 |
| **Palau Reial** | **L3** | **87** | 182 | 450 | 0,1 | 70 | 37,3 | 8,6 | 23 | 2,8 | 3 | 31 | 225 | 140 | 251 | 1505 |
| **M. Cristina** | **L3** | **80** | 122 | 476 | 0,1 | 69 | 37,1 | 6,6 | 21 | 2,8 | 3 | 29 | 244 | 133 | 246 | 1400 |
| **Tarragona** | **L3** | **77** | 130 | 480 | 0,1 | 65 | 35,1 | 9,4 | 20 | 3,8 | 2 | 32 | 241 | 130 | 277 | 1493 |
| **Poble Sec** | **L3** | **72** | 147 | 392 | 0,3 | -- | 27,9 | 7,7 | 21 | -- | 3 | 22 | 170 | 105 | 228 | 1020 |
| **Joanic** | **L4** | **70** | 89 | 537 | 0,4 | 63 | 46,7 | 4,9 | 14 | 1,4 | 97 | 41 | 314 | 469 | 268 | 149 |
| **Sagrera** | **L5** | **37** | 105 | 479 | 0,1 | 62 | 15,0 | 3,7 | 14 | 2,7 | 5 | 11 | 96 | 112 | 105 | 99 |
| **St. Ildefons** | **L5** | **42** | 80 | 400 | 0,1 | 42 | 21,5 | 3,9 | 9 | -- | 5 | 21 | 145 | 61 | 218 | 35 |
| **Collblanc** | **L9S** | **26** | 45 | 194 | 0,2 | 38 | 4,2 | 3,8 | 7 | -- | 2 | 3 | 36 | 18 | 36 | 29 |
| **Llefià** | **L10** | **32** | 62 | 194 | 0,2 | 37 | 15,5 | 2,9 | 10 | 1,3 | 15 | 17 | 103 | 41 | 70 | 14 |

The exact costs resulting from applying recommendations presented in this technical guide will depend on the detail of each subway system. The following Table 4 summarises the abatement measures involved in our proposals to improve subway air, and offers a qualitative approach to the relative costs and benefits involved.

***Table 4.*** Cost/benefit analysis of the proposed abatement measures to improve subway air concentrations.

| ABATEMENT MEASURES | | | BENEFIT | COST |
|---|---|---|---|---|
| **SOURCE REDUCTION** | **Indoor source:** Selected train components, avoiding known toxic compounds.<br>*Specific recommendations:*<br>· Brakes with the lowest percentage in antimony and copper.<br>· Graphite pantographs.<br>· Brushless motors. | | Lower passenger exposure to air pollution, associated with a reduced emission of toxic heavy metals. | Differential cost of alternative materials and supplies. |
| | **Outdoor source**: Selected location of new metro stations' ventilation grills, avoiding high traffic areas. | | Lower passenger exposure to air pollution, associated with a reduced entrance of outdoor $NO_2$, UFP and organic compounds. | |
| **SOURCE MANAGEMENT** | **Ventilation settings** | Forced ventilation at tunnels and platforms.<br>*Specific recommendations:*<br>· Impulsion of outdoor air at platforms during metro hours.<br>· Strong ventilation at platforms (> 25Hz).<br>· Ventilation at tunnels always connected during metro operating hours. | Lower passenger exposure to air pollution, associated with reduced PM concentrations. | Installation.<br>Maintenance.<br>Energy costs for equipment operation. |
| | | Air conditioning systems inside trains. | | |
| | **Air purifiers in platforms and trains** | | Lower passenger exposure to air pollution, associated with reduced PM concentrations (dependent on the distance to the passenger and flow rate). | Acquisition.<br>Installation.<br>Maintenance.<br>Energy costs for equipment operation. |
| | **Maintenance works.**<br>*Specific recommendations:*<br>· Timing of nocturnal maintenance works. They should be conducted as early in the night as possible.<br>· Use of dust suppressant when laying ballast. | | Increased passenger exposure to coarse particles averted.<br>Lowering early daytime platform $PM_{2.5}$ concentrations by at least 10%. | Cost of dust suppressant product (unless only water is used). |
| | **Platform Screen Doors (PSD)** | | Reduced exposure to tunnel - generated pollutants.<br>Passenger security. | Maintenance.<br>Energy costs for doors operation. |

The broad range of published $PM_{2.5}$ concentrations recorded on subway platforms from the Barcelona metro and other subway systems around the world are plotted on Figure 6 (see reference list in section 8). Of the > 100 data points, more than two-thirds lie below 75 µg $m^{-3}$, which coincides with the 24hr mean Interim Target Level 1 proposed by the World Health Organisation.

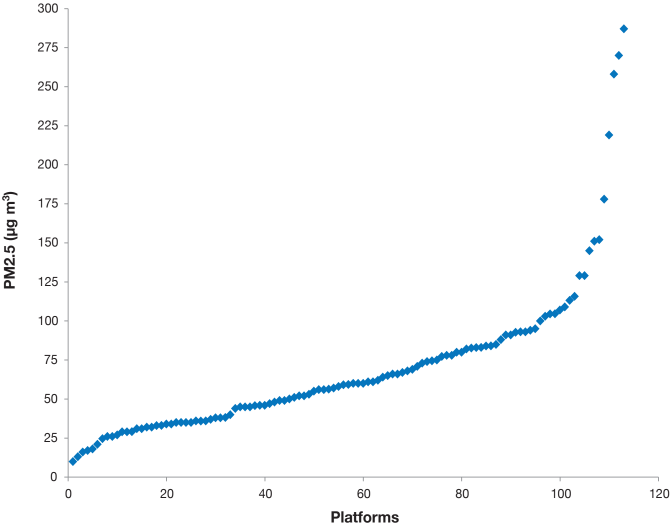


***Figure 6.*** Published $PM_{2.5}$ concentrations measured on platforms of subway systems around the world.

In an update of recommended air quality guidelines, the World Health Organisation has written: "Current scientific evidence indicates that guidelines cannot be proposed that will lead to complete protection against adverse health effects of particulate matter, as thresholds have not been identified. Rather, the standard-setting process needs to achieve the lowest concentrations possible in the context of local constraints, capabilities, and public health priorities.... Countries are encouraged to consider an increasingly stringent set of standards, tracking progress through emission reductions and declining concentrations of particulate matter" (WHO Regional Office for Europe, 2006).

In the context of subway air quality we therefore propose a targeted, colour-coded scheme based on WHO methodology and designed to encourage transport authorities to aim for progressive PM reductions on platforms (Figure 7). The method defines a series of thresholds that cascade down through bands of decreasing PM concentrations towards the WHO Annual Mean Air Quality Guideline of $PM_{2.5}$ levels of just 10 µg $m^{-3}$, which is the lowest annual mean levels at which total, cardiopulmonary and lung cancer mortality have been shown to increase (>95% confidence) in a wide ranging study by Pope et al. (2002).

> **We propose a targeted colour-coded framework with which to mark progress as underground pollution levels are reduced**

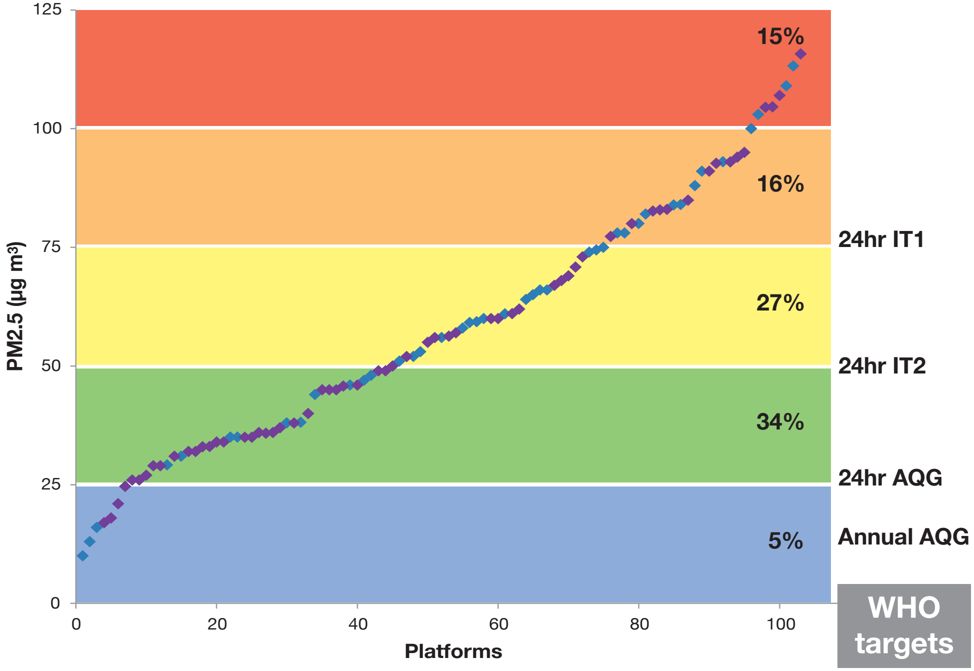


***Figure 7.*** Published mean PM$_{2.5}$ concentrations up to 125 µg m$^{-3}$ measured on platforms of subway systems around the world are plotted against a **colour-coded background aimed at encouraging the targeting of progressive improvements in air quality.** An initial Air Quality Audit will first ascertain where a given subway platform lies on this curve. For comparison, Level Yellow (75-50 µg m$^{-3}$) spans the concentrations lying between the World Health Organisation recommended 24-hour Mean Interim Targets 1 and 2 (24hrIT1 = 75 µg m$^{-3}$; 24hrIT2 = 50 µg m$^{-3}$ respectively). Level Green includes the WHO 24-hour Mean Interim Target 3 (24hrIT3 = 37.5 µg m$^{-3}$) and arrives at the 24-hour Mean Air Quality Guideline (24hrAQG = 25 µg m$^{-3}$), a level which also includes the WHO Interim Target 2 for annual mean concentrations of PM$_{2.5}$ (AnIT2). Level Blue includes the WHO Annual Mean Interim Target 3 (AnIT3 = 15 µg m$^{-3}$) and the WHO Annual Mean Air Quality Guideline (AnAQG = 10 µg m$^{-3}$). Percentages indicate the proportion of platforms (from a total of 114) within each PM range (60% of the platforms- coloured in purple- belong to the Barcelona subway system). Note that although the WHO IT and AQG recommendations initially included only outdoor air, the scope was later broadened “to be achieved everywhere in order to significantly reduce the adverse health effects of pollution” (WHO regional office for Europe, 2006).

For the most polluted subway stations, namely those with median levels of $PM_{2.5}$ higher than 100 µg $m^{-3}$ during train operating hours, the initial priority is to reach **Level Orange** ($PM_{2.5}$ 75-100 µg $m^{-3}$). This should be considered as a first step in an air quality improvement programme designed to reduce subway platform $PM_{2.5}$ concentrations below 75 µg $m^{-3}$ and thus enter the "Interim Target" (IT) levels set by the World Health Organisation. The colour-coded band marked as **Level Yellow** on Figure 7 corresponds to the $PM_{2.5}$ concentration range 50-75 µg $m^{-3}$, the limits to which are defined by the recommended WHO 24-hour Mean Interim Targets 1 and 2 (24hrIT1 = 75µg $m^{-3}$; 24hrIT2 = 50 µg $m^{-3}$). Although the WHO 2006 targets were developed with an initial focus on outdoor air, a recent report by this organisation makes it clear that they "relate to all environments" (WHO, 2017) and they are thus considered as equally appropriate for subways.

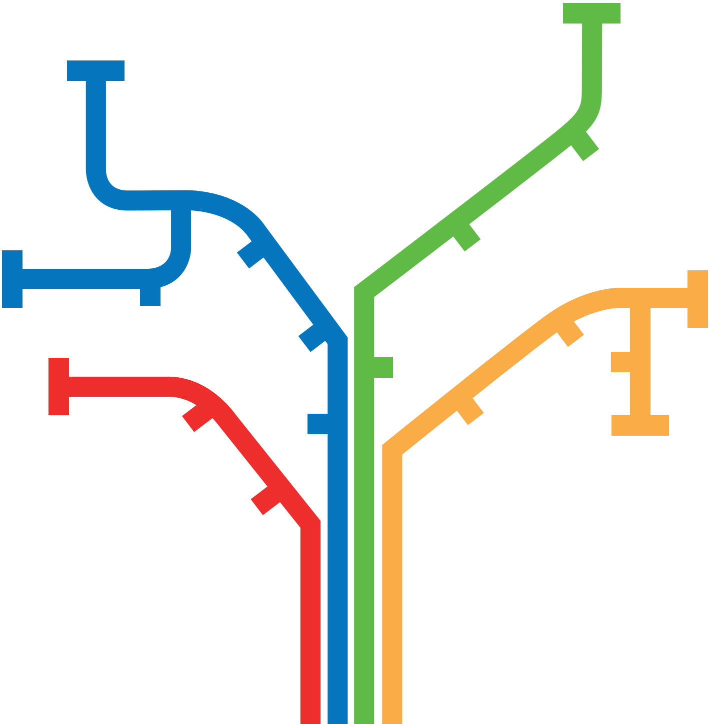
Further improvement of platform air quality by the application of the measures we have described in the preceding text would aim to move progressively from **Level Yellow** into **Level Green** ($PM_{2.5}$ 25-50 µg $m^{-3}$). The range defined by **Level Green** moves from WHO 24hrIT2 down through 24hrIT3 (37.5 µg $m^{-3}$) to reach the recommended WHO 24hr Air Quality Guideline target of 25 µg $m^{-3}$ (which coincides with the WHO annual mean Interim Target: AnIT2). Further reduction of ambient $PM_{2.5}$ mass concentration would bring air quality into **Level Blue** ($PM_{2.5}$ <25 µg $m^{-3}$), moving below the WHO 24hrAQG and towards the holy grail of $PM_{2.5}$ levels reaching just 10 µg $m^{-3}$ and the WHO annual mean AQG.

As demonstrated graphically by Figures 6 and 7 a wide range of $PM_{2.5}$ concentrations has been reported from subway platforms worldwide, and in many cases there is clearly much room for improvement. It is equally the case, however, that subway air can be clean, and that commuters would benefit from a proactive attitude to improving air quality underground.

We are confident that application of the air quality measures recommended in this document, using our colour-coded scheme presented in Figure 7 as a guideline with which to mark and compare progress, will successfully reduce underground pollution levels and improve city commuter health. Such improvements will involve financial outlay and political commitment, and will have to be judged in some cases against possible environmental costs such as increased $CO_2$ emissions. However, in many cases (particularly in the older subway systems) modernising, for example, the ventilation system will likely involve installing new machines that both improve air quality and are energetically more efficient. Similarly, the effects of installing platform screen doors, which not only improve passenger safety but also air quality, provide another example of how the results of an air quality audit underground can lead to synergistic improvements for the underground commuter. The case for improving subway air quality put forward in this document and the other IMPROVE LIFE reports is further strengthened by the rapidly growing body of published research work detailed in the reference list below.

Finally, as outdoor city air is improved by the phasing-out of diesel and petrol cars in favour of hybrid and all-electric vehicles, so the issue of subway air quality is likely to assume a higher priority in public awareness. As stated at the beginning of this report, the number of people who use the subway worldwide is huge and growing. Already all the “top ten” busiest subways in the world (Beijing, Shanghai, Tokyo, Seoul, Guangzhou, Moscow, New York, Hong Kong, Mexico City and Paris) each carry well over 1 billion people annually. In China alone more than ten new metro systems are currently under construction, with another forty or so at the planning stage. In comparison the Barcelona Metro operated by TMB carries “only” around 416 million people per year and is the eighth busiest subway in Western Europe. Despite its relatively small size, however, it has proved itself to be a pioneer in air quality by enabling the IMPROVE LIFE project to generate the largest publicly accessible physicochemical database on subway air quality currently available. The challenges and opportunities revealed by this database are directly applicable not only to the Barcelona Metro but to all subway systems worldwide.

# CLEANER SUBWAY AIR MEANS HEALTHIER AND HAPPIER COMMUTERS: IT IS WORTH THE EFFORT



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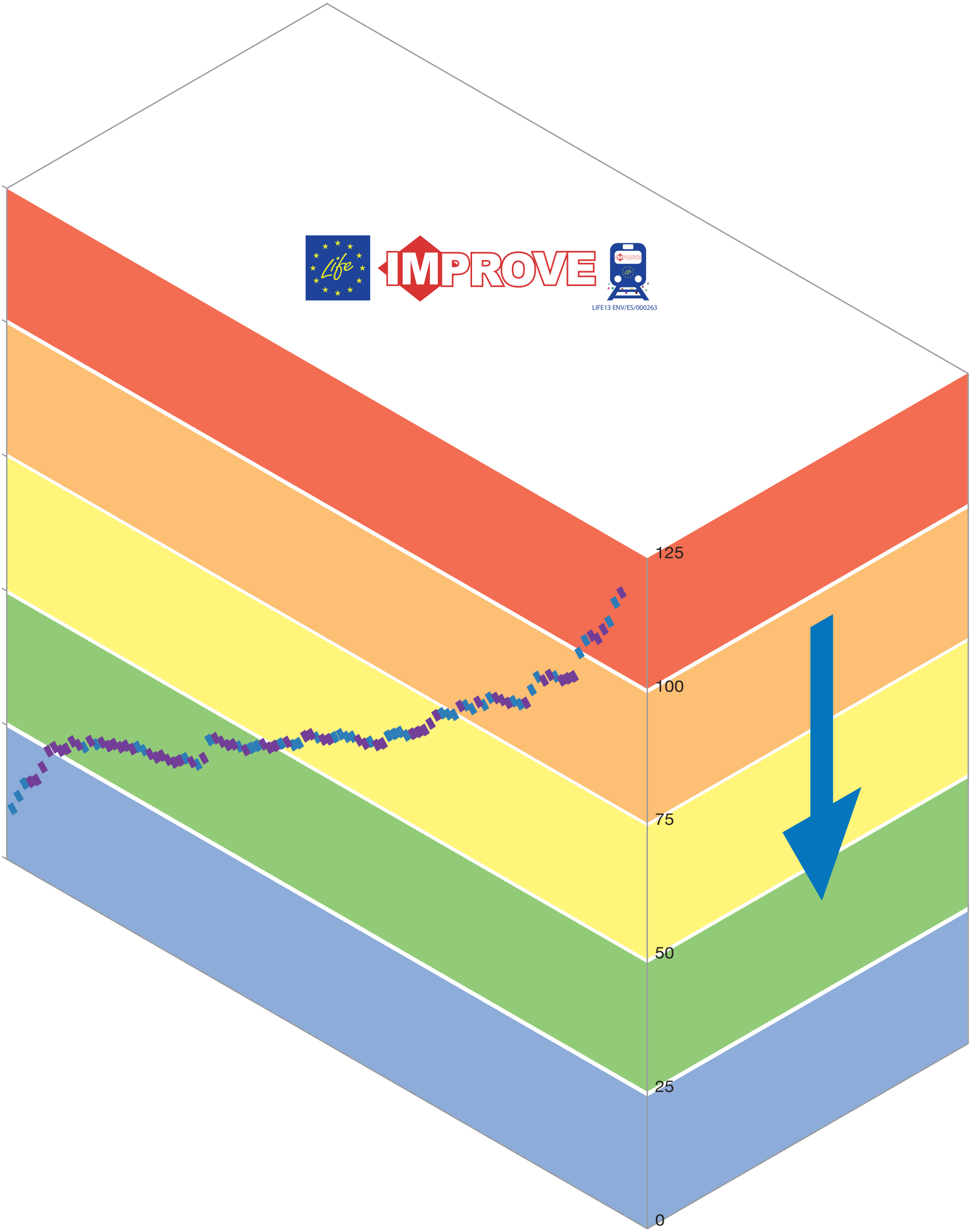
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