AIR QUALITY MITIGATION MEASURES IN THE SUBWAY ENVIRONMENT

IMPROVE

LIFE13 ENV/ES/000263

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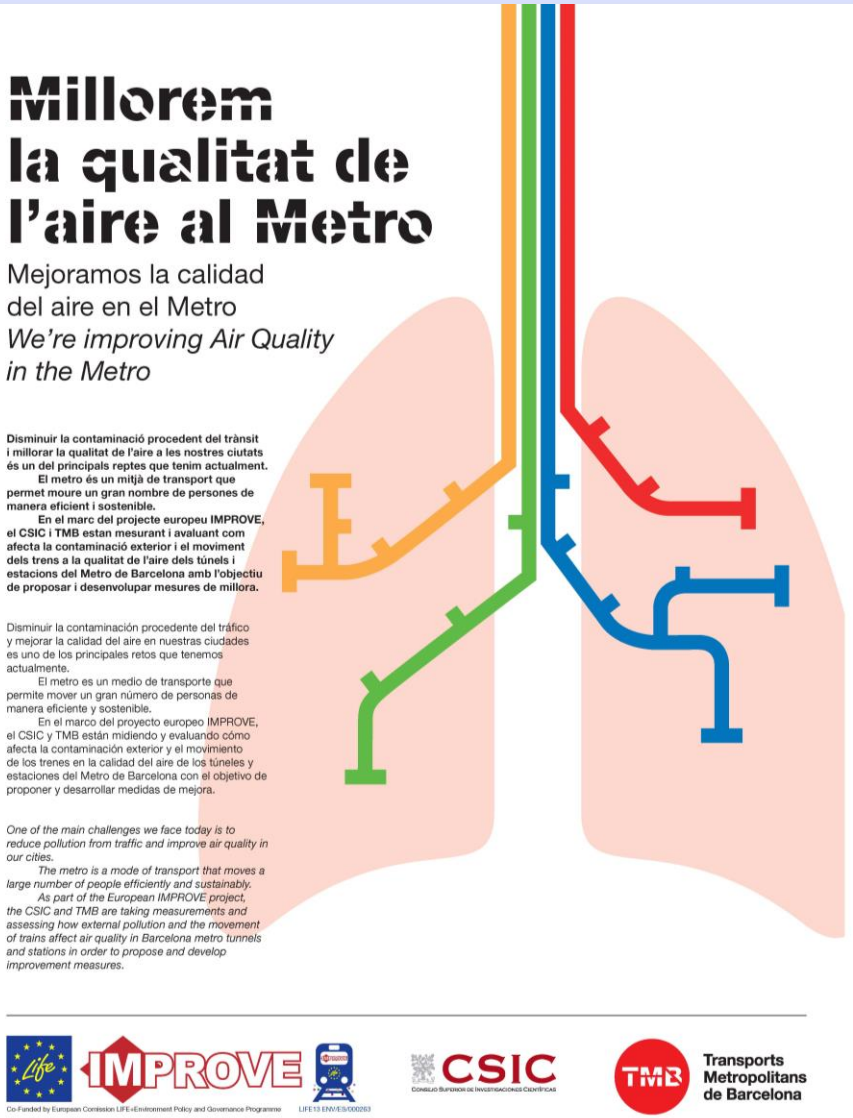
Implementing Methodologies and Practices to Reduce air pollution Of the subway enVironmEnt

01/10/2014 - 31/03/2018

The **objective** of the project is to provide to the transport authorities the appropriate measures and strategies to reduce concentrations of inhalable particulate matter (PM1, PM2.5 and PM10) and identify distinctive chemical components in underground rail air.



THE QUESTION OF AIR QUALITY IN UNDERGROUND SYSTEMS IS NOT TRIVIAL

- ✓ Underground subway systems worldwide transport > 100 million people daily.
- ✓ Ambient PM10 concentrations on platforms can be >> 50 µg/m³.
- ✓ Subway PM is extremely metalliferous and very different in chemistry from outside ambient air.

TUNNEL AND RAIL TRACK MAINTENANCE WORK ACTIVITIES

VENTILATION PROTOCOLS

AIR INFILTRATION FROM OUTSIDE

WEAR OF TRAIN MATERIALS

STATION DESIGN

HOW TO IMPROVE SUBWAY AIR QUALITY?

TUNNEL AND RAIL TRACK MAINTENANCE WORK ACTIVITIES

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 at night when the trains stop running.

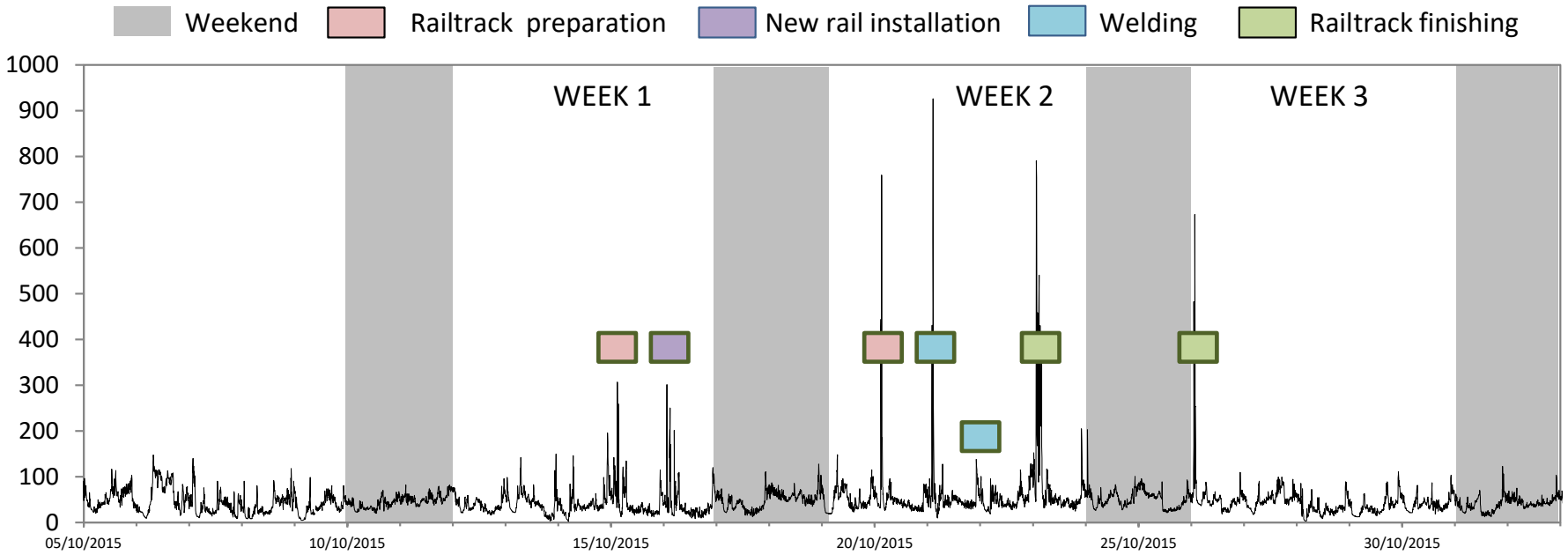
Sagrera: median daytime platform $PM_{2.5}$ concentrations of 36 µg m^{-3} dropped to 21 µg m^{-3} (weekday hours of 00.00-05.00).

✓A common exception to this general rule is when underground air quality is influenced by track maintenance work.

TUNNEL AND RAIL TRACK MAINTENANCE WORK ACTIVITIES

The night-time polluting effect of track maintenance activities

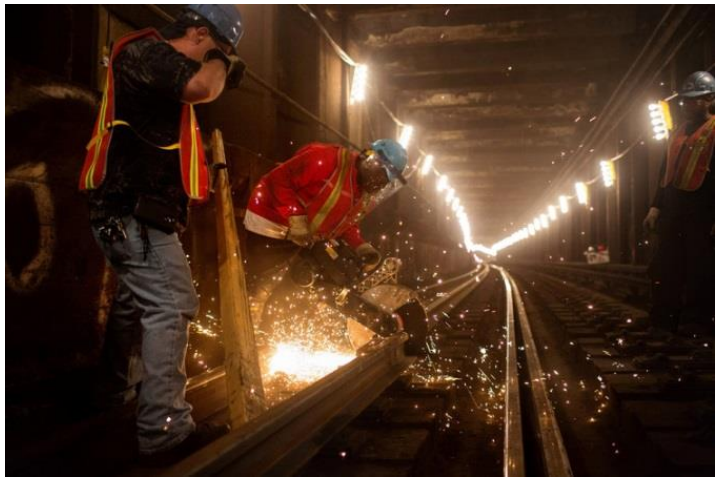
Night maintenance works typically produced an increase in $PM_{2.5}$, which in extreme cases can reach > 1000 µg m^{-3} (5-minute value) when adding new ballast, > 900 µg m^{-3} when doing welding operations or > 800 µg m^{-3} when heavy vehicles transporting material pass the station.



TUNNEL AND RAIL TRACK MAINTENANCE WORK ACTIVITIES

The daytime polluting effect of track maintenance activities

A key factor influencing morning platform PM levels is the **timing** of any high PM peaks during the night. The closer the peaks are to subway opening hours, the less time airborne particles will have to be diluted. Thus it is preferable to minimise dust generation later in the night.



PM2,5 (µg m^{-3})	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

TUNNEL AND RAIL TRACK MAINTENANCE WORK ACTIVITIES

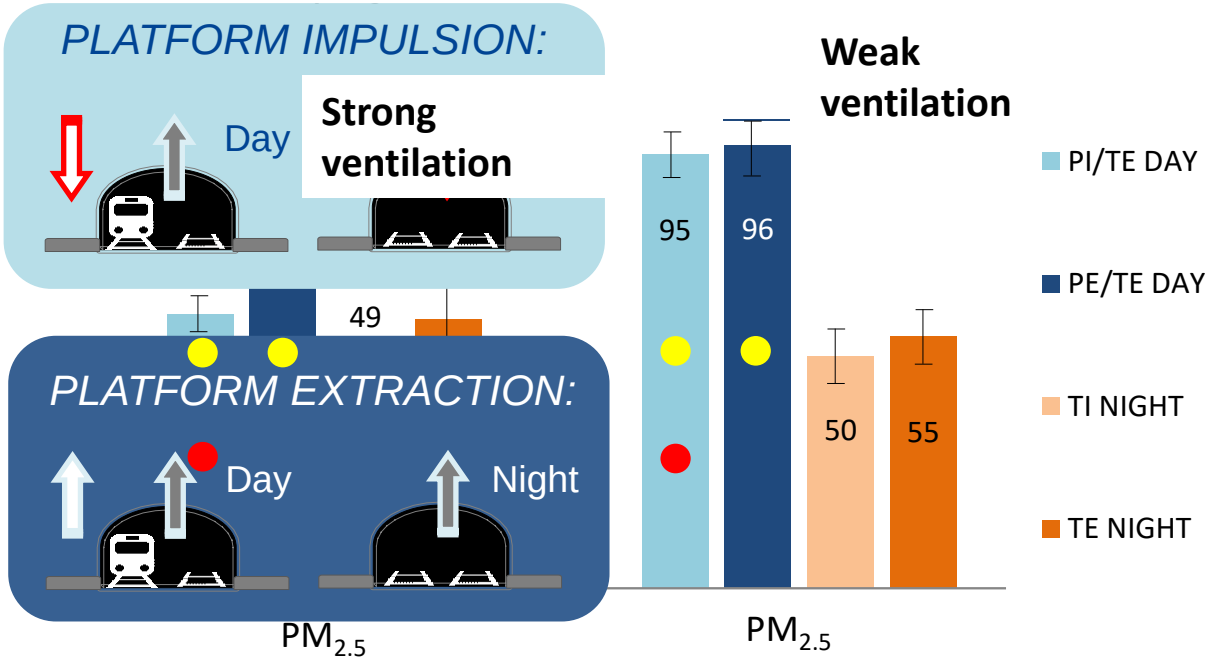
The use of dust suppressants

Using dust suppressants can produce a reduction of up to 50% in night-time dust levels during ballast laying and tamping. This translates to a lowering of early daytime platform $PM_{2.5}$ concentrations depending on when and where the work takes place.

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 distinctively “crustal” chemical signature.

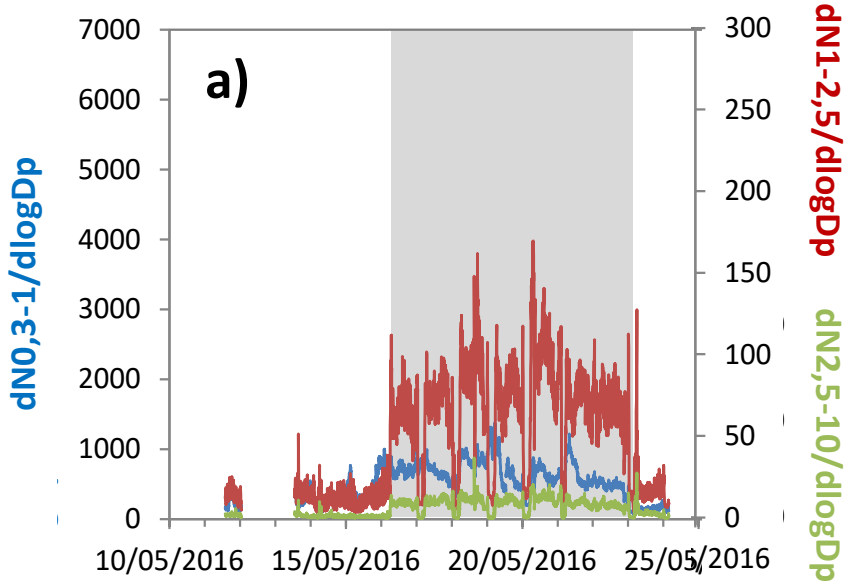
Platform air impulsion versus extraction

Platform air quality can be significantly affected by **both the direction and intensity of fan air flow.** Faster fan impulsion of outdoor air into the platform produces cleaner air by diluting ambient levels of subway particles. Changing ventilation air flow from impulsion to extraction is not a strategy likely to improve air quality on the platform.



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.



	NIGHT (00-05:00)				DAY (05-24:00)			
	Mean	Median	SD	Max	Mean	Median	SD	Max
Normal ventilation (operational platform)	22	17	17	157	26	22	16	290
Tunnel ventilation off	43	38	30	297	61	59	15	127

Platform Air Purifiers

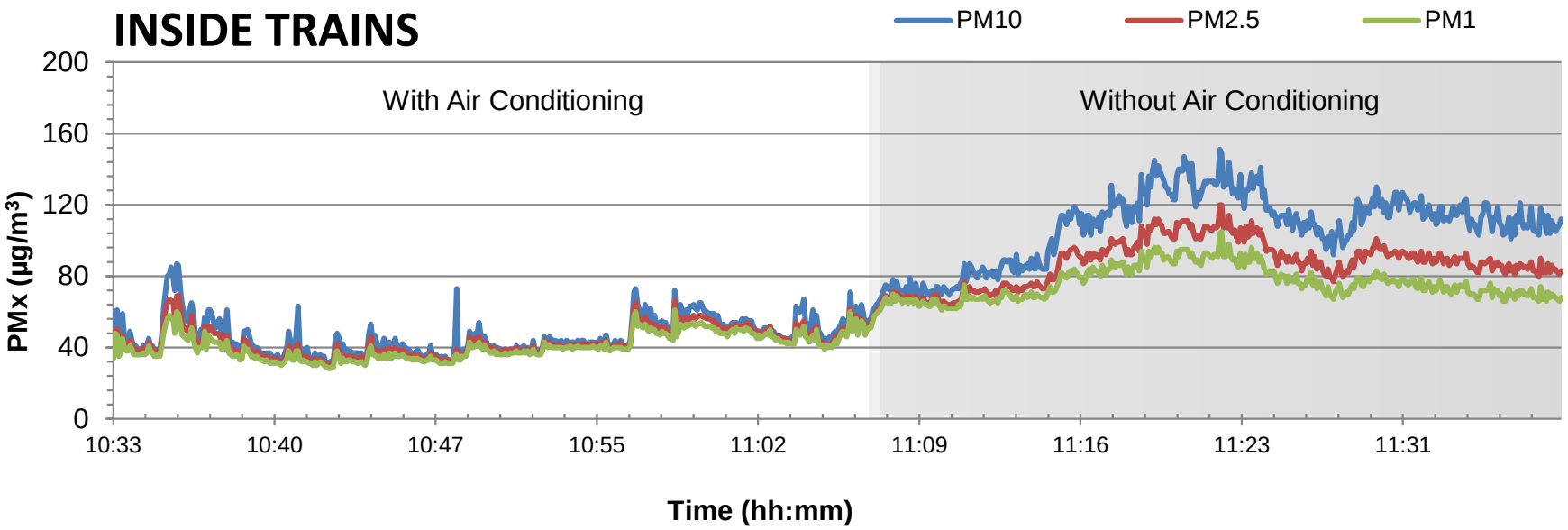
Platform air purifiers have the potential for improving subway air quality but they are still in R&D phase. The best result in terms of air quality improvement occurred during operational hours when the purifier was placed **close to the measuring equipment.**

AIR PURIFIER A	NIGHT (00-05:00)				DAY (05-24:00)			
	Mean	Median	SD	Max	Mean	Median	SD	Max
Previous conditions without purifier (10/3/16)	45	38	26	176	88	92	17	125
Air purifier at end of platform (next to equipments)	49	42	29	240	61	60	16	148
Next week without air purifier	53	64	21	125	83	82	18	154
Previous conditions without purifier (25/4/16)	70	59	43	253	94	92	15	135
Air purifier at middle of platform (45 m away)	53	49	24	141	84	86	22	194
Next week without air purifier	58	56	25	141	91	92	20	172

✓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.

Air quality inside subway trains

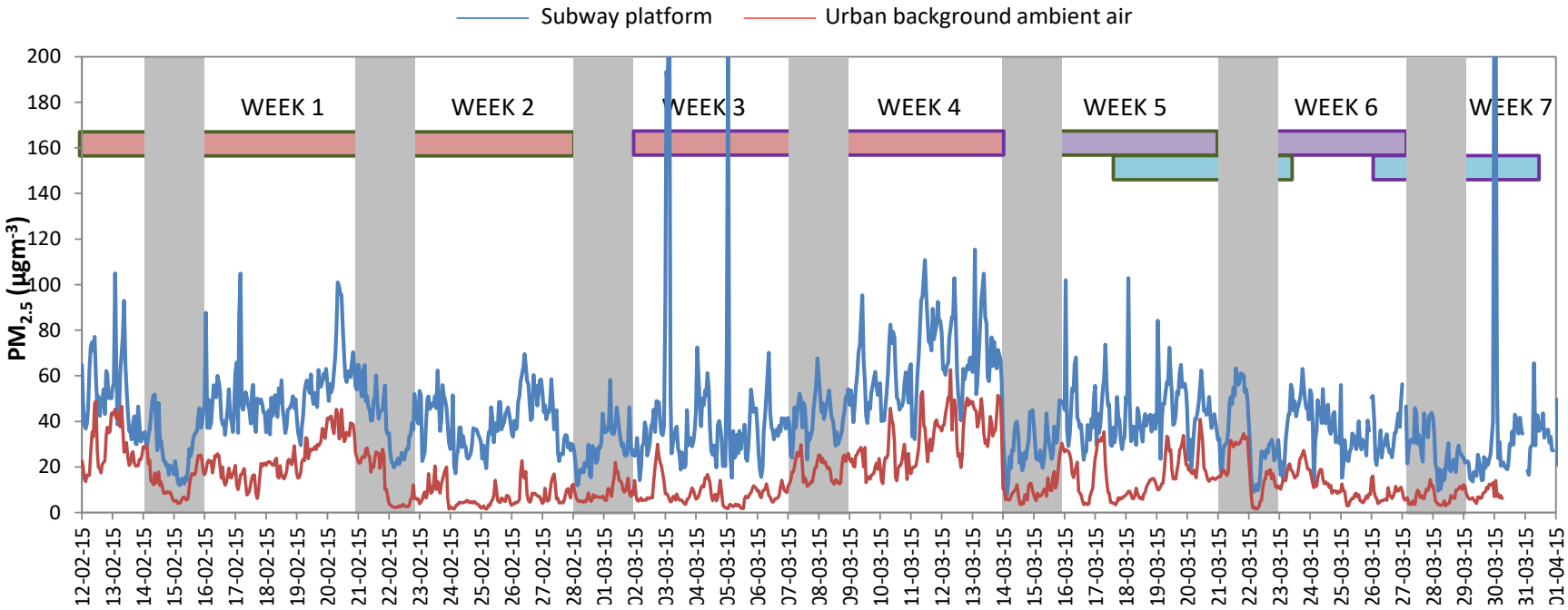
Air quality inside trains in the Barcelona subway system is always better than on platforms. One reason for this is that Barcelona subway trains travel using **air conditioning** within a closed system that does not allow open windows. Air conditioning has a clear beneficial effect on air quality inside the trains.



Martins et al. 2015

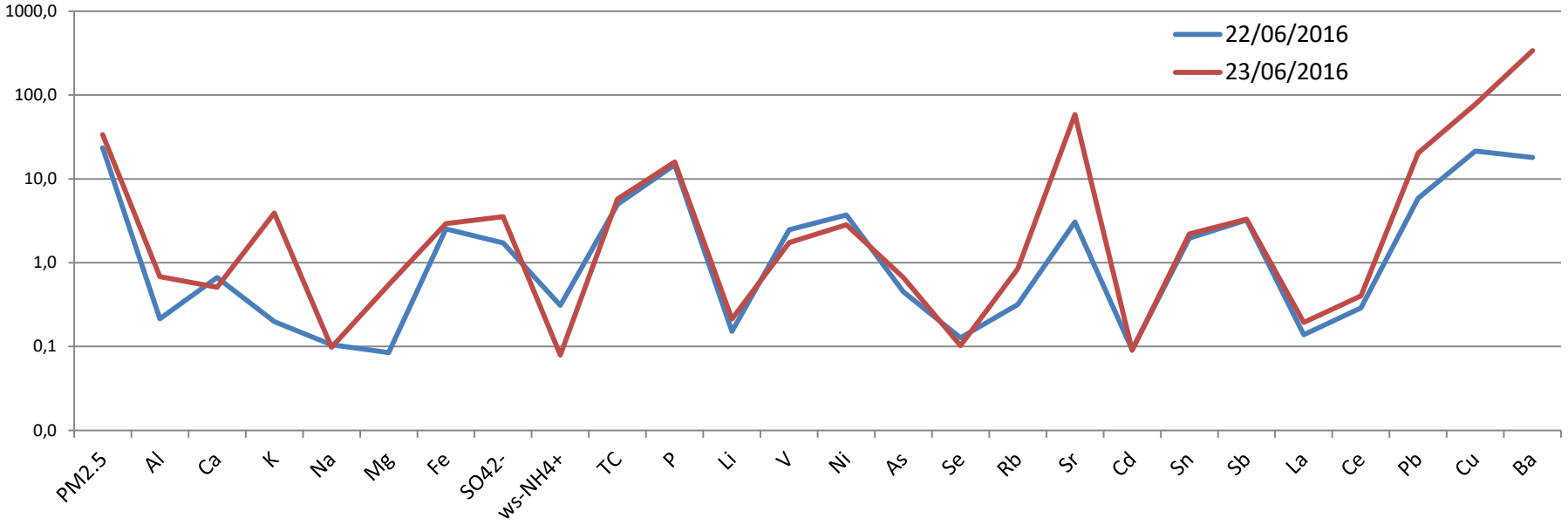
AIR INFILTRATION FROM OUTSIDE

The air quality on subway platforms can be markedly **influenced by outdoor city air quality**, especially during the arrival into the city of far-travelled pollution clouds such as anthropogenic SIC intrusions and North African desert dust events (>20 µg$PM_{2.5}$ m^{-3}, Sagrera). Similarly the arrival of a clean atmospheric advection event (northwest from the Atlantic) can result <20 µg$PM_{2.5}$ m^{-3} (Palau Reial).



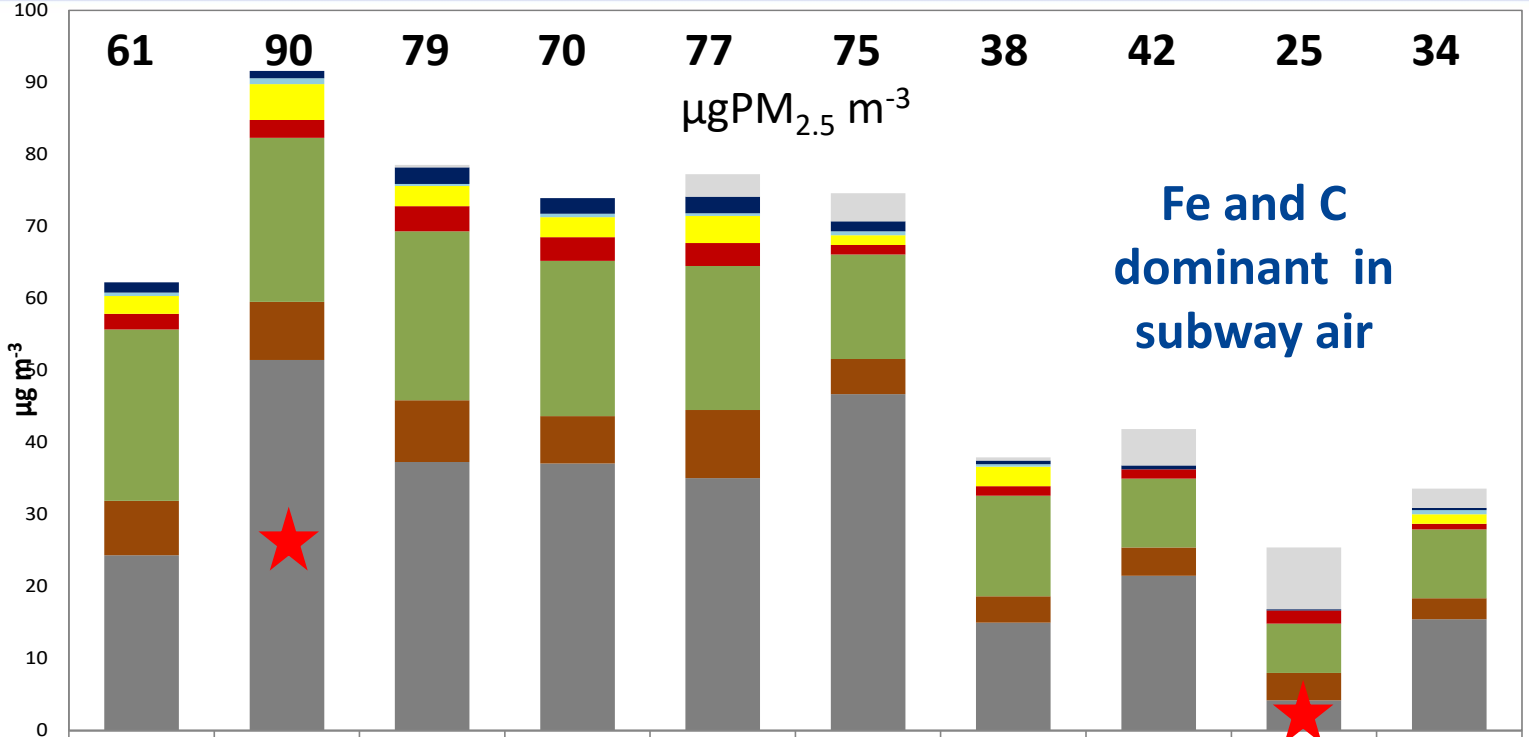
AIR INFILTRATION FROM OUTSIDE

A spectacular example of a subway system contaminated by an outdoor fireworks event is provided by the data for the San Juan festival on 23-24 June when levels of Ba suddenly rose from 18 to 338 ng m^{-3}, Sr from 3 to 59 ng m^{-3}, and K from 0.2-3.9 µg m^{-3}. This dramatic rise was accompanied by increases in Mg, Rb, As, Pb, Bi and Cu, all also known to be characteristic of firework emissions.



WEAR OF TRAIN MATERIALS

Why subway air is different from that breathed above ground

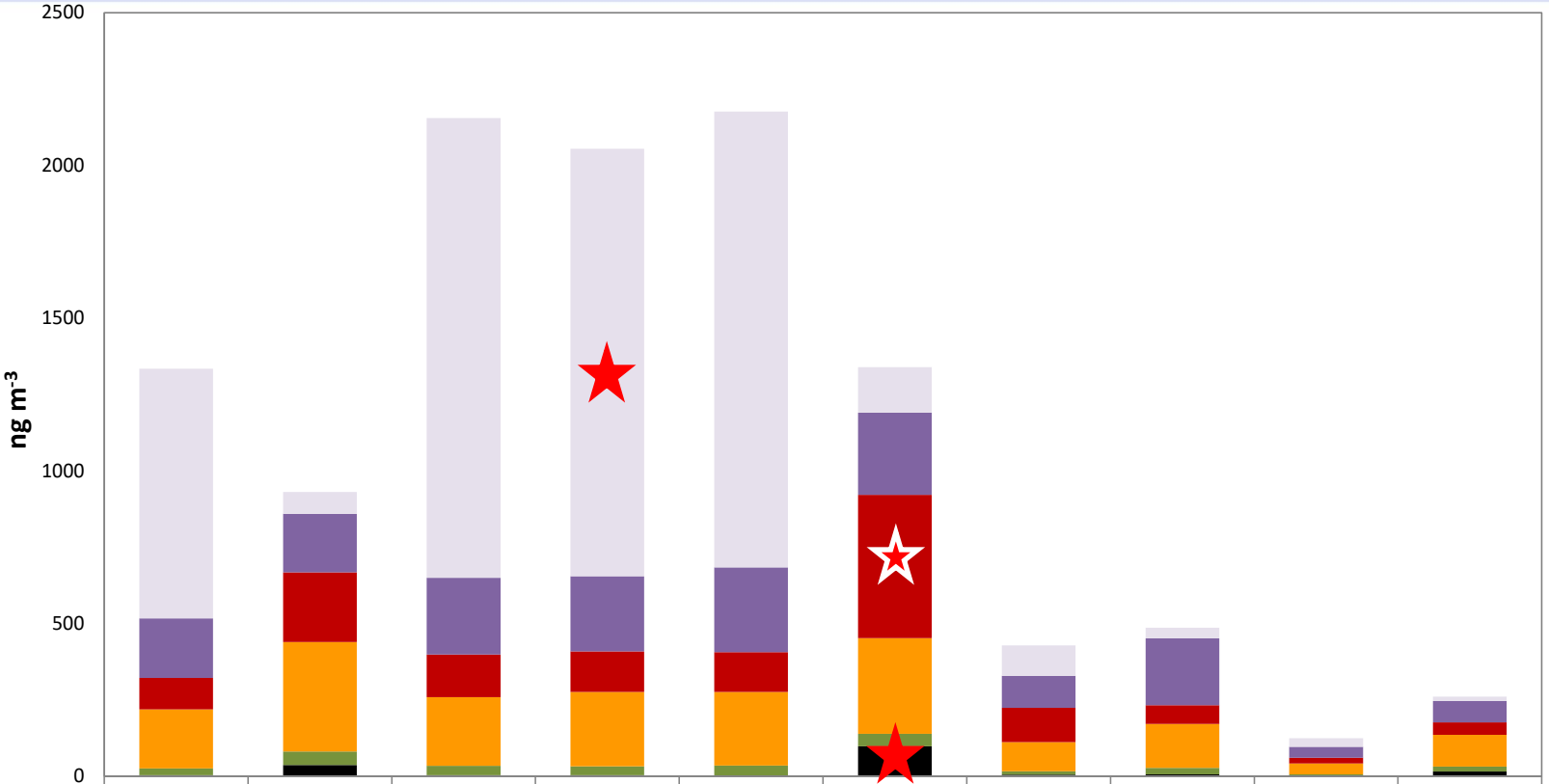


	Santa Coloma L1	Tetuan L2	Palau Reial L3	Maria Cristina L3	Tarragona L3	Joanic L4	Sagrera L5	Sant Ildefons L5	Collblanc L9	Llefia L10
Not determined			0,4		3,1	3,9	0,4	5,0	8,6	2,7
Trace elements	1,4	1,0	2,3	2,2	2,3	1,4	0,5	0,6	0,2	0,3
Na+Cl	0,5	0,8	0,3	0,5	0,4	0,5	0,3			0,6
SIC	2,5	5,0	2,8	2,8	3,8	1,4	2,7			1,3
Insoluble SO42-	2,2	2,5	3,5	3,3	3,2	1,3	1,3	1,3	1,8	0,8
CA	23,8	22,8	23,5	21,5	20,0	14,5	14,0	9,5	6,9	9,6
Crustal	7,5	8,1	8,6	6,6	9,4	4,9	3,7	3,9	3,8	2,9
Fe2O3	24,4	51,5	37,3	37,1	35,1	46,7	15,0	21,5	4,2	15,5

> 500 $PM_{2.5}$ filters analysed

WEAR OF TRAIN MATERIALS

But not all subway air is necessarily chemically the same



	Santa Coloma	Tetuan	Palau Reial	Maria Cristina	Tarragona	Joanic	Sagrera	Sant Ildefons	Collblanc	Llefia
	L1	L2		L3		L4	L5		L9	L10
Ba	817	72	1505	1400	1493	149	99	35	29	14
Zn	195	191	251	246	277	268	105	218	36	70
Cu	103	228	140	133	130	469	112	61	18	41
Mn	193	358	225	244	241	314	96	145	36	103
Cr	22	45	31	29	32	41	11	21	3	17
Sb	3,4	36,4	2,8	3,1	2,4	97,4	4,7	5,4	2,3	14,8

WEAR OF TRAIN MATERIALS

But not all subway air is necessarily chemically the same

	Ballast	Catenary	Brush.	Pant. 1	Pant. 2	Pant. 3	Brake1	Brake2	Brake3	Brake4	Rail1	Rail2	Wheel0	Wheel1	Wheel2	Wheel3	Wheel4	Wheel5
									%									
C	<0.1	<0.1	95	35	79	70	25	29	39	27	0.7	0.8	0.5	0.5	0.5	0.5	0.5	0.5
									ppm									
Al	83008	<0.1	0.03		719		816	544	26116	10346	11	15	0.1					
Ba	591	10	28	7	85	136	17199	14206	32988	373			0.1					
Ca	23491	<0.1	0	1318	1207	1026	24216	22013	38472	55577			0.1					
Cu	35	950000	1000	66056	197104	197852	77766	112119	124	212	170	160	1000	70	1960	1410	280	400
Fe	29705	9000	3000	277	1353	529	333500	369480	19119	422672	979730	979595	980000	983570	981840	982500	984130	984770
K	29221	<0.1	<0.1				83		2549				<0.1					
Mg	9783	<0.1	<0.1		272		23377	20377	47579	10385			<0.1					
Na	21952				1064		265	304	4454	1863								
P	589	<0.1	<0.1				873		437		165	150	<0.1					
S	163	<0.1	<0.1	1970	3178	2848	26442	22234	15506	19393	99	110	<0.1					
Li	28								9	1								
Sc	8								4	1								
Ti	2716	53	28	18	43	13	36	15	1937	625	13	30	10					
V	61	17	1	65	18	174	4	3	42	32	10	15	15	20	20	20	10	20
Cr	76	131	22	1.0	18	6	159	138	98	171	175	300	1173	2300	2210	2130	2430	2200
Mn	646	40	1	4	16	6	2615	1793	672	3326	10750	11300	7000	7400	7250	7290	7540	7300
Co	5	1	<0.1	1	1	4	17	12	9	10	<0.1		80					
Ni	39	54	9	67	20	193	103	169	18	51	181	210	782	1400	1270	1250	340	400
Zn	61	102	115	6	122	33	67279	95462	10161	32922			6					
As	2.1	3	<0.1		3	1.1	29	22	3	16.3			51					
Se		1	<0.1	1.5	1.4		2	3	1	2			<0.1					
Rb	112						1		9	2								
Sr	160	4	1.7	3	5	5	306	288	1210	67			<0.1					
Zr	35	1	<0.1	1	1.1		1		52	19			<0.1					
Mo	7	3	2.4	1	5	4	65	34	521	2629	10	10	451	440	550	500	470	110
Cd							1	4	0.6	2.5								
Sn	3	1	15	2	3	3	10	30	16	130	10	20	95					
Sb		12	5		30	6	3879	1947	30	15	10	25	24					
La	20						1		10	3								
Ce	43						1		20	6								
Pb	17	2	4.2	7	9	13	453	3407	7	20			<0.1					
Bi							1	9	19	5								

WEAR OF TRAIN MATERIALS

But not all subway air is necessarily chemically the same

	L1	L2	L3	L4	L5	L9	L10	L11
Brake 1		100		38		100	100	
Brake 2				62				100
Brake 3	71		80					
Brake 4	29		20		100			

	L1	L2	L3	L4	L5	L9	L10	L11
Pantograph Cu				33				
Pantograph graphite 1	71		80	33				100
Pantograph graphite 2		100		34		100	100	
Pantograph graphite 3	29		20		100			

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ANALYSIS OF BRAKE PAD WEAR

The contribution of train BRAKE particles to subway air

Brakes	71% B3; 29% B4	100% B1	80% B3; 20% B4			38% B1; 62% B2	100% B4			
Brushes	71% trains	--	80% trains			---	---			
Pantog.	71%P1, 29% P3	100% P2	80% P1, 20% P3			37% P2, 33% P1	100% P3		100% P2	
	L1	**L2**	**L3**			**L4**	**L5**		**L9**	**L10**
	STA COLOMA	**TETUAN**	**PALAU REIAL**	**MARIA CRISTINA**	**TARRAGONA**	**JOANIC**	**SAGRERA**	**SANT ILDEFONS**	**COLLBLANC**	**LLEFIÀ**
µg/m^3										
TC	17	16	17	15	14	10	10	7	5	7
SO_4^{2-}	2.2	2.5	3.5	3.3	3.2	1.3	1.3	1.3	1.8	0.8
Fe_2O_3	24	51	37	37	35	47	15	22	4	15
Al_2O_3	0.8	0.6	1.2	0.9	1.2	0.6	0.4	0.5	0.4	0.2
K_2O	0.3	0.6	0.3	0.2	0.3	0.3	0.3	0.3	0.8	0.2
Ca	1.5	1.8	1.0	0.9	1.4	0.8	0.6	0.6	0.8	0.7
Mg	0.4	0.3	0.6	0.5	0.6	0.2	0.1	0.1	0.1	0.1
Na	0.2	0.3	0.3	0.2	0.3	0.2	0.1	0.2	0.2	0.2
ng/m^3										
Ba	817	72	1505	1400	1493	149	99	35	11	14
Cu	103	228	140	133	130	469	112	61	16	41
Mn	193	358	225	244	241	314	96	145	33	103
Zn	195	191	251	246	277	268				
Cr	22	45	31	29	32	41				
V	4.6	5.3	5.6	3.2	5.0	3.5				
Co	1.1	1.5	1.9	1.6	1.6	1.9				
Ni	10.2	6.7	18.0	16.0	16.9	11.5				
As	1.5	1.9	1.7	1.5	2.0	2.7				
Rb	0.8	1.2	0.9	0.7	0.9	0.7				
Sr	18.7	8.4	39.6	36.1	41.5	4.2				
Zr	6.5	18.3	18.8	17.5	15.3	9.0				
Cd	0.2	0.3	0.2	0.1	0.2	0.2				
Sn	8.0	9.6	9.7	9.2	8.3	8.1				
Sb	3.4	36.4	2.8	3.1	2.4	97.4				
Pb	10.7	11.3	8.4	7.9	7.2	12.8				
Bi	0.9	0.5	0.3	0.3	0.3	0.2				
La	0.5	0.5	0.6	0.3	0.6	0.6				
Ce	1.0	1.1	1.1	0.7	1.1	1.2				

Ba-rich brakes contaminate subway air with Ba, Sr, Zr and Ti, whereas Sb-rich brakes produce enrichments in ambient Sb (40 times higher than in stations of other lines). Cu content of platform PM2.5 can also be traced in part to brake emissions.

Where brakes are used more, concentrations of these elements increase (e.g. 50% more Ba in L3 using same components as L1).

The contribution of train WHEEL particles to subway air

Brake	71% B3; 29% B4	100% B1	80% B3; 20% B4			38% B1; 62% B2	100% B4			
Brushes	71% trains	--	80% trains			---	---			
Pantog.	71%P1, 29% P3	100% P2	80% P1, 20% P3			37% P2, 33% P1	100% P3		100% P2	
	L1	**L2**	**L3**			**L4**	**L5**		**L9**	**L10**
	STA COLOMA	**TETUAN**	**PALAU REIAL**	**MARIA CRISTINA**	**TARRAGONA**	**JOANIC**	**SAGRERA**	**SANT ILDEFONS**	**COLLBLANC**	**LLEFIÀ**
µg/m³										
TC	17	16	17	15	14	10	10	7	5	7
SO_4^{2-}	2.2	2.5	3.5	3.3	3.2	1.3	1.3	1.3	1.8	0.8
Fe_2O_3	24	51	37	37	35	47	15	22	4	15
Al_2O_3	0.8	0.6	1.2	0.9	1.2	0.6	0.4	0.5	0.4	0.2
K_2O	0.3	0.6	0.3	0.2	0.3	0.3	0.3	0.3	0.8	0.2
Ca	1.5	1.8	1.0	0.9	1.4	0.8	0.6	0.6	0.8	0.7
Mg	0.4	0.3	0.6	0.5	0.6	0.2	0.1	0.1	0.1	0.1
Na										
ng/m³										
Ba										
Cu										
Mn										
Zn										
Cr										
V										
Co										
Ni										
As										
Rb										
Sr										
Zr										
Cd										
Sn										
Sb										
Pb										
Bi	0.9	0.5	0.3	0.3	0.3	0.2	0.5	0.4	0.1	0.6
La	0.5	0.5	0.6	0.3	0.6	0.6	0.5	0.4	0.2	0.2
Ce	1.0	1.1	1.1	0.7	1.1	1.2	1.2	0.7	0.3	0.4

Iron is the classic "subway metal", it 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% .

Cr/Fe = 0.0012 for train wheels and Cr/Fe = 0.0010-0.0015 for the ambient air in all subway lines, suggesting that much of the Cr, and therefore also Fe, present in platform PM2.5 is sourced from train wheels.

The considerable differences in measured subway FePM2.5 between stations is strongly related to how much tunnel air contaminated with rail FePM is entering the platform.

STATION DESIGN

The subway stations likely to have the **worst air quality** will be those with limited air volume, weak or inappropriately designed ventilation systems, a lack of PSDs, a topography that involves elevation changes, 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 (…not sourcing from traffic hotspots), with full length PSDs, and with a straight, horizontal trajectory that minimises brake and wheel wear.

In Barcelona the worst lines can have platform PM2.5 levels above 80 μg m^{-3}, whereas the newer lines with PSD have ambient levels below 35 μg m^{-3}.

HOW TO IMPROVE SUBWAY AIR QUALITY?

1 Recognise the problem and that improvement is possible

- ✓ Air quality inside underground rail systems is not included in legislation designed to clean up city air:

  outdoor air annual average of 25 µgPM2,5 m^{-3} (2008/50/EC, RD 102/2011)

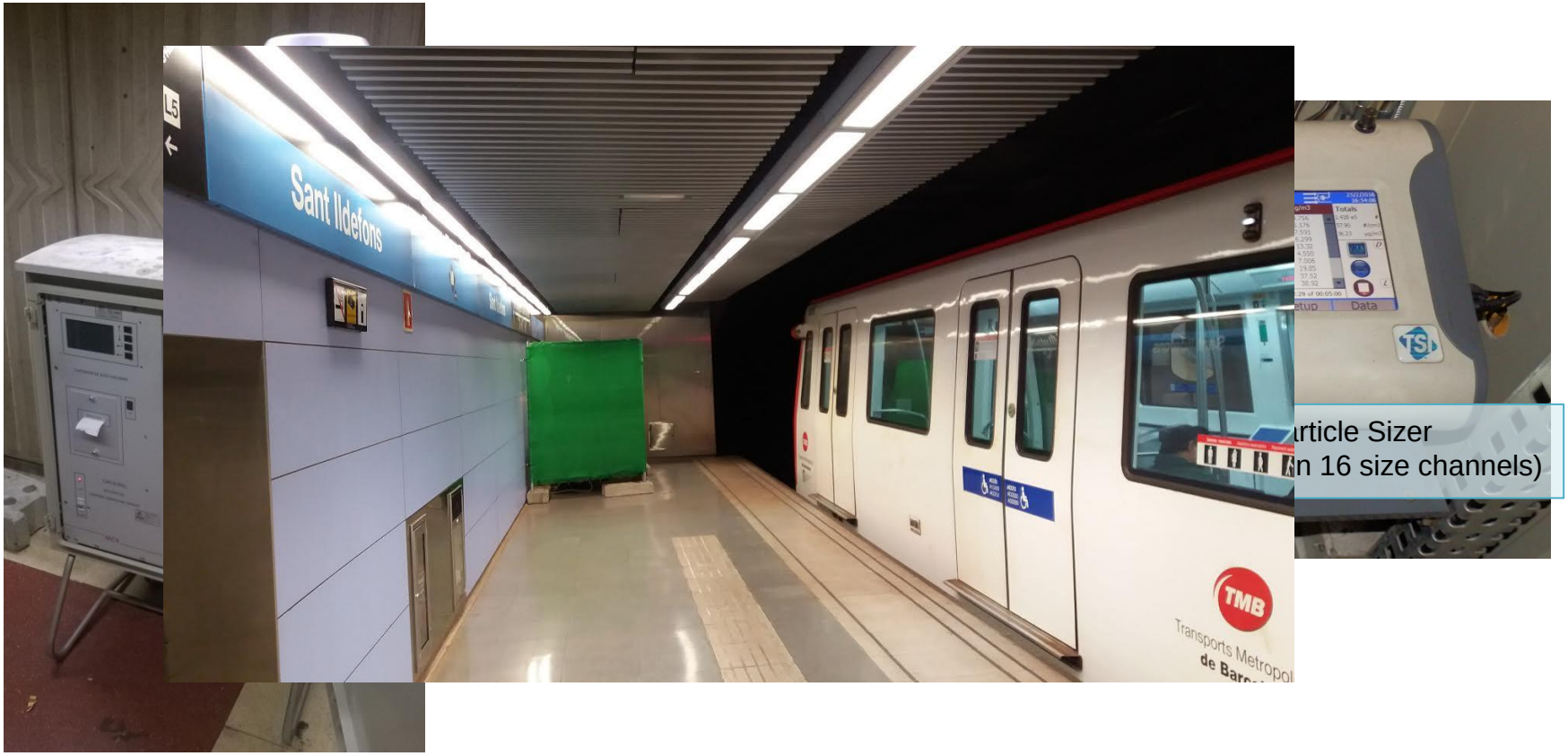
  35 to 10 µg m^{-3} (WHO)

- ✓ Many subway stations have PM2.5 levels higher than the legislated limits demanded for outdoor air…. BUT **subway stations can be remarkably clean** (25 µg m^{-3} Collblanc L9S), proving that it is perfectly possible to breathe good air even in the confined space of an underground train network.

HOW TO IMPROVE SUBWAY AIR QUALITY?

2 Commit to an Air Quality Audit for each subway line

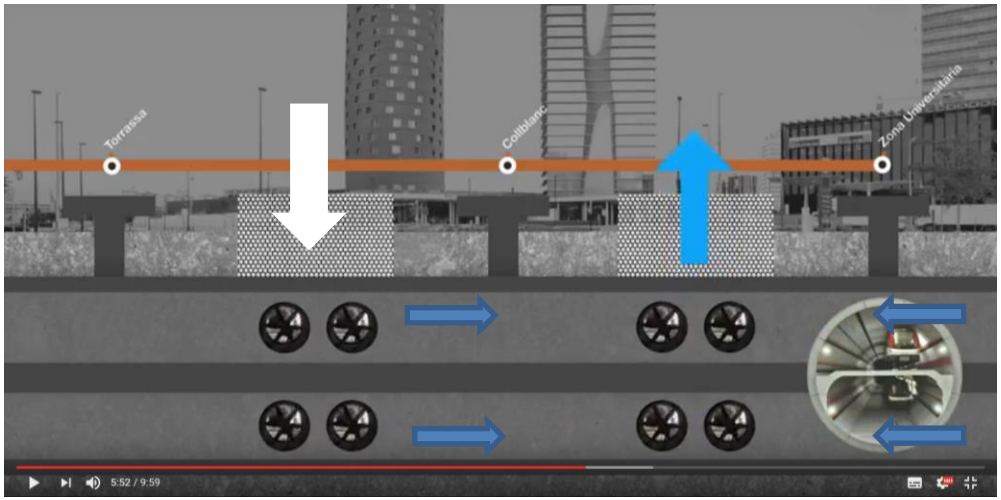
The audit will assess existing air quality on platforms and trains.



HOW TO IMPROVE SUBWAY AIR QUALITY?

3 Review the ventilation system

Outdated fan ventilation systems should be replaced by new, more efficient and intelligent designs that minimise the movement of air from tunnels into platforms. Ideally ventilation inlets should be raised above ground to lessen the inflow of traffic-contaminated air, and be capable of responding to exceptional outdoor pollution events. Consider the use of air purifiers on platforms.



HOW TO IMPROVE SUBWAY AIR QUALITY?

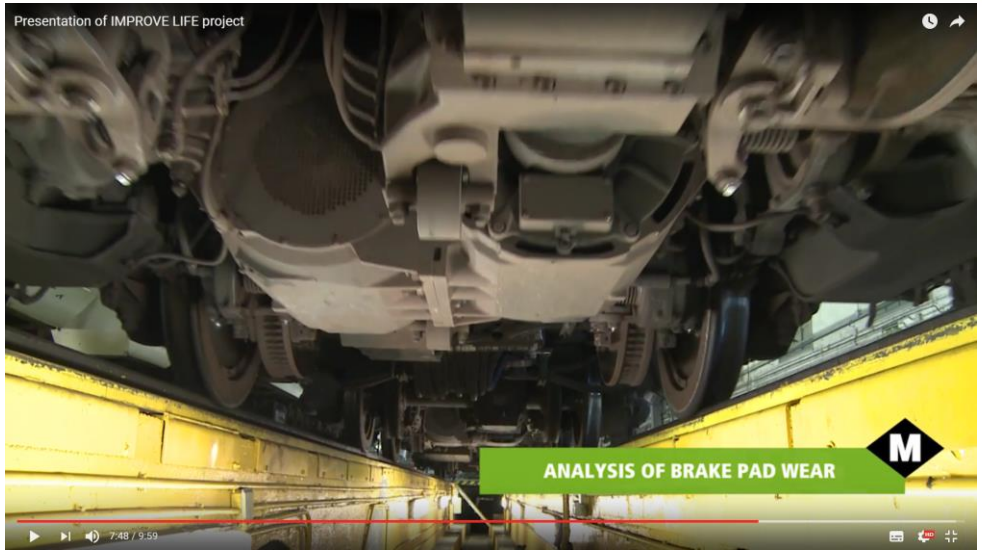
4 Reduce fugitive dust emissions underground

Introduce protocols designed to reduce fugitive dust emissions within the underground system, e.g. worker awareness and use of suppressants for ballast laying.

HOW TO IMPROVE SUBWAY AIR QUALITY?

5 Choose non-toxic materials and try to reduce train emissions

Move towards the **use of non-toxic materials** for moving parts (e.g. Sb in brakes: is it really necessary?), and introducing measures to **reduce brake and wheel wear** e.g. slowing down the speed of trains in places on lines where there are sharp curves and high gradients.



HOW TO IMPROVE SUBWAY AIR QUALITY?

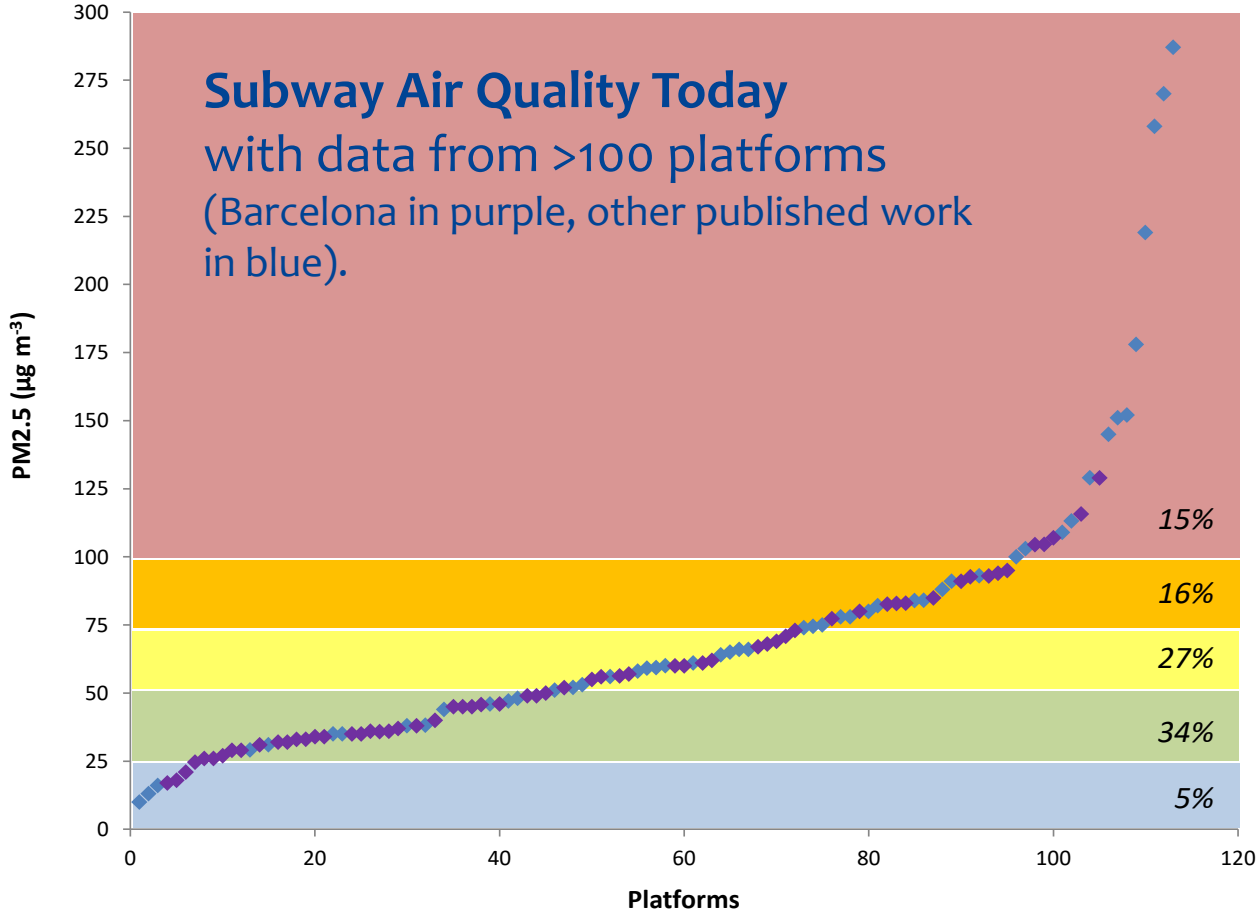
6

Long term financial planning

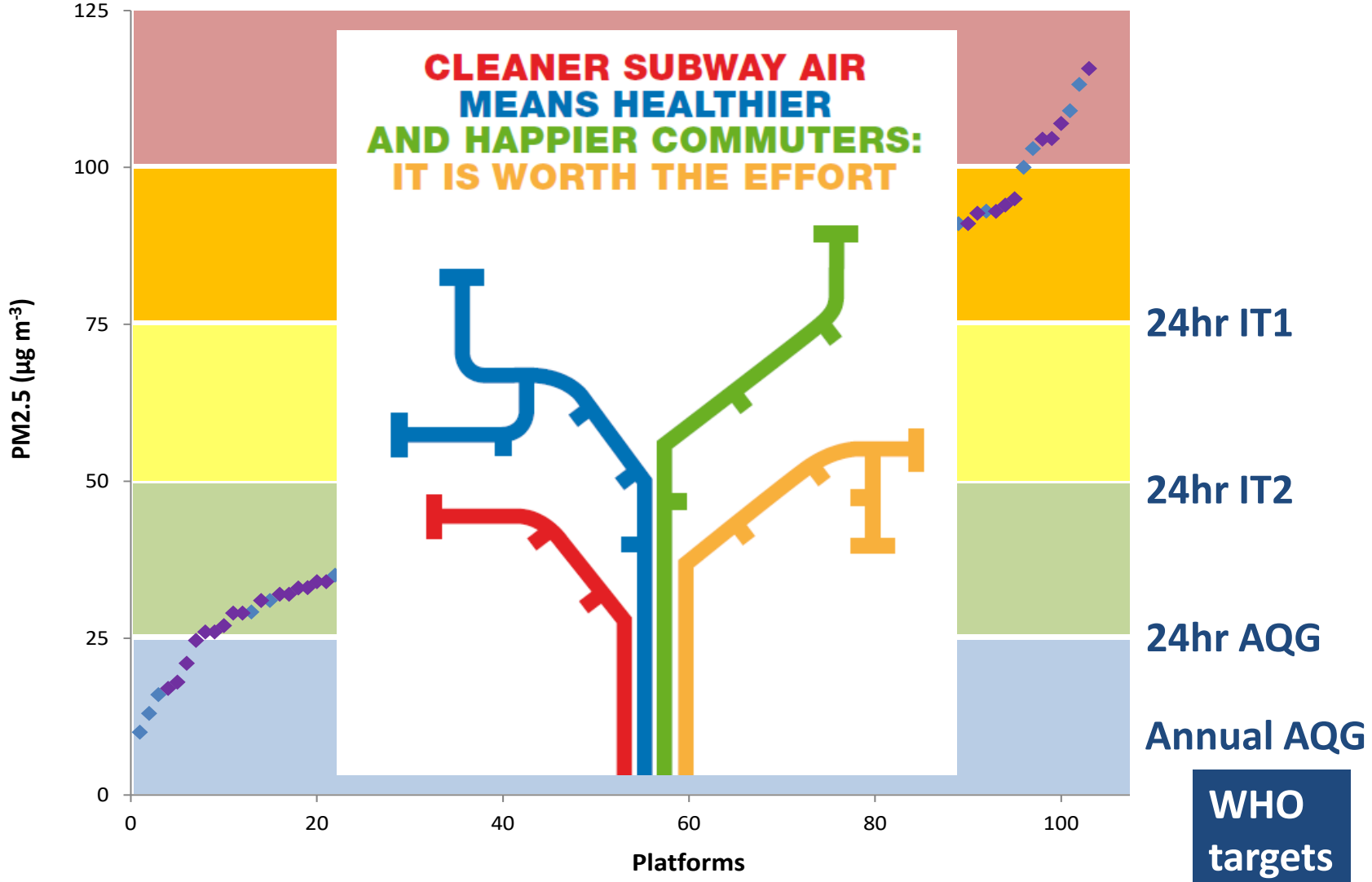
Commit to a longer term programme designed to maintain improvements achieved. Seek subventions for major works such as the fitting of full length **platform screen doors** throughout the system.

Quo Vadis?

" the (air quality) 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 PM"* (WHO Regional Office for Europe 2005).



The initial Air Quality Audit will establish where a platform lies on the colour-coded Subway Air Quality Chart. Application of PM abatement procedures will aim to move progressively through WHO targets towards the Blue Zone



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On platforms	PM10 (µg/m³)	PM2.5 (µg/m³)	Reference
Barcelona	87-325	21-186	*Querol et al. 2012*
Barcelona	133	13-154	*Moreno et al. 2014; Martins et al. 2015*
Budapest	155	51	*Salma et al. 2007*
London	1000–1500	270–480	*Seaton et al. 2005*
Los Angeles	78	57	*Kam et al. 2011*
Paris	200	61	*Raut et al. 2009*
Seoul	359	129	*Kim et al. 2008*
Stockholm	357	199	*Johansson & Johansson 2003*
Taipei	51	35	*Cheng et al. 2008*

Inside train	PM10	PM2.5	Reference
Barcelona	36-100	11-32	*Querol et al. 2012*
Barcelona		19-75	*Martins et al. 2015*
Los Angeles	31	24	*Kam et al. 2011*
Taipei	41	32	*Cheng et al. 2008*

PM SOURCES IN UNDERGROUND SYSTEMS