BEST PRACTICE GUIDE FOR RETROFITTING AIR PURIFIERS TO SPECIFIC, CLOSED ENVIRON. DOCUMENTED, BASED ON SIMULATION DATA AND FIELD EXPERIENCE

WP3, TASK3.5

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TABLE OF CONTENTS

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LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACRONYM	DESCRIPTION
AQ	Air Quality
APs	Air Purifiers
AUVASA	Autobuses Urbanos de Valladolid, S. A.
AVF	Air Volume Flow
BC	Black Carbon
BDPF	Brake Dust Particle Filter
BL	Base levels
CARTIF	Centro tecnologico CARTIF
CNG	Compressed Natural Gas
CSIC	Consejo Superior de Investigaciones Cientificas
HVS	High Volume Sampler
LPG	Liquid Petroleum Gases
M+H	MANN+HUMMEL GmbH
PM (PM2.5, PM10)	Particulate Matter (smaller than 2,5 microns, smaller than 10 microns)
UFP	Ultrafine particles

LIST OF SYMBOLS

SYMBOL	DESCRIPTION
$\mu g/m^3$	Micrograms per cubic metre

PUBLISHABLE SUMMARY

This deliverable is related to Task 3.5 and involves describing the best way to use air purifiers in transport-related semi-closed sites to achieve best results on air quality. The deliverable has been led by CSIC, with contributions from M+H, CARTIF, IUTA, Metro Lisbon, NFA and AUVASA.

Within WP3 the exposure levels of air pollutants have been measured at semi-closed demonstration sites linked to public transportation, using monitoring equipment to provide data on the concentration levels of main pollutants such as particulate matter and black carbon.

Air quality measurements were conducted in the AUVASA bus depot (Valladolid, Spain) over two one-month campaigns and in two Lisbon Metro stations (Portugal) over two months. In all four campaigns, the same protocol was followed to assess the impact of air purifiers (APs) on the microenvironment. Pollutant concentrations were measured both before (baseline) and during AP operation, with various conditions tested, including: 1) air volume flow (AVF), 2) number of APs, 3) AP location, and 4) distance from an operating AP.

The measurements have proved that the use of APs can significantly reduce the concentrations of PM2.5 and particle numbers in the 0.3-10 µm size range, with the effectiveness of APs being influenced by their positioning, number of units, and AVF. The use of efficient APs, operated at the optimal AVF and placement offers a promising, cost-effective solution to reduce PM concentrations and therefore health risks associated with particulate inhalation. However, APs should be considered as a local and/or complementary mitigation strategy rather than a replacement for ventilation, with their effectiveness enhanced when combined with improved ventilation systems.

The main consumers for this deliverable, i.e. who should read it, include not only those specifically working in transportation depots or travelling by underground rail but also all employees working in similar semi-enclosed transport-related micro-environments.

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1. INTRODUCTION

Numerous studies have been published about the adverse effects of inhalable traffic-related particulate matter (PM) on human respiratory and cardiovascular health. The complexity of the effects of inhalable PM on human health derives from the many factors influencing particle bioreactivity (size, concentration, composition, morphology, etc). Over the last two decades much attention has been given to particles with an aerodynamic diameter <2.5 µm (PM2.5), black carbon (BC) and ultrafine particles (UFP, particles with a diameter <0.1 µm) emitted in urban transport microenvironments, e.g. by buses, metro trains, and cars. In general, such studies have revealed that people inhale higher concentrations of PM2.5 and UFP during commuting than during non-commuting hours.

In this context, bus depots represent a public transport-related environment that typifies many of the pollution sources involved, where buses are parked, engines are cold started, and prolonged idling may occur in addition to maintenance activities where engines also may be turned on. Additionally, workers, staff and passengers often spend a significant amount of time at bus depots and stations, either working or, in the case of stations, waiting there, raising health concerns regarding enhanced exposure to air pollutants.

Another semi-closed transport environment is the urban metro or subway system, with millions of commuters worldwide regularly spend a proportion of their daily time in subway trains. The numbers involved are impressive: by end 2023 over 200 metro systems worldwide were running along over 20,000 km of track, with an annual ridership of around 58 billion journeys (https://www.uitp.org/publications/global-metro-figures-2024/). Something to consider is that much of the inhalable airborne PM in metro air 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.

Several studies have highlighted the importance of implementing effective ventilation and/or air purifying systems to improve air quality inside (semi-)closed transport-related microenvironments. To date, however, few data have been published on the effect of purification systems, and thus a key objective within AeroSolfd has been to deploy state-of-the-art air purifiers (APs) and measure their effect. Based on the field and modelling data collected during the AeroSolfd campaigns, this guide evaluates the effectiveness of APs in reducing particulate matter under varying configurations, contributing to our understanding of air quality in semi-closed environments, and offering insights into practical interventions to enhance occupational health. Using circular design approaches and retrofit solutions for semi-closed environments such as transport depots and underground stations, our proposed solutions are aimed at enhancing existing air cleaning technology using innovative stationary air purifiers (FilterSquare), combined with smart solutions to reduce total concentrations of airborne particles. In order to better understand the present situation regarding air quality in these transport-polluted microenvironments, we need to monitor background levels and use chemistry to understand likely pollution sources, particularly with respect to the contribution of brake (and other non-exhaust) emissions to inhalable air pollutant particles: this is the challenge of WP3.

1.1.PURPOSE AND TARGET GROUP

The primary purpose of D3.5 is to provide advice for optimizing the use of air purifiers (APs) in transport-related semi-enclosed environments, such as bus and metro environments, with recommendations based on PM2.5 concentrations. The document considers the most common variables influencing AP performance, based on extensive monitoring campaigns conducted in a bus depot and two metro stations under varying conditions. Simulation models were also used to compare campaign data. Given the AeroSolfd project’s focus on reducing brake dust emissions, the PM chemistry database was analysed to determine the presence and composition of metalliferous brake particulate matter.

While indoor rooms and halls are closed environments, the challenge of studying aerosol pollution in semi-enclosed hotspots, like bus depots and metro stations, arises from the complex airflow dynamics created by frequent vehicle movement.

The main consumers for this deliverable, i.e. who should read it, include not only those specifically working in bus depots or travelling by metro but also all employees working in similar semi-enclosed transport-related micro-environments worldwide.

1.2.CONTRIBUTIONS OF PARTNERS

Table 1. Contribution of each partner in this deliverable

PARTNER SHORT NAME	CONTRIBUTIONS
CSIC	Lead the deliverable, carry out the AQ measuring campaign, chemically analyse the PM2.5 filters, write the deliverable.
M+H	Provide support during the campaigns and check deliverable, providing simulation data.
CARTIF	Development and installation of low-cost sensors and microprocessors. Support for the AQ measurement campaigns. Electrical installation for the different air purifiers setups.
AUVASA	Provide support during the campaigns in bus depot
Metro Lisbon	Provide support during the campaigns in metro platforms. Installation of all equipment
IUTA	Provide support during campaigns and data discussion
NFA	Provide support during campaigns and data discussion, monitoring equipment

2. OBJECTIVES AND EXPECTED IMPACT

The overall goal is to present in a clear way the possibilities for retrofitting solutions of using APs in semi-closed transport-related environments such as bus depots and metro stations.

2.1. OBJECTIVES OF D3.5

Task 3.5 has the following specific objectives:

1. Understand the different variables to consider for better results when using retrofit solutions at specific areas (bus depots, metro stations).
2. Optimise the use of APs based on feedback on local requirements of operating partners.
3. Use time-resolved simulation models compared with measured data to evaluate the potential of reducing brake emissions and of improving air quality with and without air purifiers.
4. Show improvement in air quality and reduction of particle exposure proven in the field with temporal installation of retrofit version of air purifier at demo sites.

2.2. EXPECTED IMPACT

Showing in a best practice guide the way to use air purifiers to reduce the inhalable particle concentration levels within bus depots and metro platforms is the key to improving air quality within this semi-enclosed public transportation micro-environment. This document thus focuses on the impact of air purifiers on the air breathed by workers and passengers, investigating the variables that affect the effectiveness of the purifiers. The document will be openly published and communicated to the local companies and workers, following an increasing public awareness strategy focusing on 1) individual-level communication, and 2) empowering individuals and communities to advocate for policies that reduce air pollution.

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3. DESCRIPTION OF TECHNICAL/SCIENTIFIC ACTIVITIES

A description of these activities is shown below to better understand the results of this document.

3.1. SITES DESCRIPTION

Two transport-related environments were studied: a bus depot and a metro system (at two different stations). Two monitoring campaigns, each lasting at least one month, were conducted at both the bus depot and the metro system (four campaigns in total).

The study at the **bus depot** was conducted at the AUVASA facility in Valladolid, Spain (Figs. 1 and 2), located 5 km south of the city centre. Covering around 10,000 m², the depot accommodates up to 154 buses. At the time of the AeroSolfd campaigns, the fleet comprised 28 diesel, 46 LPG (liquefied petroleum gas), 51 CNG (compressed natural gas), 18 hybrid, and 11 electric buses. The depot was operated by 450 staff members, many of whom spend part of their working day within the facility and are therefore potentially exposed to air pollutants. During the monitoring period, regular maintenance activities took place, including oil changes, air filter cleaning, tire and brake servicing, and bodywork involving sanding, fillers, primers, and paint application. Two campaigns took place at the AUVASA bus depot: in May-June 2023, and April-May 2024. Both campaigns followed the same protocol, measuring PM2.5, PN, and BC concentrations before and during AP operation.

In the first week of each campaign, only baseline measurements (BL, without APs) were obtained to determine typical pollutant levels and spatiotemporal variations within the depot. After the baseline period, measurements were taken with the APs operating under various conditions to assess their impact on specific pollutants in the studied area, rather than aiming to optimize overall air quality (i.e., achieving the lowest particle concentrations with minimal energy consumption). The four main variables investigated were: (1) air volume flow (AVF), (2) number of AP units, (3) AP placement, and (4) distance from an operating AP.

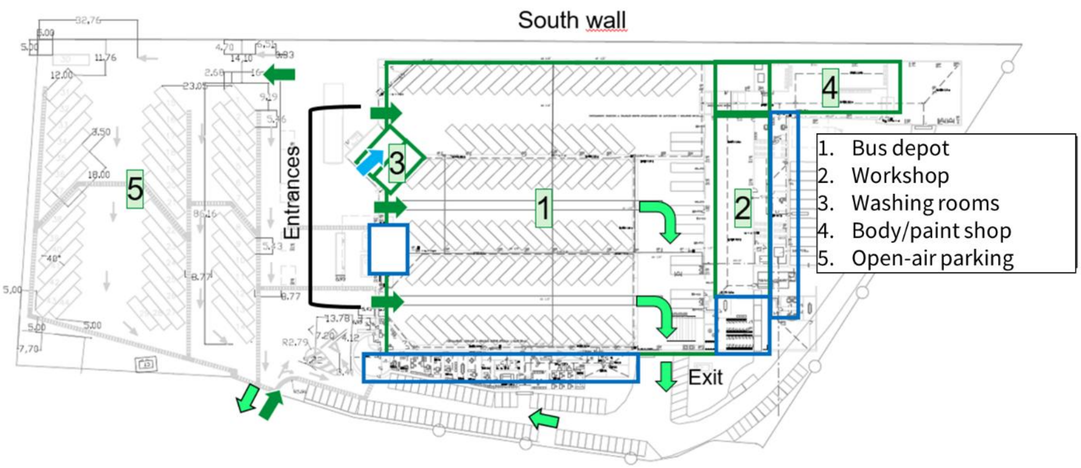

Figure 1. Layout of the AUVASA bus depot and its surrounding area. The dark green arrows indicate the inbound route buses follow to enter the depot, whereas the light green arrows show the outbound route for exiting. The blue arrow represents the route the buses follow to enter in the washing area.

A total of 10 APs were used in the measurements, with 4, 7, or all 10 APs on simultaneously at either half or full AVF (1,250 or 2,500 m³/h per unit). Regarding the APs location, two locations were used. Location "a" is represented by 7 APs surrounding the measurement equipment at a distance up to ~5 m, with 3 additional APs positioned ~17 m farther away. Two buses could park in between these 3 APs and the measuring equipment. Regarding location "b" 2 APs were moved ~12 m farther away than location "a", allowing enough space for buses to pass between these APs and the measuring equipment. The installation points and number of APs were intentionally chosen based on operational constraints. Key considerations included avoiding interference with staff or bus movement, maximizing exposure to passing buses (Figure 3), and minimizing the influence of indoor–outdoor air exchange by positioning the setup away from depot entrances and exits.

Figure 2. Illustration of CSIC measuring equipment and M+H air purifiers at AUVASA bus depot.

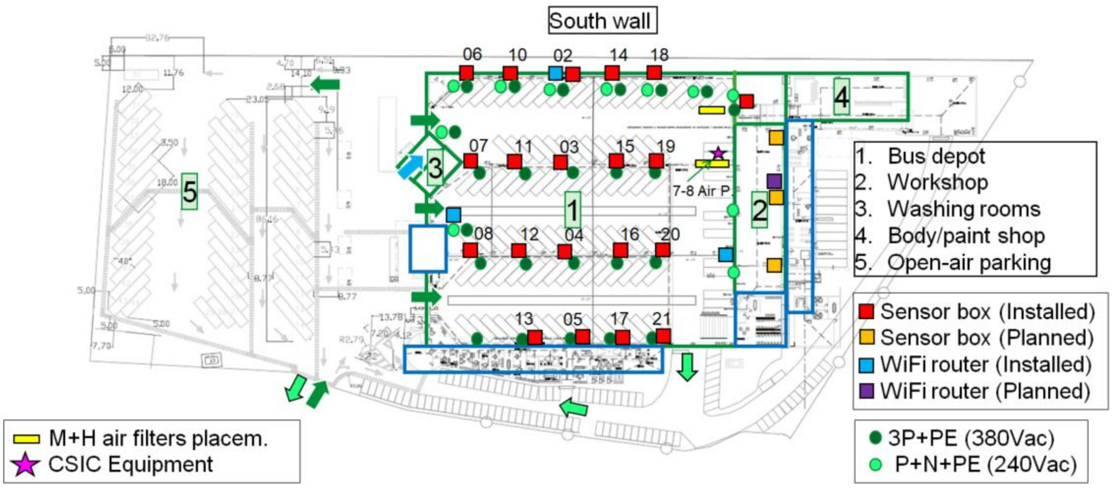

Figure 3. Layout of the installed sensor boxes and routers in the AUVASA Bus Depot.

Twenty-one sensor boxes, provided by CARTIF, were installed throughout the AUVASA bus depot to analyse the spatiotemporal distribution of particulate matter (PM). These low-cost PM sensors were evenly distributed across the depot area (see Figure 3). Data from the sensors were transmitted wirelessly to three Wi-Fi routers installed on-site.

Two **metro stations** in the Lisbon Metro system were monitored (Figure 4): Alto dos Moinhos on the Blue Line (March–April 2024) and Quinta das Conchas on the Yellow Line (March–April 2025). Founded in 1948, Metro Lisbon currently operates four independent lines spanning 44.5 km with 56 stations, serving approximately 169 million passengers annually. Since 2020, Metro Lisbon has monitored air quality at its stations using probes on platforms, identifying several instances of PM10 and PM2.5 exceedances. The stations selected for this study were chosen based on their high potential for emission reduction. Temporary installations of an enhanced FilterSquare system enabled targeted air pollution measurement campaigns to evaluate the impact of air purifiers on air quality. The campaigns also assessed influences from outdoor air, natural and forced ventilation, passenger flow, and train frequency.

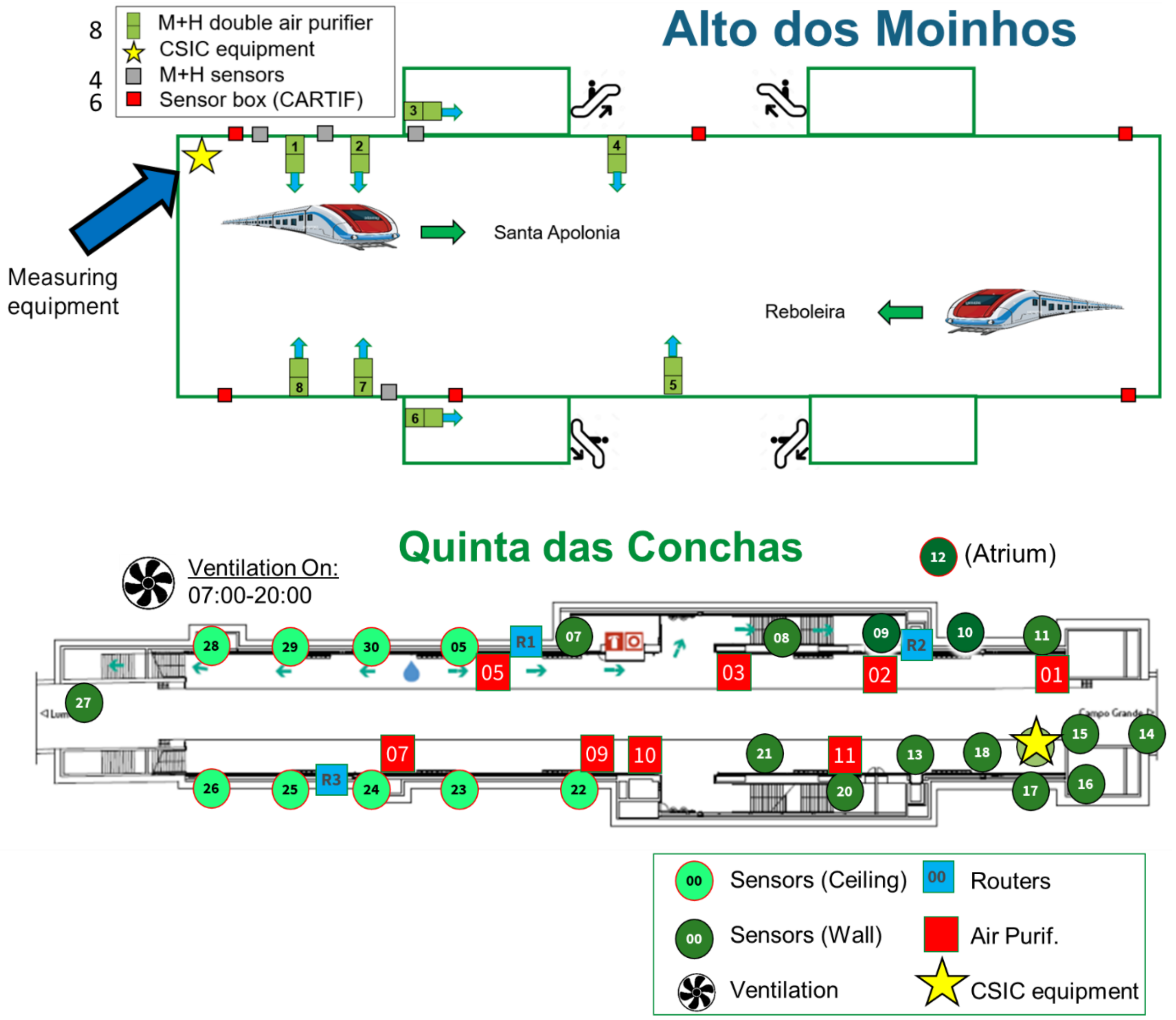

Figure 4. Schematic illustrating the positions of the used equipment in Alto dos Moinhos (top) and Quinta das Conchas (bottom) metro stations (Lisbon Metro). The scale of the schematics is not representative of the real dimensions.

At Alto dos Moinhos (Figure 4, top), eight remotely controlled double APs were deployed, with air quality monitored using 10 sensors distributed along both platforms. At Quinta das Conchas (Figure 4, bottom), eight APs were also used, but the number of sensors increased to 25. Monitoring equipment from CSIC was positioned near one end of the platform, close to a train entrance (Figure 4).

3.2.SIMULATION MODELS

CFD simulations were carried out for the **AUVASA bus depot** to determine where ten APs should be placed in order to reduce dust concentration as efficiently and as uniformly as possible. It was not possible to place the APs in these locations during the campaign as space was limited.

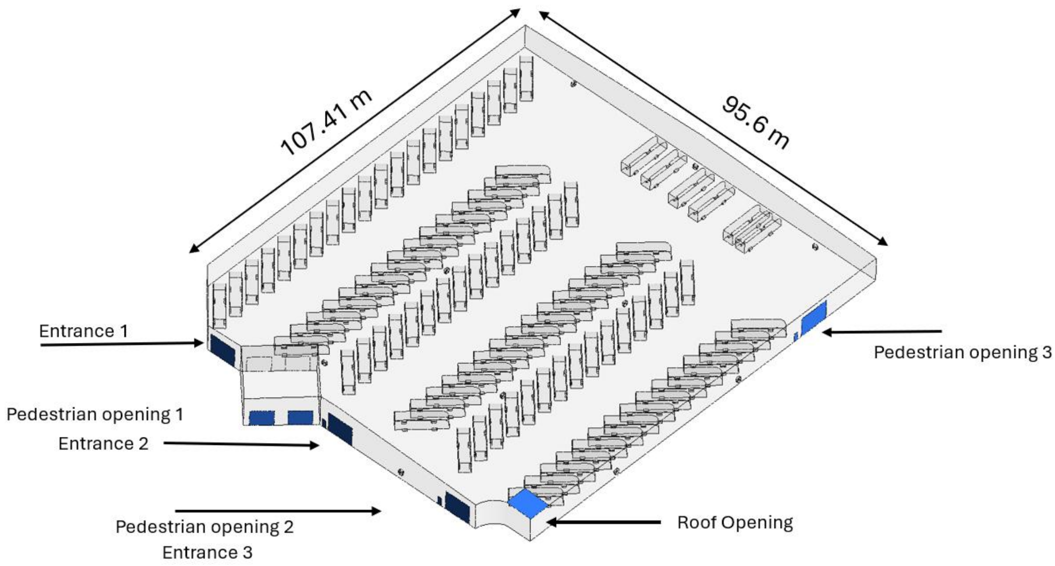

Figure 5. A full-scale three-dimensional model of the building was created from customer CAD data.

At **Metro Lisbon**, eleven possible locations for APs were identified, these locations ensured that the safety of the platforms was not impacted, prevent covering art on the station walls, and avoid advertisements and other permanent structures on the platform. CFD simulations were then carried out to choose the optimal locations for the 8 APs used in the project.

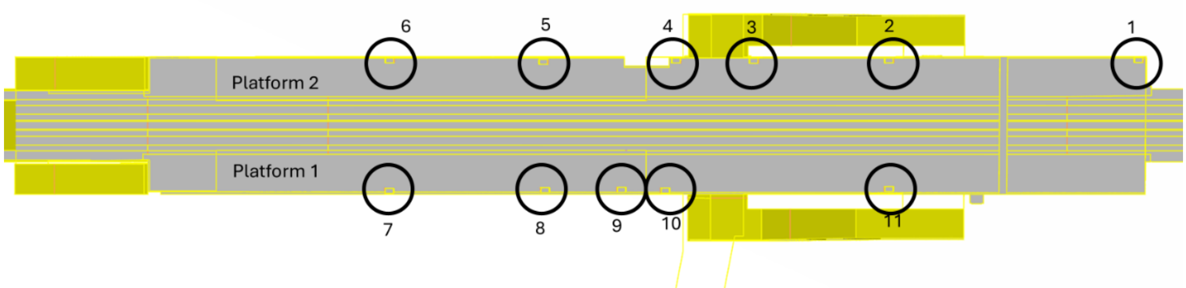

Figure 6. Potential locations of Filter Squares based on CFD simulations.

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3.3. AIR QUALITY MONITORING EQUIPMENT

PM2.5 concentrations were continuously monitored by means of a light-scattering laser photometer DustTrak (Model 8533, TSI). For understanding the spatial distribution of PM2.5, Sensors (SEN54) were distributed at the depot and platforms, operating continuously with a time resolution of 1 ± 0.03 s. Particle number concentrations were measured using a DiSCmini (Testo), covering a range of 10^3–10^6 #/cm³ and particle sizes between 10–700 nm, with a time resolution of up to 1 second. Particle number size distributions (0.01–10 µm) were obtained using a combination of a NanoScan (TSI NanoScan 3091) and an Optical Particle Sizer (TSI Model 3330). Black carbon (BC) concentrations were monitored with a microAeth AE51 aethalometer.

An MCV high-volume sampler was also used to collect PM2.5 for gravimetric and chemical analysis. The sampler, equipped with quartz microfiber filters, was set to sample for 12 or 24 hours at a flow rate of 30 m³/h. The gravimetric mass concentrations served as a reference for calibrating and adjusting the PM2.5 measurements from the DustTrak.

All equipment was positioned in a corner of the platform, secured in a metallic-net box for safety (Figure 7). For comparison, ambient PM2.5 data were also obtained from the nearest official air quality monitoring station during each campaign.

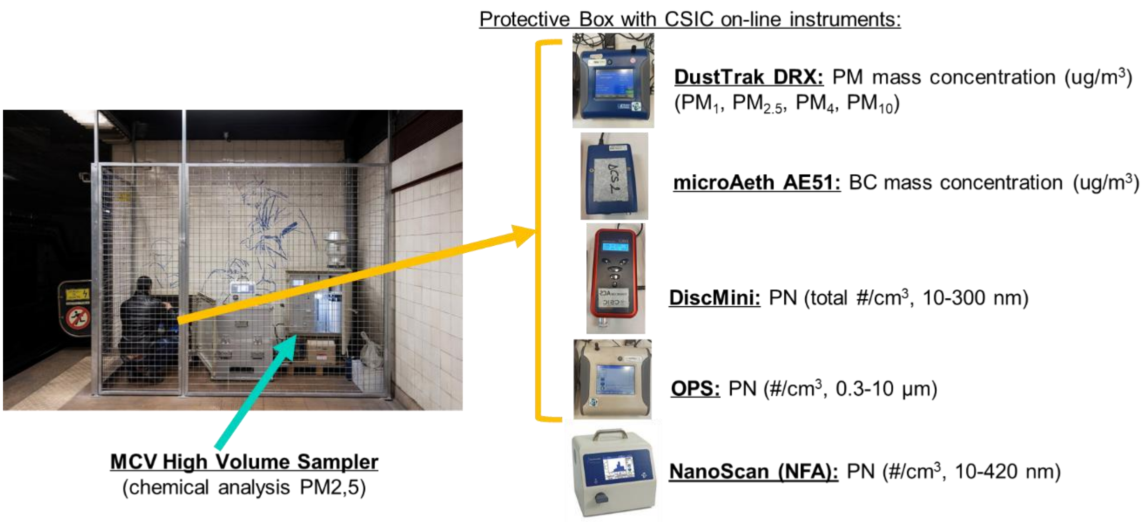

Figure 7. Air quality monitoring equipment used in all the campaigns (photo from Alto dos Moinhos platform)

3.4. AIR PURIFIERS

Air purifiers were designed and manufactured by MANN+HUMMEL GmbH (Ludwigsburg, Germany). These APs are low-cost, highly-efficient stationary air purification systems, with their filters specifically designed for (semi-)closed environments such as bus, tram, and subway depots/stations to significantly decrease the concentrations of particles. Two APs types were used during the measurement campaigns: OurAir SQ 2500 and Filter Square II.

OurAir SQ 2500 was used at the bus depot, weighs approximately 150 kg and measures 1004 mm (H) × 1051 mm (W) × 523 mm (D) (https://www.mann-hummel.com/en.html). It has a maximum power consumption of 600 W and offers 10 adjustable airflow levels ranging from 0 to 2500 m³/h. It features a 4.3" LED touchscreen that allows users to program various settings, including operation times and airflow levels. Filter Square II was used at the metro stations, weighs over 300 kg, with dimensions of 2165 mm (H) × 1004 mm (W) × 523 mm (D). It consumes up to 1400 W and provides adjustable airflow up to 7200 m³/h. Through the M+H platform, users can schedule operation times and configure airflow settings.

As mentioned before, these APs were deployed to assess their impact on the studied pollutants under different setups within a specific area, rather than to improve overall air quality at the site. This is the reason, why the measurement equipment, excluding sensors, was installed at fixed location(s). Before the beginning of the campaign, completely new high-efficiency particulate air (HEPA) filters were installed. However, as the HEPA filters were rated with a lifetime of ~ 2 years, the same filters were used for both campaigns.

4. RESULTS AND DISCUSSION

4.1.SENSOR BOXES PM ANALYSIS

Bus depot. Data from the sensors were analysed to assess the distribution of PM levels in the different areas of the AUVASA bus depot and to evaluate the variation of PM levels throughout the day. Figure 8 shows how the PM spatial distribution is quite homogeneous throughout the AUVASA bus depot. PM2.5 values from the sensors are provided numerically in each red square, representing a sensor box, and range from 6-8 µg/m³. This PM2.5 distribution was expected for two main reasons. Firstly, the bus depot is large (approximately 10,000 m²), with three entrances and one exit, allowing particles to disperse easily through advection and diffusion. Secondly, as a restricted public facility, bus operations are limited to specific times. In contrast, bus stations typically constantly experience more localized and intense activities, such as braking, idling, and accelerating, concentrated in areas like platforms or parking zones rather than waiting areas. It is important to note that the sensor values have not been corrected against certified equipment, because most sensors were installed far away from the HVS. However, the presented data preserve the PM2.5 spatial distribution across the entire area.

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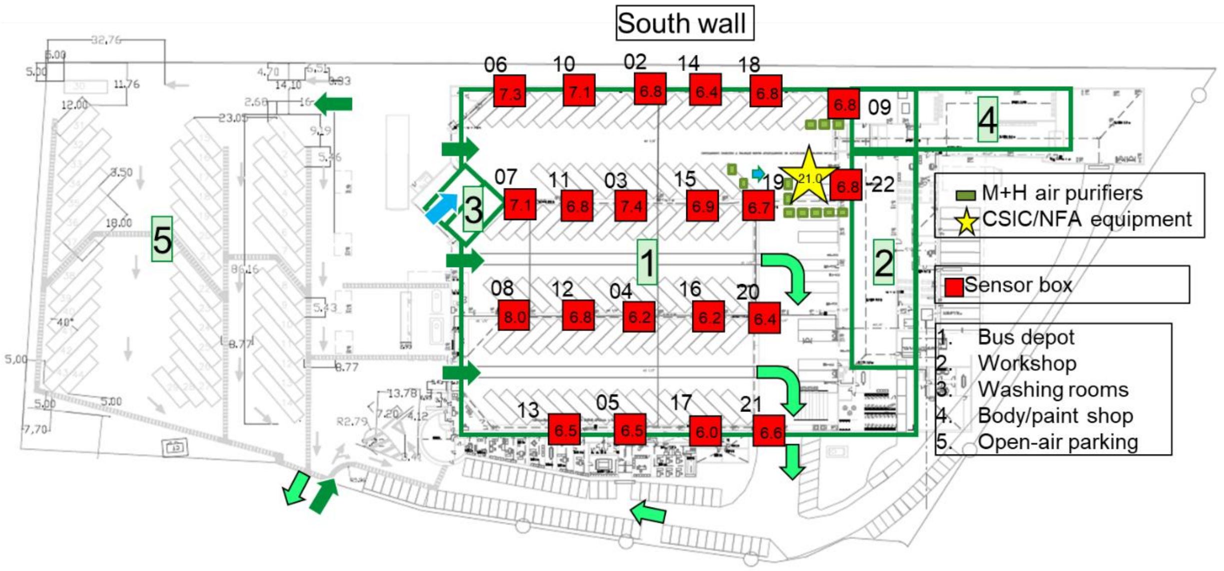

Figure 8. Median PM2.5 concentration of CARTIF sensors and CSIC equipment for the period without APs functioning (BL measurements) in the bus depot.

Metro platforms. The insights gained from the first campaign at Alto dos Moinhos station (Lisbon Metro) were applied to organize a second campaign at Quinta das Conchas. Prior to the campaign, an air quality modelling study was conducted to identify the best scenarios for comparison. At Quinta das Conchas, a higher number of sensors and additional equipment were used. Median PM2.5 concentrations recorded before the APs usage ranged from 46 to 66 µg/m³ (Figure 9). The distribution showed a clear difference between the right half (> 55 µg/m³, red circles) and the left half (< 55 µg/m³, blue circles) of the platform. This variation is linked to the platform's ventilation system, which introduces fresh air through a long inlet along the top of the wall at one end (left side in Figure 9, purple lines). Operated from 7 am to 8 pm, the ventilation creates a noticeable air quality difference, dividing the platform into a lower-PM blue sector and a higher-PM red sector.

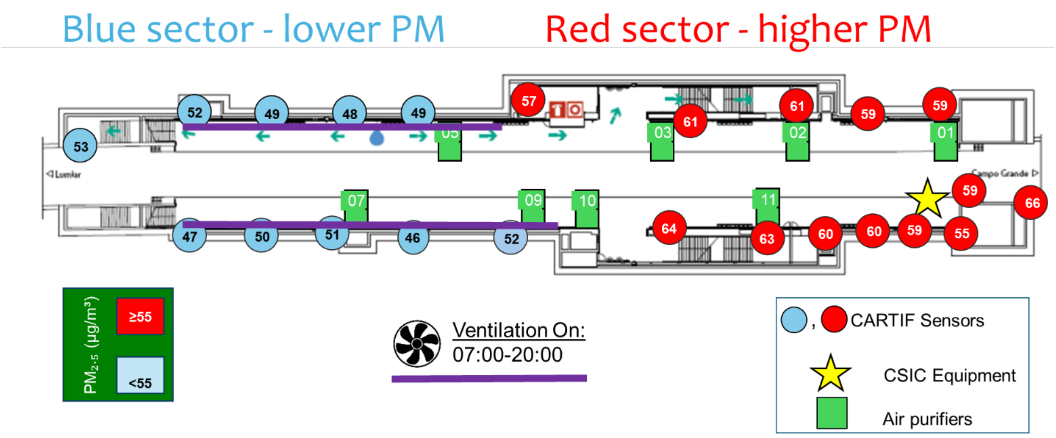

Figure 9. Median mass concentrations of PM2.5 for the baseline (BL) week in Quinta das Conchas platforms. The blue colour represents PM2.5 concentrations < 50 µg/m³, while the red colour indicates concentrations > 50 µg/m³, based on data from sensors.

Average hourly PM2.5 concentrations during the baseline week on the platforms showed a similar pattern for the weekdays and weekends, with lower concentrations on Saturdays and Sundays due to fewer trains and passengers (Figure 10). Generally, higher concentrations occurred during rush hours, from 8–10 am and from 6 pm to 1 am when the trains stop running. The shutdown of platform ventilation at 8 pm led to an obvious increase in PM2.5 concentrations.

In the metro systems, PM mostly originates from friction between moving train components, such as wheels and rails, brake discs and pads, as well as power supply materials, giving the particles a metalliferous composition. These ferruginous and carbonaceous particles mix with PM from other sources, including rock ballast and infiltrating outdoor air, which are driven through the tunnels by train movement and ventilation systems. Increased concentrations during non-operational hours (e.g., 2–4 am) are typically linked to night time maintenance activities.

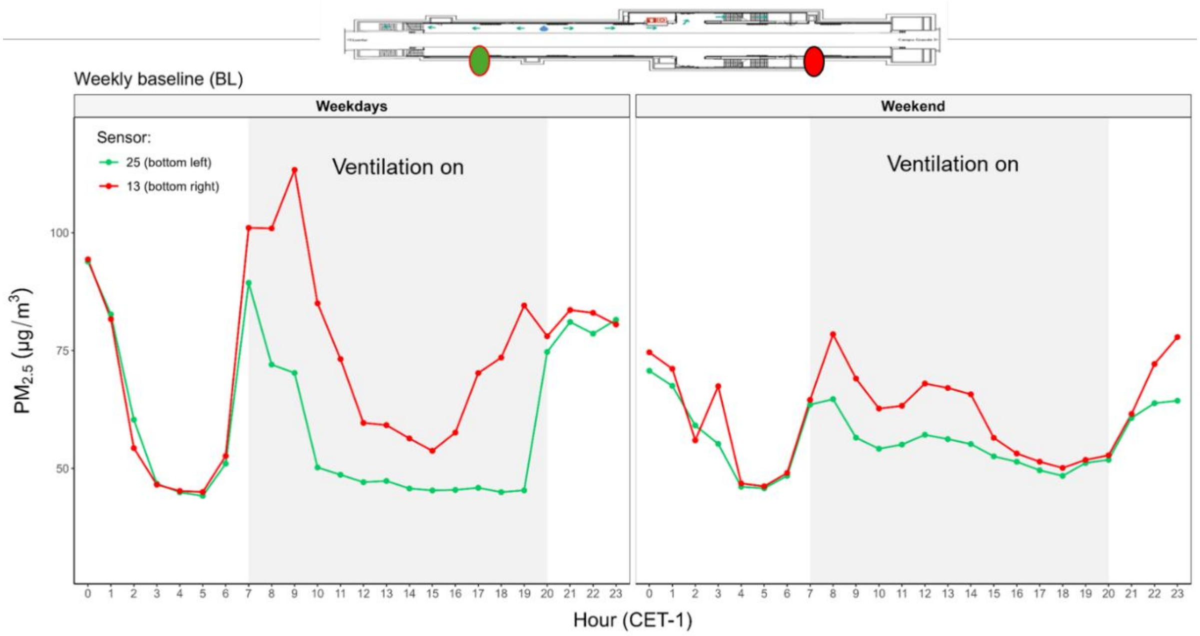

Figure 10. Average hourly PM2.5 mass concentrations for the baseline (BL) week on the Quinta das Conchas platforms. The red line represents PM2.5 data from the sensor located far from the ventilation system, while the green line shows data from the sensor positioned near the ventilation system.

4.2. SIMULATION ANALYSIS

4.2.1. AUVASA BUS DEPOT

Four layouts were considered for the bus depot (Figures 11 and 12). At a height of 0.5 m, air purifiers at Positions 1 and 4 removed 33.9 % and 34.3 % of particulate matter, compared with 33.3 % for Position 2 and 33.5 % for Position 3. At 2 m height, the corresponding reductions were 32.4 %, 31.0 %, 32.1 % and 32.9 %. The data confirm that the relative ranking of the layouts is consistent across both elevations. Visual contour plots for Position 2 revealed a persistent hotspot near the south-western corner of the hall. No purifier was installed in that zone, and the nearest unit (AP3) discharged in the opposite direction, which explains the locally inferior performance.

The simulation demonstrates that all four layouts would markedly improve air quality, but the degree of homogeneity varies. Position 4 marginally outperforms Position 1 in absolute percentage terms, yet Position 1 delivers the most even distribution of clean air. A uniform field is especially valuable when only a limited number of sensors is available, because it minimises the risk of blind spots. In addition, Position 1 aligns well with existing power feeds and avoids obstructing service lanes, which should reduce implementation costs. Placing the ten SQ2500 air purifiers according to Position 1 is expected to reduce the average PM level in the AUVASA bus depot by roughly one-third within the first hour of operation while yielding the most uniform air-quality profile among the four layouts studied.

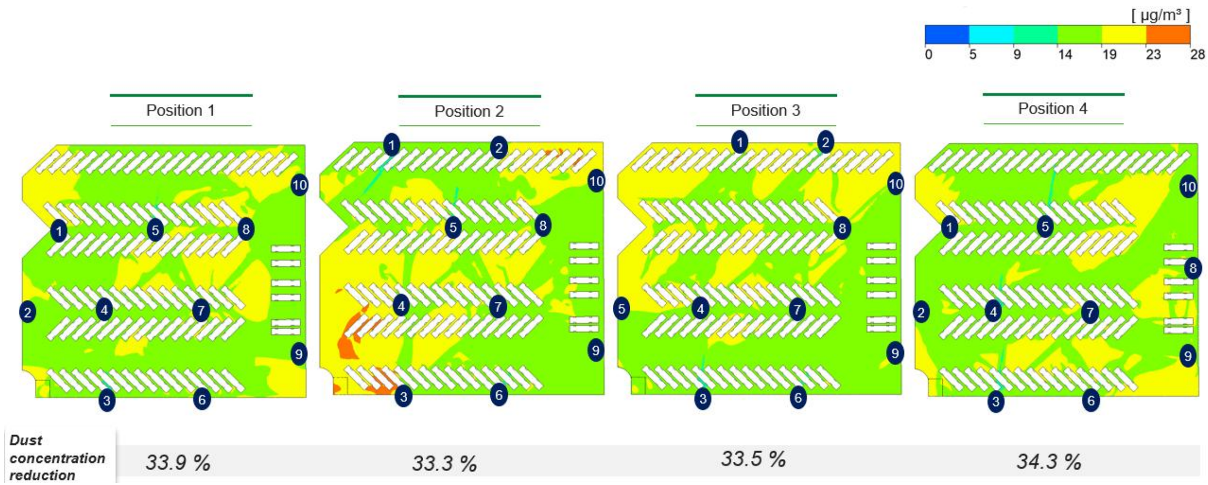

Figure 11. Dust concentration reduction – 0.5 m height. The black circles show the location of the air purifiers.

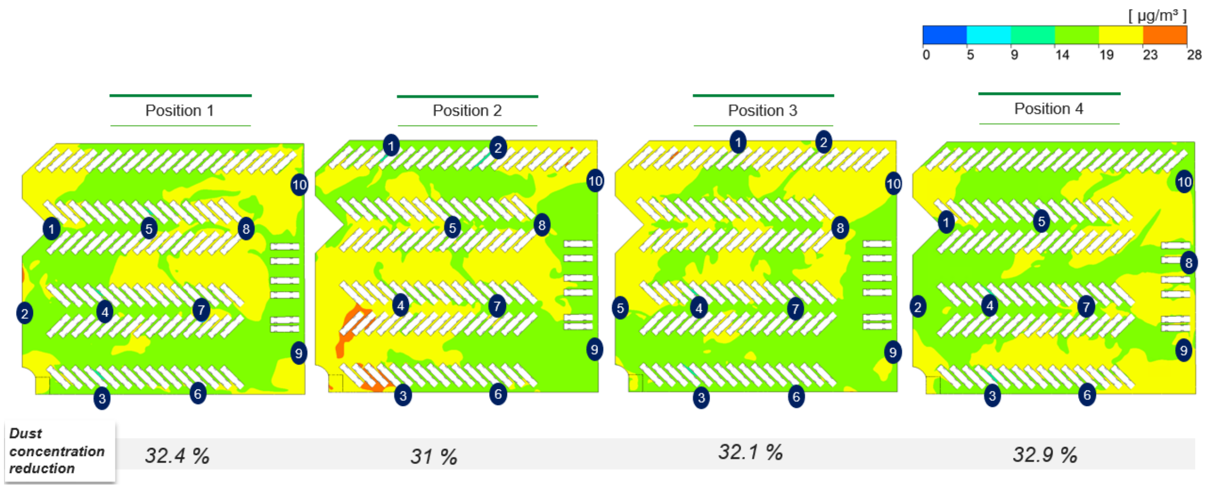

Figure 12. Dust concentration reduction – 2 m height. The black circles show the location of the air purifiers.

After one hour of operation, Position 1 lowered the mean PM concentration from 27.25 µg/m^3 to 18.31 µg/m^3, which corresponds to a 32.7 % reduction. Position 4 achieved an almost identical 33.0 % reduction, while Positions 2 and 3 produced slightly smaller improvements of 31.0 % and 32.4 % respectively. The standard deviation of the sensor data was only 0.76 µg/m^3 for Position 1, the lowest of all layouts. Position 4 followed with 0.93 µg/m^3, whereas Positions 3 and 2 exhibited larger spreads of 1.43 µg/m^3 and 1.64 µg/m^3. A lower deviation indicates a more homogeneous air-quality improvement throughout the depot (Figure 13).

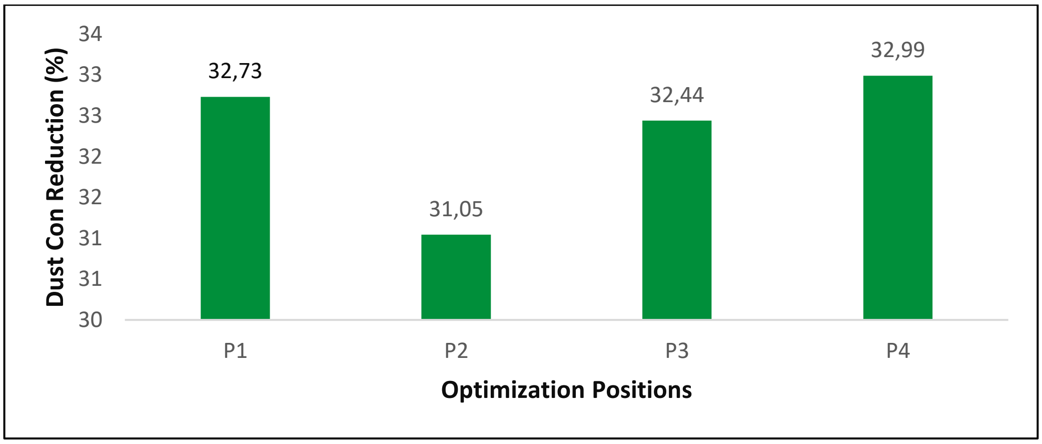

Figure 13. Average dust concentration reduction for the four simulated layouts shown above.

4.2.2. QUINTA DAS CONCHAS (METRO LISBON)

The APs should be arranged in the station so that PM concentrations on the two platforms are reduced as quickly and as evenly as possible. A model of the station was built based on CAD drawings provided by ML, including the ventilation shafts to the tunnel, all staircases to street level, the existing HVAC outlets in the ceilings and the connecting atrium (Figure 14). Boundary conditions were taken from the operator: the tunnel extraction fan, the station HVAC, and each Filter Square II.

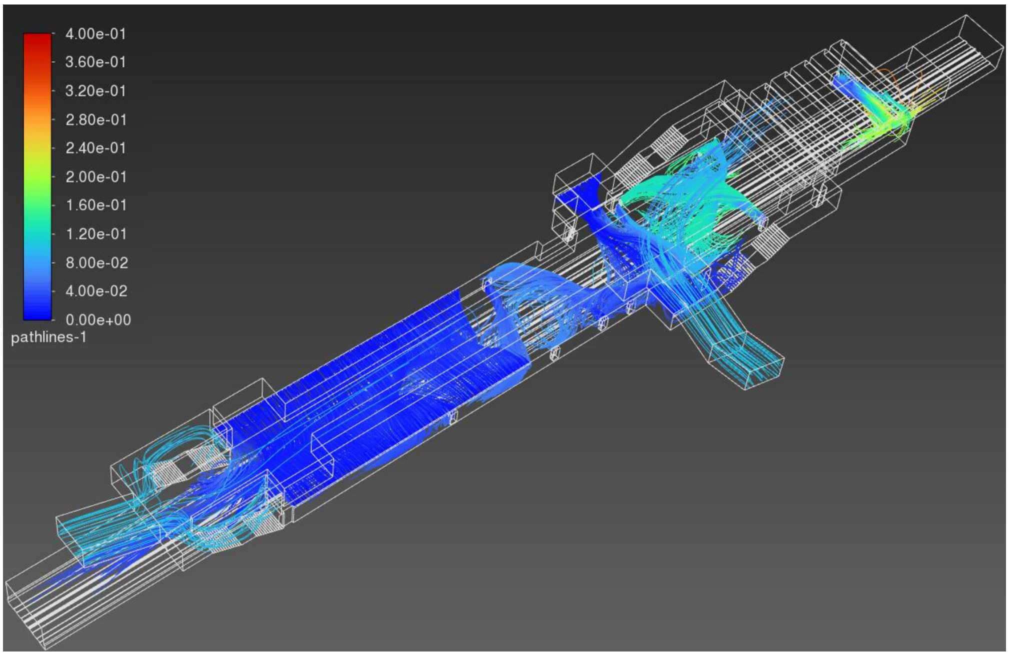

Figure 14. Air flow in the station

Because eleven geometric positions are structurally available but only eight units could be installed, 165 combinations would be possible; a preliminary screening left three that were simulated in depth. Two operating scenarios were considered one with the existing ventilation as well as the APs and one with only the APs.

That best-performing layout uses positions 1, 2, 3, 5, 7, 9, 10 and 11, leaving positions 4, 6 and 8 idle. With the tunnel fan and HVAC running, existing ceiling outlets flush the upper-platform halves, clean air is pulled down the stairwells, and the Filter Squares located close to the tunnel portal pre-clean part of the incoming stream (Figure 15). When the tunnel fan and HVAC are switched off, the same staggered arrangement still outperforms the other variants because the units blow clean air across the tracks instead of directly facing an opposite unit; this cross-jet reaches the other platform and mixes efficiently, whereas mirrored pairs merely collide in mid-track and leave the passenger areas less diluted. It should be noted that this model does not include train activity.

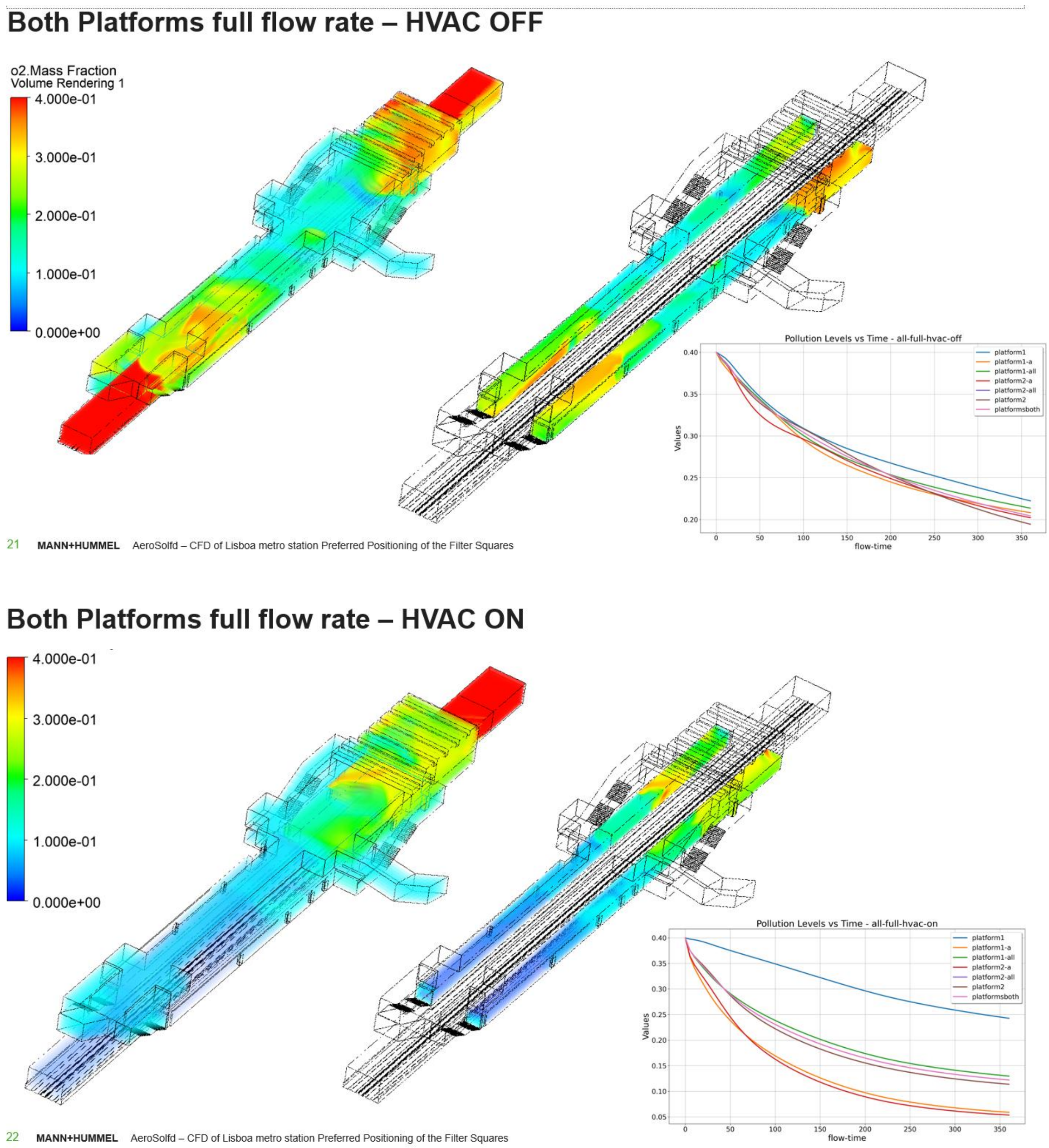

Figure 15. Air cleaning after 10 minutes at full flow rate of Filter Squares

Performance was also tested at half flow rate and with single units disabled. Halving the flow extends decay times but does not qualitatively change the spatial pattern, suggesting that off-peak operation at reduced speed is feasible (Figure 16).

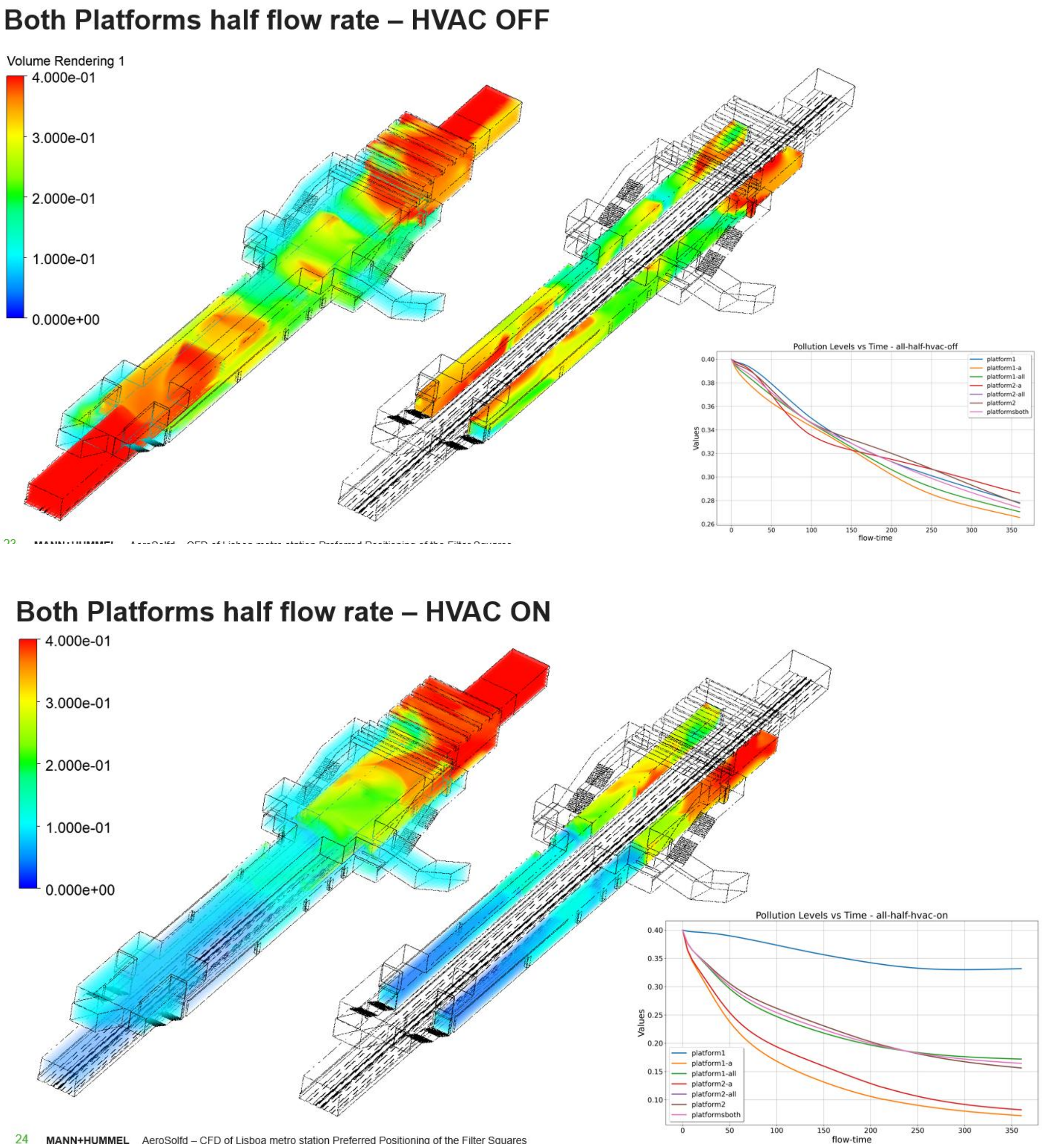

Figure 16. Air cleaning after 10 minutes at half flow rate of Filter Squares

All in all, the CFD campaign demonstrates that eight AeroSolfd Filter Squares, installed in the staggered arrangement 1-2-3-5-7-9-10-11 and operated in the designed flow direction will roughly triple the cleaning rate compared with the present ventilation alone and will keep both platforms at comparable air-quality levels even when the tunnel fan or the HVAC system is offline.

In the baseline case without filters, pollutant levels fall by roughly 25 % after 75 s and then asymptote because dirty air is continuously sucked in from the tunnel (Figure 17). Once filters are added, the 25 % mark is already hit after 30-50 s and at least 50 % reduction is reached after three minutes in every tested layout; the best layout pushes the reduction to roughly 75 % after six minutes on both platforms.

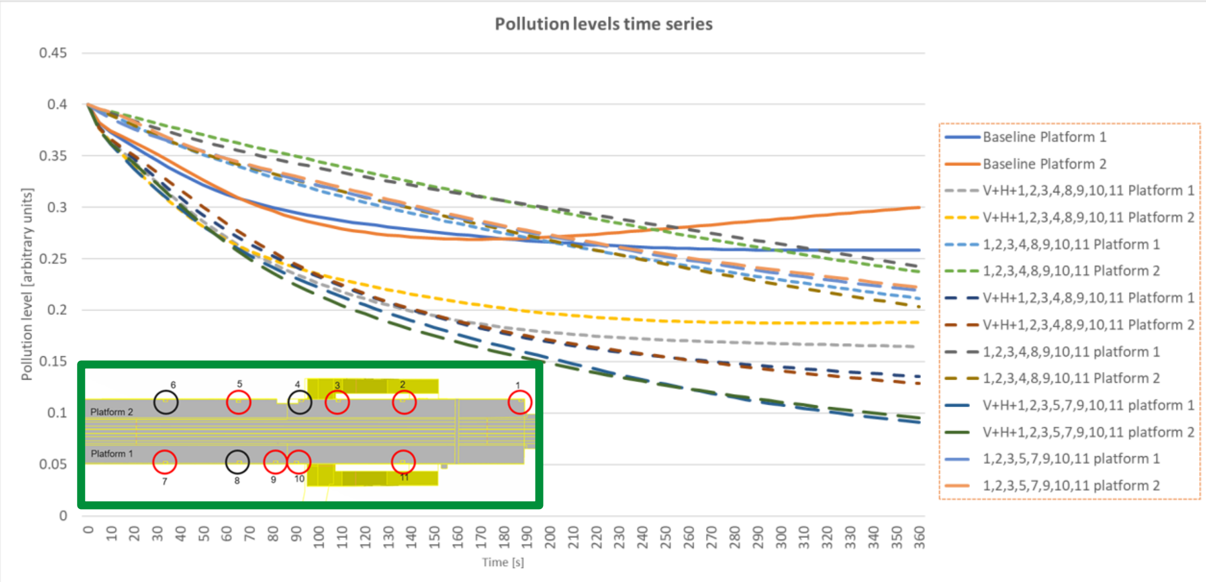

Figure 17. Air pollution time series indicating a map with the chosen locations of Filter Squares (red)

4.3.PM2.5 CONCENTRATIONS DURING MEASUREMENTS

Bus depot. The 24-hour PM2.5 ambient mass concentration measured by gravimetric filter samples at the AUVASA bus depot during baseline (BL) conditions averaged 27.1 µg/m³, while the overall campaign average was 24.7 µg/m³. Daily averages ranged from a minimum of 16.7 µg/m³ to a maximum of 39.8 µg/m³. These levels were constantly higher than those measured at the nearest official outdoor air quality monitoring station in Valladolid (Vega Sicilia). Average PM2.5 levels outdoor were 6.3 µg/m³, significantly lower than the bus depot's average of 26.8 µg/m³, with no overlap between the two interquartile ranges (red and blue in Figure 18). The data also show a morning "rush-hour" peak after 7:00, reflecting higher pollution during the morning compared to the afternoon. Examining the data on a more detailed timescale reveals PM2.5 concentrations to record sharp, transient peaks within each 24-hour period, as demonstrated by Figure 19 which shows time series of PM2.5 (and BC) levels throughout one day. The peak timings are consistent across days, with notable spikes around 01:00, 07:00, and between 16:00 and 18:00. These peaks are primarily caused by bus movement, idling, maintenance activities, and particle resuspension.

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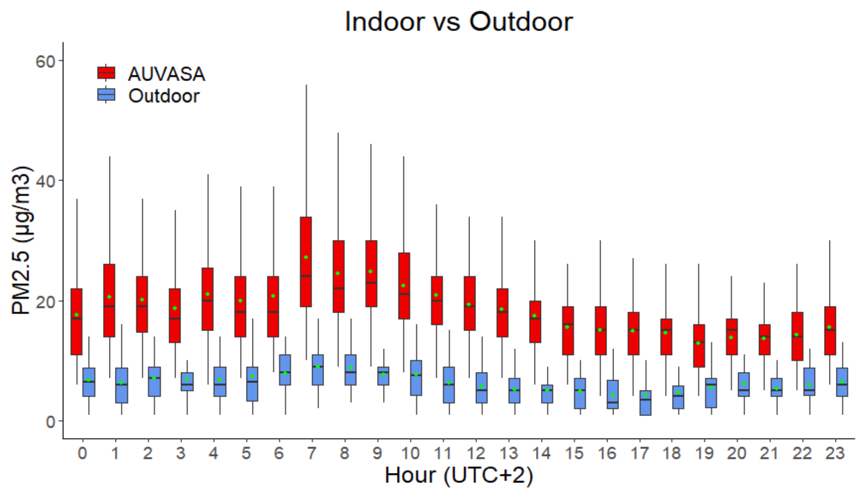

Figure 18. Daily distribution of baseline (BL) PM2.5 at AUVASA bus depot and outdoor (Vega Sicilia air quality official monitoring station) environment. The dots represent the average.

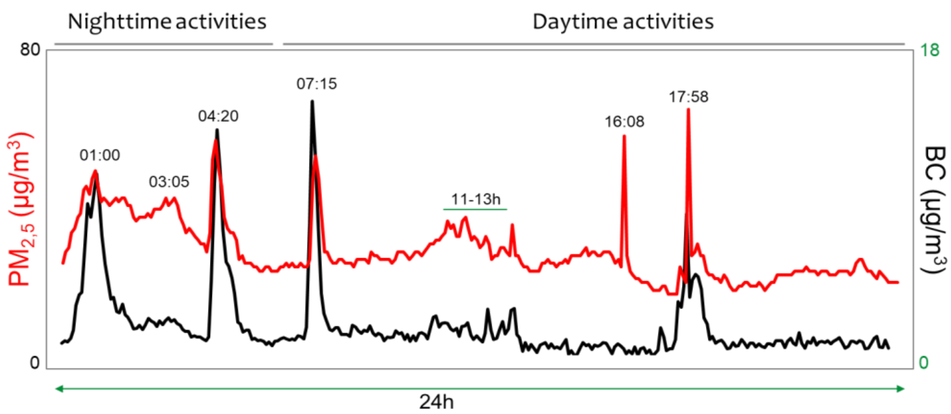

Figure 19. Time series of PM2.5 and BC during 2023/06/01, illustrating the presence of transient air pollution peaks.

Metro platforms. For the metro measurements, gravimetric samples were collected every 12 hours (instead of 24 hours as in AUVASA) to increase the number of filters for data correction. PM2.5 filters operated from 9 am to 9 pm (daytime) and from 9 pm to 9 am (night time). Twelve-hour concentrations ranged from 36 to 118 µg/m³, with overall lower concentrations on the weekends. The average concentration for the entire campaign was 67 µg/m³. Generally, night time samples exhibited higher concentrations than daytime filters, likely due to the combination of ventilation absence during the night and maintenance activities occurring when the metro operation stops.

The concentrations registered during the whole campaign are shown in Figure 20. Although PM2.5 concentrations are quite variable, a daily trend is observed following a similar pattern with that described for the sensor data. Most peaks take place in the time range 21:00-09:00, which is the time range used for the night time filter's function. This aligns with the previously mentioned higher PM2.5 concentrations during night time compared to daytime levels.

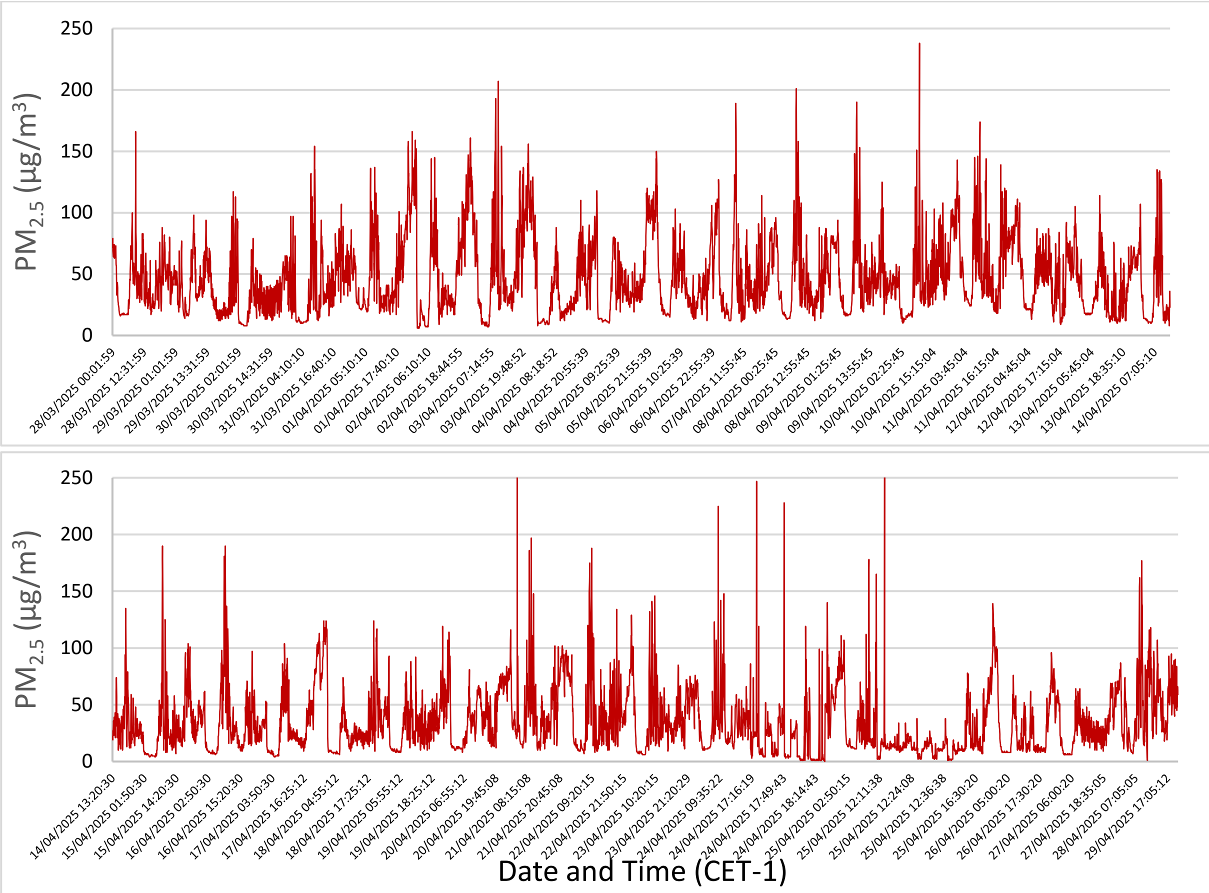

Figure 20. PM2.5 concentrations measured continuously with DustTrak in Quinta das Conchas, separated in two diagrams for clearer view.

4.4. EFFECT OF AIR PURIFIERS AS RETROFIT SOLUTION

Bus depot. Several parameters were considered to assess the impact of the APs on PM2.5 concentrations in the bus depot, including air volume flow (AVF, half or full power), the number of APs on, their placement, and the effect of distance from them.

Figure 21 demonstrates the impact of **air volume flow** (AVF) of the APs on PM2.5 concentrations, with a reduction during the APs operation. Interestingly, higher reduction was observed when the APs functioned at half AVF compared to maximum AVF. The less effective reduction when operating the APs on full AVF was probably a result of particle resuspension. Resuspension is something which cannot be overlooked, especially in environments such as bus depots and stations where PM originating from bus exhaust and non-exhaust emissions, maintenance activities, and resuspension will be passively deposited on surfaces throughout the facility. Based on these findings, by using the APs at half instead of maximum AVF, not only reduces the mass concentrations of particles more effectively but also results in lower energy consumption.

Regarding the importance of the **number** of the APs, 4 and 10 APs operating at the maximum AVF were compared (Figure 21). The concentrations' reduction with 4 APs operating showed little difference compared to the reduction observed with 10 APs on. However, PM2.5 demonstrated statistically significant differences, suggesting that using more APs could significantly enhance PM2.5 reduction, even if these differences are not so high (i.e., from a PM2.5 median of 15 to 13.9 µg/m^3). The relatively small difference in PM2.5 concentrations between 4 and 10 APs also suggests that particle resuspension may have contributed, as all the APs were operating at the maximum AVF.

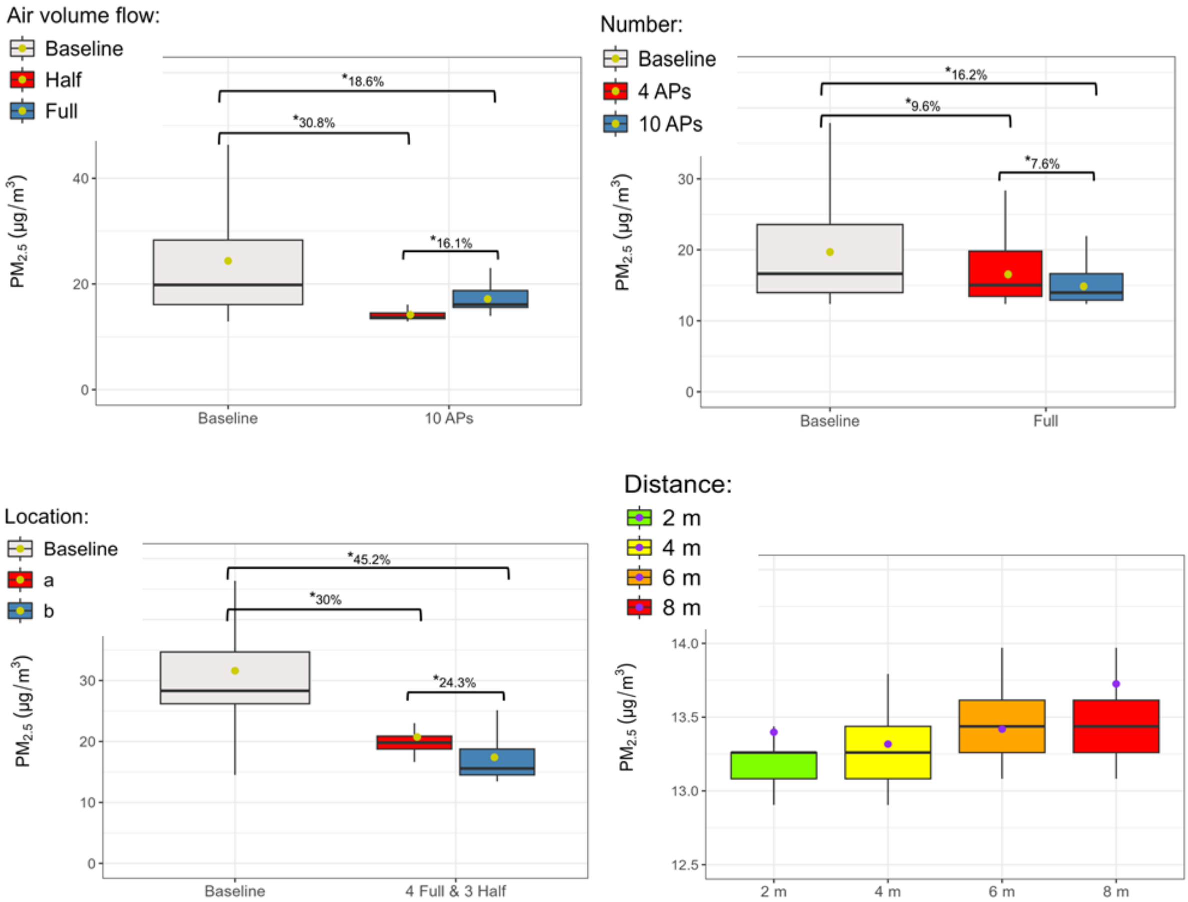

Figure 21. Effect of air purifiers' (APs) on PM2.5 concentrations depending on air volume flow (AVF), number of APs, their location and the distance to them. The percentages above boxplots represent the percentage differences between median concentrations. The asterisks indicate statistically significant differences, while the yellow and purple dots represent the average concentrations.

Seven APs were running in two different **locations** to investigate the effect on PM2.5 concentrations. Interestingly, this reduction was much higher when two APs were moved ~12 m further away (location b) than when the same two APs were installed at <5 m away from the measuring equipment (location a). The generally lower concentrations of particles observed at location b compared to location a is something which was not really expected. This may have occurred due to the crossed ejection of purified air, which can lead to turbulence and therefore increased particles' resuspension.

The effect of the **distance** between an AP at the maximum AVF and the measuring equipment on PM2.5 concentrations is shown in Figure 21. As expected, the closer to the AP, the higher the reduction of particle concentrations as shorter distances result in stronger airflow influence and particle dilution. Although these findings may seem to contradict the location experiment (where PM concentrations decreased more when the two APs were farther apart), they emphasize the strong influence of APs with high AVF on resuspension. Overall, significant reductions in particle concentrations were observed up to 6 meters. Based on these findings, the APs should be ideally placed within 6 meters of the target area blowing purified air directly on the subjects. However, it should be noted that if the AP was running at its half AVF instead of its full AVF, different results would be expected based on what is already discussed.

Metro platforms. Several parameters were considered to evaluate the effect of the APs on the PM2.5 concentrations at the platform, including their air volume flow (half or full power), the number of APs functioning and their location. Special experiments with APs operating for 2 hr, 1 hr and 30 min on/off measurements were carried out.

It is worth noting that no significant difference was observed when only 4 APs were used in various locations, indicating constant PM emissions and the complexity of metro systems. However, with 8 APs operating at full flow, a notable improvement in air quality was observed, highlighting the positive impact of the air purifiers on air quality. The negative correlation between the APs and PM2.5 concentrations emphasizes the importance of clustering multiple APs to achieve a significant effect in environments where polluted air is constantly exchanged due to frequent train movement, especially in the stations with double platforms in which trains move in both directions.

When looking at the impact of using 8 APs at full power in the Quinta das Conchas platforms from 08 to 20h (when the general ventilation in the station is on), we observe that despite the maximum AVF, air quality differences remained between the left sector (stronger ventilation) and the right sector (weaker ventilation). In the left sector, PM2.5 concentrations did not decrease independently on whether the APs were on or off, showing a 4-13% increase, although we should consider that concentrations were always very low (2.5-4.3 $\mu g/m^3$). In contrast, the APs had a more significant impact on air quality in the right sector, reducing PM2.5 concentrations by 18-25% (9.1-14.5 $\mu g/m^3$).

Considering that this set-up achieved the largest reduction on PM concentrations during the day a shorter analysis was done measuring only during 2 hours to see how to get the maximum effect with minimum energy consumption. Two measuring periods were considered:

- from 8-10h in the morning, rush hour with the station ventilation on, higher reductions in PM concentrations were observed in the right sector (28-42%) compared to the left sector (18-37%) when the APs were on in addition to the platform's ventilation. This indicates the higher the PM concentrations, the greater the influence of the APs on them. This should be considered during the APs installation and operation of APs.

- from 20-22h in the evening, when the ventilation in the station was off and only the APs were on. This case resulted in the biggest reduction on PM2.5 concentrations of all setups tried. A reduction of 31-47% was observed on the right sector of the platforms. Notably, a high PM reduction was also observed in the left sector (72-77%), highlighting the air purifiers' effectiveness, especially when the ventilation is off. Again it should be noted that in this sector PM concentrations were lower (2.9-4.8 µg/m^3), so percentage differences are more obvious. This scenario is transferable to most metro stations that do not have forced ventilation.

Based on these findings, the APs should be used especially in those cases when there is no general ventilation, or when this is not evenly distributed, or when concentrations are highest (e.g. during the rush hours etc.).

5. DEVIATIONS FROM THE PLAN

Two measuring campaigns were carried out in AUVASA bus depot in Valladolid as planned. In the case of the measurement campaigns at metro stations, the original plan was to have a first campaign in Lisbon Metro and a second one was planned to be done in Sofia (Bulgaria). However, due to encountering major logistical challenges mainly related to bureaucratic paperwork, local regulations and major restrictions for access to the station due to national security reasons, it was finally decided to also have the second campaign in Lisbon Metro, but in a different station.

6. LINKS WITH OTHER WPS

WP3 is closely related to WP4 (Sustainability Assessment) and WP5 (Dissemination and Exploitation), and all data generated are used in both of them. WP4 uses the results of WP3 on the study to reduce human exposure and environmental impact of brake-wear and engine exhaust.

7. CONCLUSIONS AND RECOMMENDATIONS: BEST PRACTICE GUIDE FOR RETROFITTING AIR PURIFIERS TO SPECIFIC CLOSED ENVIRONMENTS

This document summarises the methodology applied in bus depots and metro platforms to achieve the best possible results when using air purifiers.

It should be noted that the installation of air filtration systems in existing metro infrastructure presented significant technical and operational challenges due to various physical and logistical constraints. During the installation phase, several stations limitations were identified, including low ceilings, short platforms, the presence of wall-mounted artwork, and restricted access points. The equipment, filtration units exceeding two meters in length and weighing over 350 kg, required detailed planning for safe handling and positioning. All installation activities were conducted during non-operational hours, needing close coordination between maintenance, logistics and security teams.

Despite these constraints, the implementation of the two pilots in Lisbon Metro proceeded without major incidents. Overall reception of the project was positive. Informational displays were installed to explain the function of the equipment, contributing to passenger awareness and engagement. Noise levels remained within acceptable thresholds, with some variation depending on station characteristics. Minor incidents of vandalism (graffiti) were recorded during the final stages, but overall disruption was minimal.

Our results from measurements in AUVASA bus depot and Lisbon Metro stations demonstrate that:

(1) Given the complicated nature of the problem, with pollutants being emitted from different sources then mixing and moving through the depot and through tunnels and platforms in the metro, we recommend for any action an initial air quality audit aiming to assess the nature of the existing air quality in the closed environment. This initial study will need to obtain measurements of inhalable PM mass concentrations on the site, so the patterns of pollutants are established and problem areas identified.

(2) Several variables that can affect the air quality in the closed environment should also be considered, including air pollution conditions in the immediate outdoors, the design and dimensions of the area to be assessed, the ventilation mechanisms being operated, and the frequency/intensity of traffic (number of buses or trains running).

(3) Determining the number of air purifiers (APs) to use requires a balance between air-cleaning effectiveness and cost, including both initial investment and ongoing expenses (e.g., energy and filter replacements). Operating costs can be optimized by using APs on demand, based on real-time PM sensor readings. In any case, the number should be decided after considering the dimensions of the site and the specific variables affecting air movements.

(4) Using an optimal number of air purifiers (APs) in key microenvironments, particularly during rush hours and maintenance operations, offers an effective and promising way to improve air quality and the quality of the working environment for the employees working in the depot and the passengers in the metro platform.

(5) Best practices for installing APs should focus on locating them in the zones where PM levels show the highest concentrations (less than 6 m away from the main pollutants source). The ejection orientation of the APs should be upward (e.g. 45°) or horizontal (e.g. 0°) for higher and faster removal of PM and never downward (e.g. -45°), as the latter can cause more recirculation and less distribution of the purified air. Crossed airflow should be avoided to reduce turbulence and consequently PM resuspension.

(6) If located in the correct place (following advice above) APs working at full power can considerably reduce PM2.5 concentrations (up to 40% reduction was shown on the metro platform).

(7) Regarding operational and installation issues, several potential future applications have been identified for this type of equipment:

- Temporary Ventilation Reinforcement: Deployment of mobile filtration units during planned maintenance works to reduce airborne particulates.
- Targeted Improvements: Implementation of localized mitigation measures, such as airflow adjustments or additional filtration in areas with recurring air quality issues.
- Portable Equipment: Assessment of modular or mobile filtration solutions for use during temporary events or specific incidents.
- Energy-Efficient Ventilation: Optimization of fan operation based on real-time air quality data to improve efficiency and environmental performance.
- Integration in Future Station Design: Inclusion of air quality requirements in the early planning stages of new or refurbished stations, incorporating airflow modelling, sensor systems, and adaptable infrastructure.

(8) The use of APs potentially presents a social and economic benefit especially in those cases when there is no HVAC ventilation, or when this is not evenly distributed, or when concentrations are highest (e.g. during the rush hours etc.).

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