AIMS Environmental Science

http://www.aimspress.com/journal/environmental

AIMS Environmental Science, 3(2): 199-219.
DOI: 10.3934/environsci.2016.2.199
Received 15 December 2015,
Accepted 23 March 2016,
Published 31 March 2016

Research article

Particulate matter levels and comfort conditions in the trains and platforms of the Athens underground metro

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Abstract: A study of indoor environmental quality inside the old (naturally ventilated) and new (air-conditioned) train cabins and platforms of four main stations of the Athens subway system (Attiko Metro), took place in different two-day measurements from June to August 2012. Portable instrumentation provided continuous measurements of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1), carbon dioxide (CO_2) along with temperature (T) and absolute humidity (AH). PM concentrations were significantly higher on the underground platforms of the network from 3 to 10 times, as compared to outdoor measurements. In particular, mean PM_1, $PM_{2.5}$ and PM_{10} concentrations at the deeper and most crowded station of Syntagma reached 18.7, 88.1 and 320.8 $\mu g\ m^{-3}$ respectively. On the contrary, the ground level, open station of the Airport, showed values comparable to the outdoor (2, 6.4 and 34.4 $\mu g\ m^{-3}$, respectively). All PM fractions were lower than the platforms inside the old and new train cabins while the air conditioned trains experienced lower particulate pollution levels. More specifically, mean PM_1, $PM_{2.5}$ and PM_{10} concentrations were 5.5, 16.8 and 58.3 $\mu g\ m^{-3}$, respectively in new cabins while in the old they reached 10.3, 47.5 and 238.8 $\mu g\ m^{-3}$. The $PM_{2.5}/PM_{10}$ and $PM_1/PM_{2.5}$ ratios did not exceed 0.33 on both platforms and trains verifying the dominance of crustal coarse particles originating from the train and ground materials. As expected CO_2 levels were higher inside the trains as compared to the platforms and in some cases surpassed the 1000 ppm limit during the hottest days of the experimental campaign. Temperature and humidity remained relatively stable on the platforms, whereas measurements inside the cabins fluctuated, depending on the type of train and track locations. Correlations between measured PM along the routes to and from the Airport indicated covariance of concentrations along train cabins of the same direction.

Keywords: PM_{10}; $PM_{2.5}$; PM_1; Athens underground; indoor air quality; train cabins; transport microenvironment

1. Introduction

The modern way of life has lead commuters to spend 8% of a working day inside public transport means such as the underground systems in order to reduce travelling times and avoid traffic congestion [1,2]. The behavior of pollutants in the particular microenvironment is of great interest because of the large number of passengers present, the dependence on mechanical ventilation, the indoor pollutant sources and the exchange rates with the frequently polluted urban air. This diversified microenvironment observed on platforms and train cabins of underground metro networks presents higher levels of particulates as has been observed by numerous studies conducted globally [3]. The association between elevated levels of particles, particularly the finer fractions (2.5 μm or less), with adverse health effects has been well documented [4-8].

According to [9], that monitored the PM levels at the Taipei underground system platforms and cabins, the residence time of people has increased. More specifically it is important to know the exposure times of employees of the underground system as well as of vulnerable population groups (elderly and/or children) [10], since [11] found that spending 2h in the metro system of London per day would increase personal 24-h exposure of $PM_{2.5}$ by 17 μg m^{-3}.

In this respect, measurements in the subway of Helsinki demonstrated that concentration levels of PM in the underground environment were 3 to 4 times higher compared to the corresponding external [1]. This behaviour seemed to be more pronounced during the summer period as cases of discomfort for passengers and employees especially in non air conditioned cabins were reported. It should be noted that in the subway system of Beijing (where there is a mechanical ventilation system and natural openings are closed) internal concentration of particles was mainly influenced by external sources [12]. In the Buenos Aires subway, one of the oldest in the world, concentrations of total suspended particles (TSP) were measured at different stations, both underground and ground level. They were up to 3 times higher in the underground stations, while chemical analyses demonstrated the presence of iron (Fe) and copper (Cu) originating from ground excavations and zinc (Zn) that is associated with vehicle traffic [13]. In the study of [14], for the assessment of exposure to fine particulate matter ($PM_{2.5}$) in relation to the means of transport used (metro, bicycle, bus and car) in the city of London, 3 to 10 times higher concentration levels were recorded in the subway which was the most burdened means of transfer. Moreover, fluctuations of exposure to particles showed strong seasonality (higher in summer). The researchers also stressed the fact that the chemical composition of fine particles in the underground is different from that of the road surface as it consists of iron (Fe) and silicon (Si). Similarly, at the Stockholm subway, passenger exposure levels to PM were 5 to 10 times higher than those measured at the most crowded streets [10]. In line with the reports above, PM_{10} and $PM_{2.5}$ consisted of iron (Fe), manganese (Mn) and copper (Cu) which probably are produced by construction materials. Regarding the chemical composition of particulates, [15] reported that the underground suspended particles are more toxic than those of the surface due to the presence of iron (Fe). Similar studies with extensive chemical analyses were carried out in the subways of Budapest [16], Milan [17], Zurich [18], Mexico City [19], Seoul [20-22], Istanbul [23] and Barcelona [24-26].

High concentrations of suspended particles have also been measured in other subway systems all over the world, as in Rome [27] where PM_{10} and $PM_{2.5}$ levels were 3.5 times higher in the platforms and tunnels compared to the local roads, Prague [28], Berlin [29], New York [30,31], Montreal [32], Paris [33] and Sao Paulo [34]. Experimental measurements in newer underground rail networks such as that of Los Angeles (1993 operating year) showed that levels of PM_{10} and $PM_{2.5}$ were 2.5 and 2.9 times higher than those of the outside environment. Measurements were also performed at the ground level part of the rail, which proved that the concentrations of PM_{10} and $PM_{2.5}$ were strongly correlated with the external values of particles but at lower levels than those of the underground network [35]. Generally most studies concluded that the levels of suspended particles were associated with the ventilation system, the frequency of routes, the construction features of the trains and the maintenance of the lines [26]. In light of the above, efforts are being made to improve the air quality in burdened underground systems, such as in the Hong Kong Motor Rail Transport system where the active ventilation and the instalment of full height glass platform screen doors across the stations have improved the air quality making it less polluted than bus, train cabins and bus stations [36].

The Athens underground network (Attiko Metro) is one of the newest in the world and commenced operating in 2000. Previous short measurements of TVOCs, PM_{10}, $PM_{2.5}$, PM_1, T and RH that were performed in train cabins in order to develop a fuzzy inference system to assess air quality, identified elevated pollutant levels although measurements were limited to draw conclusions on the spatial and temporal variations of the pollutants [37]. Moreover, [26], measured $PM_{2.5}$ concentrations and performed chemical analyses of the samples collected in three European subway systems including Athens on selected platform stations and outdoor environments as well as some measurements during travel times. The Athens measurements took place at a suburban area station that is close to the ground for a route travelled and showed that $PM_{2.5}$ concentrations were higher in the platform and during the train travel time than in the outdoor air, while the train frequency affected their levels. Concentrations were lower at night-time when the station was closed. The chemical analyses, in agreement with previous researchers indicated that higher metal concentrations were found on the subway platforms compared to ambient air. Fe was the most abundant element, followed by other metals originating from rails, wheels and brakes (e.g. Ba, Cu, Mn, Zn etc.).

Within that frame, the main aim of this work is to present results from the experimental campaign that took place in the platforms and train cabins of the Athens underground network (Attiko Metro) from June 27 to August 9, 2012. More specifically, the concentrations of PM_{10}, $PM_{2.5}$ and PM_1, CO_2, as well as temperature, relative humidity and the number of passengers were monitored during six two-day periods from 6:30 am to 7:00 pm. The scope of the experimental campaigns was to: a) Identify the air quality status and indoor environmental conditions within the old (naturally ventilated) and new (air-conditioned) train cabins while travelling across the whole length of Line 3, b) monitor the air quality on four main platforms along the train route located at different depths below ground (Syntagma, Egaleo and D. Plakentias) and at ground level (Airport), c) examine the influence of outdoor environmental conditions on the indoor quality.

2. Experimental site, instrumentation and methodology

2.1. Description of Athens

The Greater Athens Area (including the Athens basin) features a complex topography (covering an area of 450 km^2 with approximate 4 million inhabitants), surrounded by mountains to the east, north and west and the sea to the southwest. The Thriassion Plain is located to the west of the Athens basin (mainly an industrial zone) and the Mesogia Plain is located to the east, a rural and suburban rapidly developing area due mainly to infrastructure works such as new highways and the Athens International Airport. The topographical features in combination with the local pollution sources (traffic, central heating, industries, shipping) and the prevailing weather conditions (sea-breeze cells, strong temperature inversions, calm wind) that impede ventilation, lead to pollution episodes in the summer [38,39].

Athens, lies at the southeastern-most part of the mainland of Greece and enjoys a prolonged warm and dry period during the year with July and August being the hottest and driest months. The normal value of the summer (JJA) daily maximum temperature (Tmax) at Athens (NOA) is 31.6 °C while the 90th/95th percentiles correspond to 35.3 °C/36.3 °C, respectively [40]. During the monitoring period three consecutive heat waves occurred with maximum temperatures higher than 37 °C for more than three consecutive days, i.e. from 9 to 17/7 (Tmax = 40.5 °C), from 28/7 to 1/8 (Tmax = 38.3 °C) and from 6 to 10/8 (Tmax = 40.9 °C), making this a very hot summer with poor comfort conditions.

2.2. Experimental methodology and instrumentation

The Athens subway system (Attiko Metro) is the only underground network in Greece. In 2012 it consisted of 3 lines with 54 stations in total [41]. On a daily basis, an average of 614,000 commuters uses it. Line 1 has been operating since 1869 and its largest part is over ground, while the modern lines 2 and 3 commenced operation in 2000 and are almost entirely underground. Line 3, where the measurements took place, had at the time 20 stations covering a distance of 37.7 km across the Athens basin from the Athens International Airport to the northeast to Egaleo at the southwest. The only terrestrial part of the line is between the stations of D.Plakentias and the Airport. In Figure 1, the Attiko Metro network is presented.

Figure 1. Map of Athens subway system (2012).

Two types of train were in service on lines 2 and 3 in the subway: a) First generation (manufactured in 1999) naturally ventilated through windows, non-air-conditioned and commuting strictly on the underground part of the network (from Egaleo to D. Plakentias) and b) Second generation (manufactured in 2003) air-conditioned, travelling with windows closed and covering the whole Line 3 route (Egaleo to the Airport). Both types of train consisted of 7 wagons (cabins). The frequency of the routes depended on the time of the day. During the rush hours the frequency of train service was 3 minutes and for the rest of the day it was 10 minutes.

The experimental instrumentation consisted of portable continuous recording equipment. More specifically, Tinytag Plus 2 thermo-hygrometers were used for T and RH measurements, Turnkey Osiris and Lighthouse Handheld 3016 continuous monitors of mass particulate pollution (PM_{10}, $PM_{2.5}$ and PM_1) and CO_2 concentration monitors IAQ RAE and MultiRAE IR. All parameters were measured at 10 seconds intervals and quality assurance of instrumentation was achieved by inter-calibration measurements. It should be noted that hourly values of temperature, relative humidity, wind speed and gaseous pollutants were obtained from the National Observatory of Athens [42], the Ministry of Environment [43] and the Athens International Airport Environmental Services [44].

In-cabin, measurements were taken in the middle - car of the moving trains and at 1 m from the ground (approximately the breathing height). As for stations, measurements were taken on the platform's end, 5 minutes before the departure of each train and for 5 minutes after its arrival to the station. The selected platforms were Egaleo (suburban traffic—approximately 20 m below ground), Syntagma (centre traffic—approximately 200 m below ground), Doukissis Plakentias (suburban traffic—approximately 50m below ground) and the Airport (ground level) (Figure 1).

At the end of the experimental campaign, raw data were examined qualitatively and quantitatively and were analysed firstly with the aid of boxplot diagrams. The median, minimum, maximum, first and third quartile (25% and 75%) of every distribution is indicated simultaneously along with the dispersion and the existence of outliers. The distance between the two quartiles is denoted as the interquartile range (IQR) while the median refers to a perpendicular equal to the width of the box. From each lateral side, a line is extended from the maximum to the minimum value on condition that they do not exceed the IQR by 1.5 times. These lines are labeled as whiskers. The ±1.5 IQR interval is called inner fence and ±3 IQR is the outer fence. Values outside the inner fence are considered suspected outliers while those outside the outer fence, extremes. Figure 2 describes in detail the structure of a boxplot.

The relative humidity data (RH) were converted to absolute humidity (AH) as that is a conservative property, independent from temperature. Absolute humidity was calculated by the following formula proposed by [45]:

$$AH = \frac{6.112 \times e^{\frac{17.67 \times T}{T+243.5}} \times RH \times 2.1674}{273.15 + T}$$

where, T is the temperature in °C and RH is relative humidity in %. AH values are measured in g_{H2O} m^{-3}.

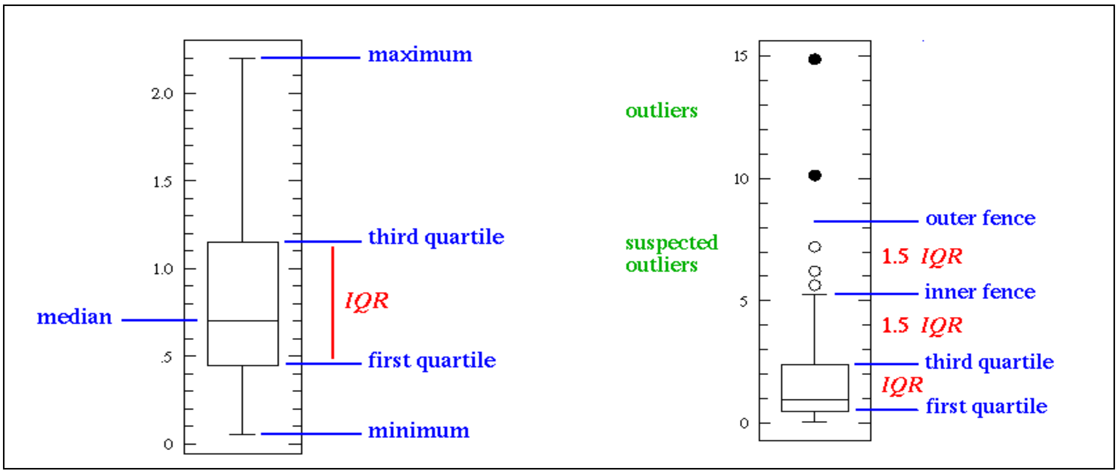


Figure 2. Description of a boxplot.

3. Results and discussion

Particulate pollution appears increased on platforms compared to the train cabins. Indicatively, the average concentrations of PM_1, $PM_{2.5}$ and PM_{10} on all platforms were 12.16 µg m^{-3}, 50.18 µg m^{-3} and 195.27 µg m^{-3} respectively while in the cabins they reached 7.49 µg m^{-3}, 26.06 µg m^{-3} and 89.22 µg m^{-3}. This may be attributed to the in-tunnel particulate sources (sparks of rubbing when trains commute on rails, brakes of trains, ventilation system, construction and maintenance works), the frequency of train arrivals as well as the number of commuters, that directly affect the platform microenvironment (which is open) and secondarily the cabins (that mostly travel with closed windows and are confined spaces). In both cases, the majority of the recorded values exceeded the respective 24 hr-average exposure limits of $PM_{2.5}$ (25 µg m^{-3}) and PM_{10} (50 µg m^{-3}). A plethora of PM outliers was also observed, which for the case of platforms are related with the piston effect—as the train travels the confined air is forced to move along the tunnel. Behind the moving vehicle suction is created and the air is forced to flow into the tunnel. This movement of air by the train is similar to the operation of a mechanical piston and affects the recording of the instruments located on a platform, causing instant increase of PM levels. Outliers in cabins are observed due to frequent movement of the passengers inside and/or the occasional window-opening.

On the other hand, the average CO_2 concentration in cabins reaches 796 ppm and that of the platforms does not exceed 598 ppm. This result makes sense, as numerous passengers huddle in the limited space of the train cabin and a large amount of CO_2 is released by exhalation. For that reason many outliers are observed in cabins and very few on platforms.

In general the temperature levels were elevated on all platforms as compared to the trains. More specifically, the average temperature on the platforms was 30.7 °C while in the cabins it did not exceed 28.8 °C. This may be attributed to the fact that the new generation trains are air-conditioned.

3.1. Station platforms

Regarding the station platforms, Tables 1 and 2 present the overall environmental quality status and Figures 3 and 4 the boxplot diagrams. In order to ensure that differences between various stations are statistically significant, a Kruskal-Wallis (non-parametric) test ($p < 0.05$) was applied since the measured data are highly skewed (as can be seen from Figures 3 and 4). Each case includes four grouping variables (station platforms) and one parameter. For all cases the p-value computed was very close to zero, demonstrating a statistically significant difference between pollutants among the stations.

Table 1. Descriptive statistics of PM and CO_2 for all platforms.

		Platforms			
		Egaleo	*Syntagma*	*D.Plakentias*	*Airport*
PM_1 ($\mu g\ m^{-3}$)					
Mean		3.8	18.7	4.9	2
Minimum		1.5	1.8	1.7	.7
Maximum		9.8	69.9	29.2	21.7
Percentiles (median)	25	2.8	9.7	3.6	1.2
	50	3.6	16.8	4.1	1.7
	75	4.5	26.4	5	2.4
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000
$PM_{2.5}$ ($\mu g\ m^{-3}$)					
Mean		14.2	88.1	20.9	6.4
Minimum		5.5	8.31	6.9	3.3
Maximum		50	294	127.5	45.8
Percentiles (median)	25	10.2	55.8	14.4	4.5
	50	12.5	84.6	16.8	5.6
	75	16.7	116.4	20.7	7.9
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000
PM_{10} ($\mu g\ m^{-3}$)					
Mean		90.5	320.8	105	34.4
Minimum		16	30.6	21.3	9.7
Maximum		290.2	974.5	814.5	321.7
Percentiles (median)	25	64.8	221	77.7	21.3
	50	81.4	305.3	95.3	28.7
	75	106.4	407.4	116.4	43.5
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000
CO_2 (ppm)					
Mean		771	649	516	791
Minimum		389	511	320	350
Maximum		1109	1864	1700	1156
Percentiles (median)	25	64	221	78	21.3
	50	816	627	420	814
	75	106	407	116	43.5
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000

Table 2. Descriptive statistics of temperature and absolute humidity for all platforms.

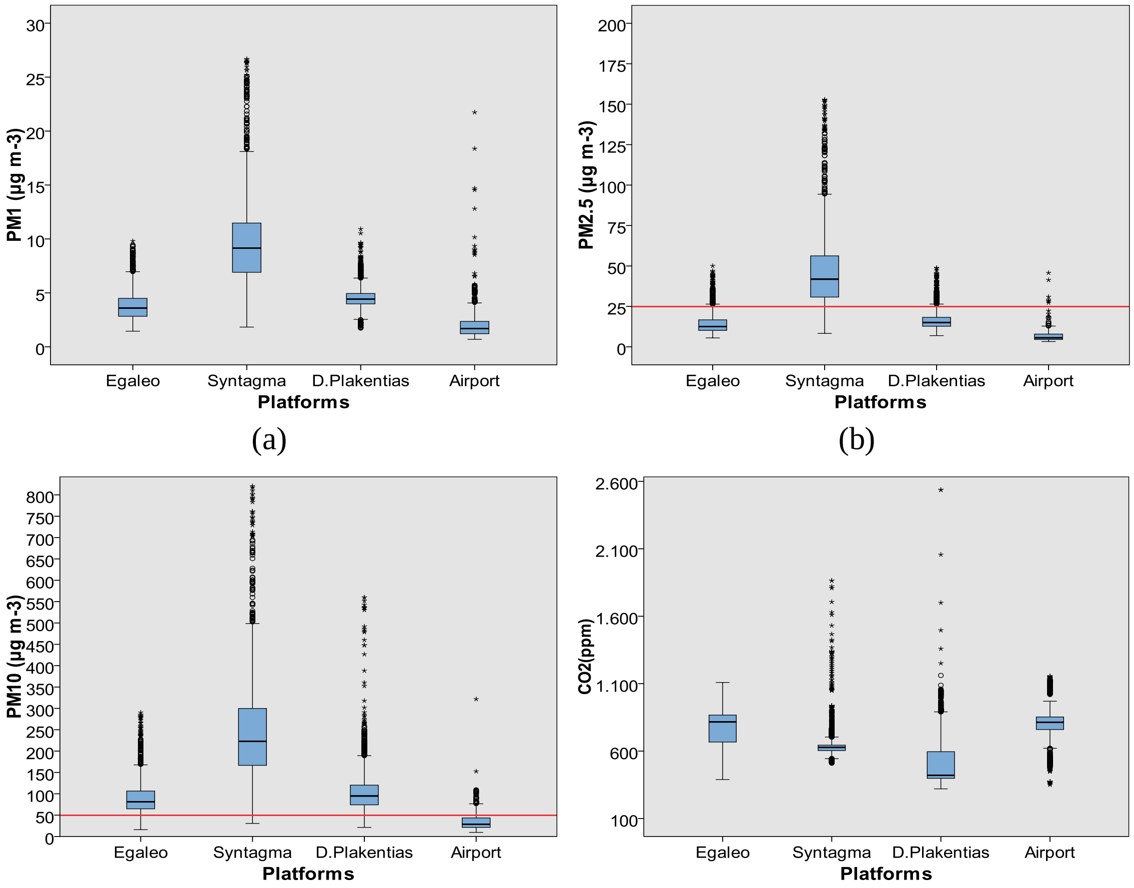
		Platforms			
		Egaleo	*Syntagma*	*D.Plakentias*	*Airport*
T (^{o}C)					
Mean		29.1	30.7	32.3	28.4
Minimum		24.5	26.8	27.1	25
Maximum		32.7	32.5	34.8	32.6
Percentiles	25	28	30.5	30.9	27.4
(median)	50	29.1	30.8	32.9	28.2
	75	29.9	31	33.7	29.5
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000
AH (g m^{-3})					
Mean		13.6	15.4	11.1	12.6
Minimum		9.1	11	7.8	7.8
Maximum		23	21.7	20.2	17.7
Percentiles	25	11.6	14.8	9.7	10.1
(median)	50	13.1	15.6	10.9	12.1
	75	15.5	16.1	12.3	15.1
Kruskal-Wallis (H) test (*p*-value)		.000	.000	.000	.000

The most congested microenvironment was the platform of Syntagma, the central and deeper underground station. The average concentrations of PM_1, $PM_{2.5}$ and PM_{10} were 18.7 μg m^{-3}, 88.1 μg m^{-3} and 320.8 μg m^{-3} respectively, the PM_{10} maximum being 974.5 μg m^{-3}. D.Plakentias and Egaleo stations presented lower PM levels. The open (ground level) platform of the Airport indicated the lowest PM concentrations with mean values of 2 μg m^{-3}, 6.4 μg m^{-3} and 34.4 μg m^{-3} for PM_1, $PM_{2.5}$ and PM_{10}, about a 1/10 of those of Syntagma. Figure 3c shows that PM_{10} concentrations exceeded the 24-hour limit at all platforms, except in the Airport platform. In Figure 3b, it is observed that only Syntagma station presents $PM_{2.5}$ concentrations over the annual limit of exposure. Moreover, a significant number of outliers (1.5 and 3 times the inter-quartile range) was observed. The appearance of these values is associated with the arrival of trains at the stations and the movement of passengers, where the particles re-suspend and the instrumentation records momentary peaks.

The highest carbon dioxide levels were recorded at the Airport platform. The average concentration was 791 ppm with a maximum of 1156 ppm. Similar concentrations were recorded at the Egaleo station (771 ppm) a relatively small but crowed platform, especially in the morning and evening rush hours. The majority of outlier values are observed at Syntagma station owing to the large numbers of passengers. D.Plakentias station exhibited the lowest mean concentration (516 ppm), (Figure 3d).

Elevated temperature levels were observed at D.Plakentias station (average value 32.3 °C). The same platform also presented the highest maximum temperature compared to all others (34.8 °C). This may be attributed to the fact that the platform is quite close to the ground and because a big part of the roof is made of glass thus allowing the solar radiation to enter. The lowest average temperature was recorded at the Airport platform (28.4 °C), which was excepted since it is open.

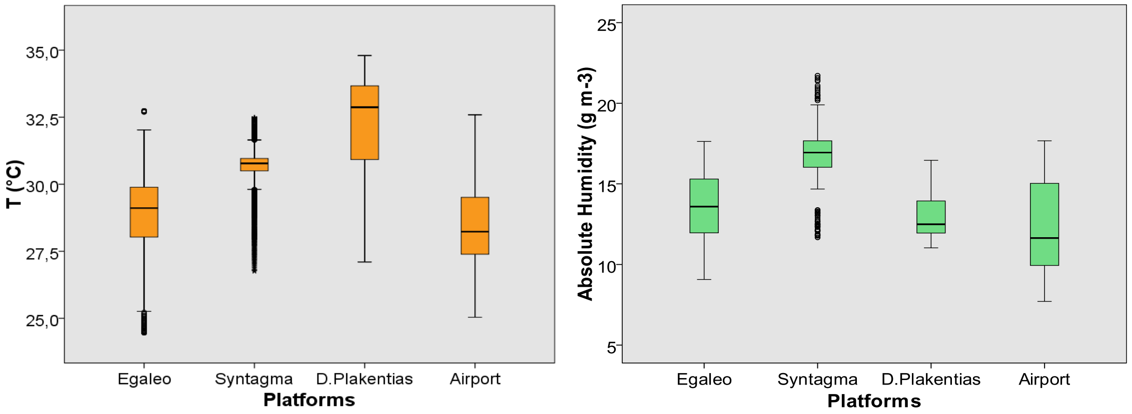
Absolute humidity varies for each station. The highest concentration was found in Syntagma (15.4 g m^{-3}), followed by Egaleo (13.6 g m^{-3}), the Airport (12.6 g m^{-3}) and D.Plakentias (11.1 g m^{-3}). Concentrations of humidity are influenced by the operation of the ventilation system and the presence of people.



(a) (b)

(c) (d)

Figure 3. Concentrations of (a) PM_1, (b) $PM_{2.5}$, (c) PM_{10} and (d) CO_2 for all platforms. The horizontal line represents the respective limit.



(a) (b)

Figure 4. Levels of (a) temperature and (b) absolute humidity in all platforms.

3.2. *Old and new train cabins*

The analysis of results shows that old train cabins are more burdened than the new ones. A Mann-Whitney (non-parametric) test ($p < 0.05$) has been applied to investigate if the differences of values are statistically significant. New and old trains were examined in pair-wise comparisons for every parameter (PM, CO_2, T, and AH). The results indicate that the two types of trains have statistically significant differences as the p-value of all parameters approaches zero. Table 3 summarizes the results.

Table 3. Descriptive statistics of PM and CO_2 for both types of cabins.

		new trains				*old trains*			
		PM1 (μg m^{-3})	PM2.5 (μg m^{-3})	PM10 (μg m^{-3})	CO2 (ppm)	PM1 (μg m^{-3})	PM2.5 (μg m^{-3})	PM10 (μg m^{-3})	CO2 (ppm)
Mean		5.5	16.8	58.3	826	10.3	47.5	238.8	684
Minimum		0.7	2.3	3.1	350	2	8.2	289	408
Maximum		85.8	291.7	492.9	2204	30.1	159	1081.9	2384
Percentiles	25	2.1	6.6	25	763	7	27.8	116.4	572
(median)	50	3.8	11.6	46	824	9.3	40.8	185.6	728
	75	6.2	20.4	76.5	872	12.6	59.2	315.5	777
Mann-Whitney (U) test (*p*-value)		.000	.000	.000	.000	.000	.000	.000	.000

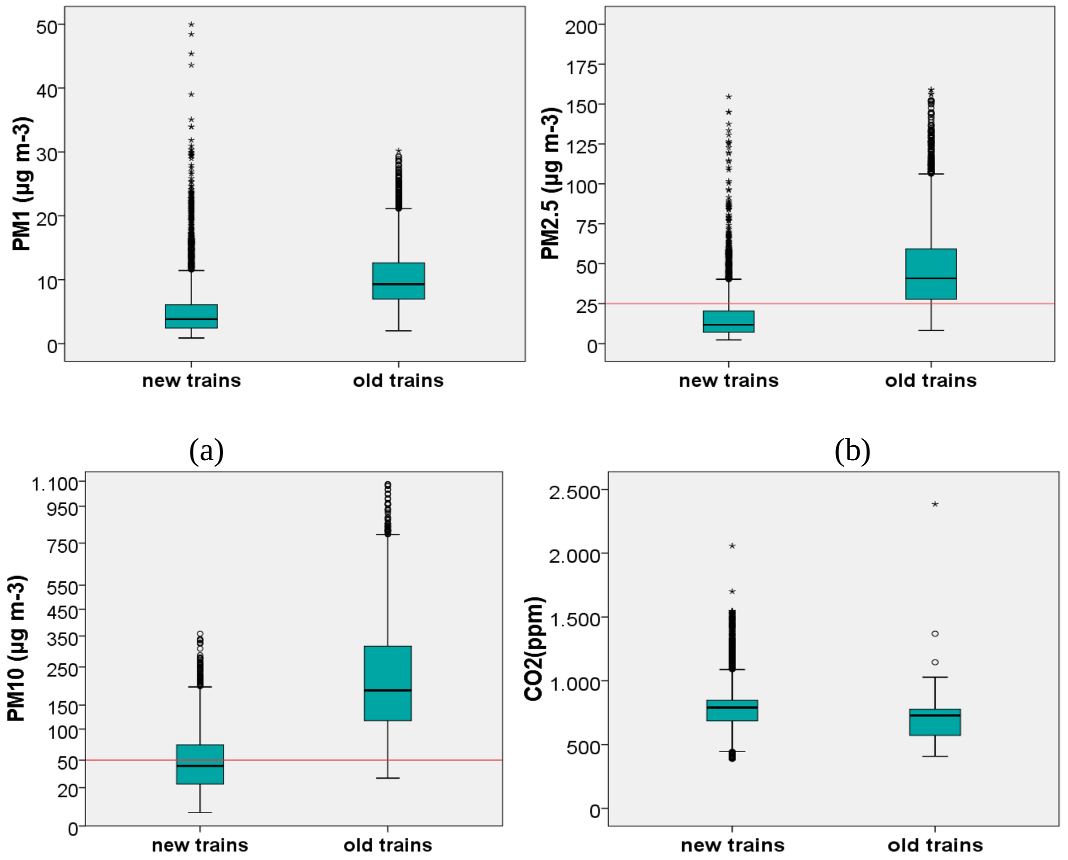
The particulate concentration range in the two types of train cabins is quite large. Measurements in old cabins indicated average PM_1, $PM_{2.5}$ and PM_{10} concentrations of approximately 10.3 μg m^{-3}, 47.5 μg m^{-3} and 238.8 μg m^{-3} while in the new they were lower, i.e. 5.5 μg m^{-3}, 16.8 μg m^{-3} and 58.3 μg m^{-3} respectively. It becomes obvious that in new (air-conditioned) trains, the PM concentrations are 2 to 4 times lower. This may be explained by the fact that over the summer period in air-conditioned cabins most of the windows are closed while in old ones they remain open. The open windows in a moving cabin in an underground tunnel will lead to increased PM concentrations even though the commuter perceives the illusion of natural ventilation. All PM fractions appear numerous outlier values because of the re-suspension phenomenon caused by the movement of passengers within the cabin, the regular door opening and the open windows. It is also noted that in the new trains travelling to the Airport, higher particle concentrations were recorded compared to the opposite direction (i.e. towards Egaleo), most probably due to a greater number of passengers on these routes.

The mean concentration of carbon dioxide in the new (air-conditioned) cabins reached 826 ppm and was higher than that of the old ones (684 ppm), although they do not differ much when examining the 50% median. In closed air-conditioned cabins, the air renewal rate is lower thus leading to higher CO_2 levels from exhalation, while natural ventilation through windows helps keep CO_2 at lower levels. Figure 4 shows the behavior of airborne particles and carbon dioxide inside old and new trains for all experimental days. One may also observe that even though the median and quartile values for all PM fractions are lower for the new trains, the outliers are more and in some cases exceed the values measured in the old trains especially the finer PM fractions. This may be attributed to the frequent door opening at the stations and the performance of the ventilation system that can filter coarser particles more effectively.

The average recorded temperature in the new trains reached 28.4 °C while the concentration of the mean absolute humidity was found to be 13.7 g m^{-3}. These values, as expected, are lower than those of the old trains (31.5 °C and 17.6 g m^{-3}) since the air conditioners contribute to the air temperature reduction and to dehumidification (Table 4). This behavior is due to the non-continuous operation of the air conditioning, the quick change in the number of passengers in the limited space of the cabin and the influence of the terrestrial segment of the metro (Figure 6).

Table 4. Descriptive statistics for temperature and absolute humidity for all types of cabins.

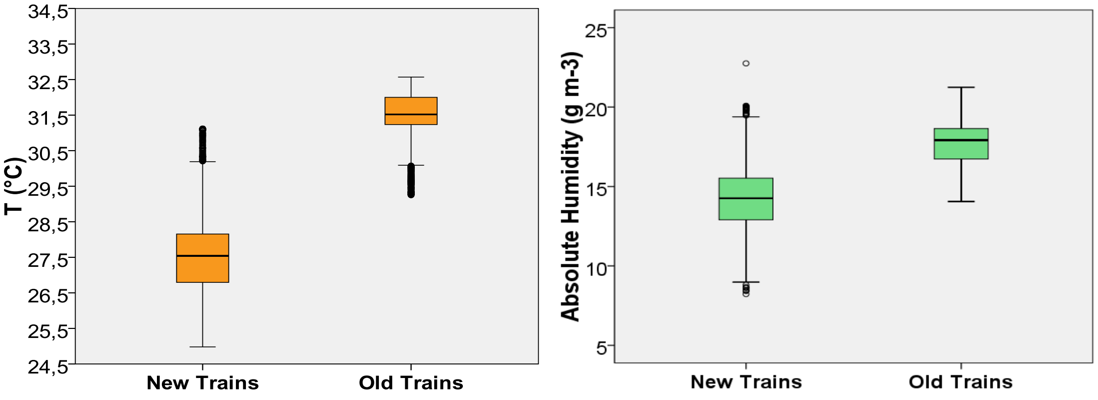
		new trains		*old trains*	
		T (°C)	AH (g m^{-3})	T (°C)	AH (g m^{-3})
Mean		28.4	13.7	31.5	17.6
Minimum		24.6	7	29.3	14.1
Maximum		33.9	22.8	32.6	21.2
Percentiles	25	27.7	12.4	31.3	16.7
(median)	50	28.3	13.7	31.5	17.9
	75	29.2	14.9	32	18.6
Mann-Whitney (U) test (*p*-value)		.000	.000	.000	.000



(a) (b)

(c) (d)

Figure 5. Concentrations of (a) PM_1, (b) $PM_{2.5}$, (c) PM_{10} and (d) CO_2 inside the cabins. The horizontal line represents the respective limit.



(a) (b)

Figure 6. Levels of (a) temperature and (b) absolute humidity in cabins.

A statistical comparison of PM_{10} at the central station of Syntagma and within the train cabins is presented in Table 5. Because of the highly skewed data distributions, Spearman's rank correlation coefficient (rho) has been applied. The results vary, depending on the location in the subway. The primary observation is that within the trains, routes of the same direction showed very good correlations, while those of antisense are strongly negative, which demonstrates the covariance of PM_{10}. The Syntagma platform values did not show any significant correlation with those measured inside the train cabins indicating that the cabin microenvironment is relatively independent from the tunnel besides the frequent door and window opening.

Moreover, another correlation that was examined was the CO_2 concentrations with the number of passengers between the Syntagma platform and the train cabins. As a product of exhalation, CO_2 is inextricably associated with the human presence in indoor environments. A linear regression of the two variables is presented in Figures 7 and 8. Due to the remarkable skewness and kyrtosis of the raw data, a logarithmic transformation was implemented to the CO_2 data.

Inside the trains, CO_2 varies depending on the number of passengers. The coefficient of determination (R^2) is equal to 0.205 while the correlation coefficient (R) was found to be 0.452. The p-value of the ANOVA (parametric) test ($p < 0.05$) approached zero, indicating a high level of significance. It is clear that, 20.5% of the variability of CO_2 concentrations can be accounted to the number of passengers and that there is a moderate correlation between the two variables. In the limited space of a cabin, CO_2 is slightly influenced by the presence of commuters. The air flowing through the open windows may reduce concentrations and affect correlations. On the contrary, CO_2 concentrations at the platform do not seem to be influenced by the commuters. The station is large enough to create a microenvironment without major fluctuations of CO_2. Characteristically, R^2 and R are 0.066 and 0.258 respectively, indicating that only 6.6% of the variability of CO_2 is explained by the changes in passengers' numbers, while the correlation between the two variables was found to be relatively weak.

Table 5. Spearman correlations of PM_{10} between routes of trains and the platform of Syntagma. Every route is denoted with the letter ''R''. Routes with odd number represent one direction and with even number the reverse. Notice the strong correlations for routes of the same direction.

PM_{10} Routes of Trains vs. Syntagma station			R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Syntagma
Spearman's rho	R1	Cor. Coef.	1.000										
		Sig. (2-tailed)	-										
	R2	Cor. Coef.	-.190**	1.000									
		Sig. (2-tailed)	.000	-									
	R3	Cor. Coef.	.648**	-.459**	1.000								
		Sig. (2-tailed)	.000	.000	-								
	R4	Cor. Coef.	-.321**	.466**	-.414**	1.000							
		Sig. (2-tailed)	.000	.000	.000	-							
	R5	Cor. Coef.	.607**	-.372**	.778**	-.397**	1.000						
		Sig. (2-tailed)	.000	.000	.000	.000	-						
	R6	Cor. Coef.	-.301**	.774**	-.554**	.556**	-.444**	1.000					
		Sig. (2-tailed)	.000	.000	.000	.000	.000	-					
	R7	Cor. Coef.	.524**	-.306**	.762**	-.215**	.791**	-.254**	1.000				
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	-				
	R8	Cor. Coef.	-.166**	.737**	-.393**	.368**	-.266**	.792**	-.315**	1.000			
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	-			
	R9	Cor. Coef.	.664**	-.342**	.763**	-.365**	.726**	-.391**	.746**	-.451**	1.000		
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	-		
	R10	Cor. Coef.	-.251**	.638**	-.418**	.506**	-.361**	.654**	-.379**	.711**	-.490**	1.000	
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	-	
	Syntagma	Cor. Coef.	-.155**	-.067**	-.225**	.151**	-.267**	-.024	-.235**	-.185**	-.136**	-.165**	1.000
		Sig. (2-tailed)	.000	.001	.000	.000	.000	.232	.000	.000	.000	.000	-

**. Correlation is significant at the 0.01 level (2-tailed).

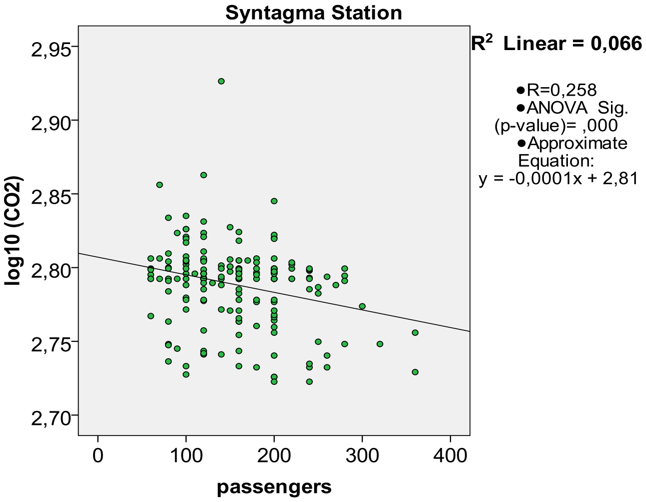


Figure 7. Scatter plot and linear fitting of logarithmic CO_2 concentrations and the number of passengers for Syntagma station.

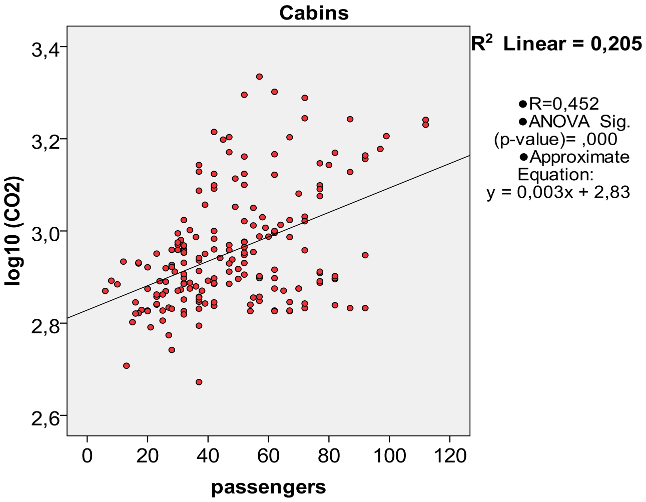


Figure 8. Scatter plot and linear fitting of logarithmic CO_2 concentrations and the number of passengers for the trains.

3.3. Comparison with outdoor measurements

In order to assess the impact of the outdoor environment on the indoor air quality, PM_{10} concentrations from stations of the Athens Air Quality Monitoring Network were compared with data from the four platforms and cabins for each experimental day. Line 3 was divided into three sectors depending on the underground depth and location with respect to the ground. Sector 1 covers the densely populated area of west and central Athens (stations Egaleo to Panormou). Sector 2 is the suburban area between to the northeast (stations Katehaki to D.Plakentias). Sector 3 includes the ground level part travelling through the eastern suburbs outside the Athens basin (stations Pallini to Airport). The nearest stations are Aristotelous, Ag.Paraskevi and Spata, respectively (Table 6).

Table 6. PM_{10} concentrations of platforms and local outdoor stations for all experimental days.

PM10 ($\mu g\ m^{-3}$) Daily mean	Locations of measurements Syntagma (underground)	Aristotelous str. (ground level)	D.Plakentias (underground)	Aghia Paraskevi (ground level)	Airport (ground level)	Spata (ground level)
06/27/2012	-	-	-	-	38.4	20.1
06/28/2012	-	-	-	-	24	16.5
07/11/2012	247.5	33.2	95.2	37.1	42.4	29.8
07/12/2012	276.5	44.1	103.3	43.2	54.1	31.8
07/18/2012	-	-	-	-	30.3	21.3
07/19/2012	-	-	-	-	27	17.4
07/25/2012	203.5	33.1	118.5	41.2	-	-
07/26/2012	207	25.2	92.9	31.1	-	-
08/01/2012	376.6	22.2	-	-	29.5	19.7
08/02/2012	301.3	26.1	-	-	38.5	23.7
08/08/2012	-	-	106.8	37.1	56.5	31.8
08/09/2012	-	-	80.3	39.1	57.9	33.3

Results show that during all experimental days the concentration of PM_{10} in Syntagma is higher by 4 to 7 times with respect to the busy local street of Aristotelous, and constantly above 50 $\mu g\ m^{-3}$. Subsequently, the same behavior is observed at D.Plakentias station with air pollution levels exceeding almost three times those of the outdoor environment. At the Airport station the PM_{10} concentrations are quite smaller, compared to the other platforms but still higher than those of the Spata station. Furthermore, with the exception of the Airport station platform, no significant correlation was observed between indoor and outdoor PM_{10} levels, indicating that they are not affected by the air pollution changes that occur outside, (Table 7).

Regarding the in-cabin data, in Sector 1 a passenger taking the route Egaleo-Panormou (or vice versa) will be exposed to PM_{10} concentrations almost three times higher compared to someone who moves on Aristotelous street. A similar behavior but at lower concentration levels was found in Sector 2, where for the Katehaki – D.Plakentias route the values were higher than these of the suburban station of Ag. Paraskevi. On 25 and 26 of July measurements were taken in old cabins only, which explains the significantly higher values. Sector 3 is the biggest part of the route to the Airport and it can be seen that PM_{10} levels remained lower than the external, approximately for half experimental days. Finally, as expected, Table 9 demonstrates that no significant covariance of PM_{10} among trains and the local meteorological stations is observed.

In figures 9a and b one may observe the PM_{10} and $PM_{2.5}$ fluctuations within the new train travelling the route from Egaleo to the Airport, while measurements are taken across the Syntagma platform. It is observed that in the deeper parts of the route the concentrations are higher (from LST 9:20 am to 9:41 am approximately) and unsteady, while moving towards the Sectors 2 and 3 they drop and finally remain almost constant until it reached the Airport station and they peak again for a short while. It is also observed that PM concentrations are significantly higher and vary on the platform while the train arrivals further increase their values.

Table 7. Spearman correlations of PM_{10} between platforms and the local meteorological stations.

PM_{10} *Platforms vs. Local outdoor stations*			Syntagma	D.Plakentias	Airport
Spearman's rho	Aristotelous str.	Cor. Coef.	-.377	.232	.881**
		Sig. (2-tailed)	.461	.658	.001
	Aghia Paraskevi	Cor. Coef.	-.543	.377	.884**
		Sig. (2-tailed)	.266	.461	.001
	Spata	Cor. Coef.	-.800	-.316	.985**
		Sig. (2-tailed)	.200	.684	.000

**. Correlation is significant at the 0.01 level (2-tailed).

Table 8. PM_{10} concentrations of trains and local outdoor stations for all experimental days.

	Locations of measurements					
PM10 ($\mu g\ m^{-3}$) Daily mean	Sector 1 (underground)	Aristotelous str. (ground level)	Sector 2 (underground)	Aghia Paraskevi (ground level)	Sector 3 (ground level)	Spata (ground level)
06/27/2012	95.9	28.1	78.8	28.2	29.1	20.1
06/28/2012	104.9	22.1	71.7	21.2	21.7	16.5
07/11/2012	109	33.2	73.3	37.1	24.1	29.8
07/12/2012	129.8	44.1	92.9	43.2	27.0	31.8
07/18/2012	96.2	29.2	71.9	26.1	23.4	21.3
07/19/2012	84.6	23.1	68.3	22.1	26.6	17.4
07/25/2012	282.5	33.1	236.3	41.2	-	-
07/26/2012	236.2	25.2	163.8	31.1	-	-
08/01/2012	66.4	22.2	46.4	27.2	23.4	19.7
08/02/2012	59.8	26.1	43.7	26.1	20.1	23.7
08/08/2012	70.1	40.2	61.1	37.1	33.1	31.8
08/09/2012	64.6	36.2	51.5	39.1	21.2	33.3

Table 9. Spearman correlations of PM_{10} between trains and the local meteorological stations.

PM_{10} Trains vs. Local outdoor stations			Sector 1	Sector 2	Sector 3
Spearman's rho	Aristotelous str.	Cor. Coef.	.147	.253	.412
		Sig. (2-tailed)	.648	.428	.237
	Aghia Paraskevi	Cor. Coef.	.347	.435	.346
		Sig. (2-tailed)	.269	.157	.328
	Spata	Cor. Coef.	-.103	.018	.091
		Sig. (2-tailed)	.776	.960	.802

**. Correlation is significant at the 0.01 level (2-tailed).

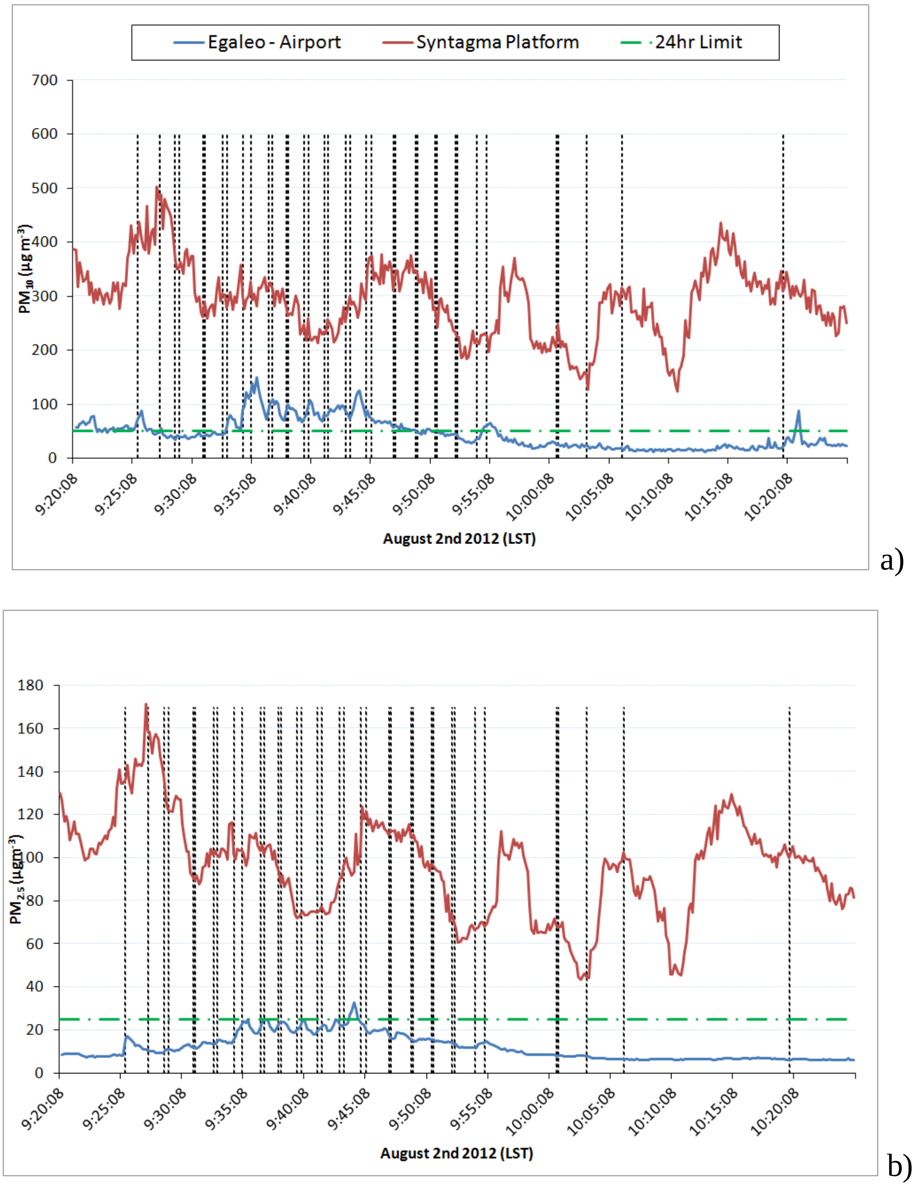


Figure 9. a) PM$_{10}$ and b) PM$_{2.5}$ concentrations for a single route from Egaleo to the Airport (blue line), with simultaneous measurements on the Syntagma platform (red line).The vertical dotted lines indicate train stops at all stations of the route.

4. Concluding remarks

The monitoring of indoor air quality in the Athens Metro took place during the summer of 2012 and lasted for 12 days, between June 27th and August 9th. Continuous measurements of PM$_1$, PM$_{2.5}$, PM$_{10}$, CO$_2$, T and RH were taken with the aid of portable instrumentation between 6:30 am and 7:00 pm. The experimental methodology included simultaneous measurements across the full length of the platforms of Egaleo, Syntagma, D.Plakentias and Airport, as well as measurements in old (naturally ventilated) and new (air-conditioned) train cabins of Line 3 (Egaleo–Airport). Line 3 has an underground segment from Egaleo to D.Plakentias and a terrestrial from there to the Airport.

All PM fractions exhibited higher concentrations in the underground platforms as compared to old and new cabins and the outdoor air. Syntagma, the most crowded and deep station platform presented the most polluted environment, followed by Egaleo and D.Plakentias that are closer to the ground. The frequent movement of passengers on platforms along with the frequency of train services led to the re-suspension of particulates emitted from sources such as train brakes and excavation material. On the other hand PM concentrations in the old and new trains were lower because of the confined space that limits passenger movements and the closed (air-conditioned) windows that isolate the in-cabin air from the polluted tunnel air. Sudden peaks (characterized as outliers) appeared during embarkation-disembarkation of passengers at each station. PM_{10} levels on the Airport were similar to the outdoor ones since it is a ground, open air space.

New train cabins that are air-conditioned presented the lowest (although still burdened) PM levels since the windows on the coaches were closed. However, CO_2 concentrations were elevated as compared to the platforms and old cabins because of the recirculation of air and the number of passengers on board. CO_2 measured on the platforms was unaffected by the number of people present. The temperature in the trains was lower than on platforms. Absolute humidity was slightly elevated in the cabins. Both variables remained almost constant on the platforms in contrast with the trains where they fluctuated depending on the position of the train (terrestrial or underground) and the number of commuters.

Continuous measurements of all variables in the moving trains showed that PM levels are higher in the underground parts of the route and reduce significantly at the terrestrial part. However, statistical comparisons between the outdoor and indoor measurements showed that the underground environment is not affected by the outdoor conditions. Moreover, the biggest part of PM consists of coarse particles that originate from the excavation and construction works, the train materials and the re-suspension. The external particulate pollution had no significant influence on the underground platforms of Syntagma and Doukissis Plakentias and did not affect the interior environment of the cabins. However, strong correlations were observed with the terrestrial platform of the Airport.

Acknowledgements

The authors wish to thank the Mariolopoulos-Kanaginis Foundation for Environmental Sciences for supporting financially this work and the ATTIKO METRO S.A. for facilitating the experimental campaign.

Conflict of interest

The authors declare there is no conflict of interest.

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