Safety and Health at Work 10 (2019) 377–383

Contents lists available at ScienceDirect

Safety and Health at Work

journal homepage: www.e-shaw.org

Original Article

Exposure to Particles and Nitrogen Dioxide Among Workers in the Stockholm Underground Train System

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ARTICLE INFO

Article history:
Received 3 December 2018
Received in revised form
16 May 2019
Accepted 13 June 2019
Available online 20 June 2019

Keywords:
Airborne exposure
Occupation
Particle exposure
Subway

ABSTRACT

Objectives: Exposure to fine particles in urban air has been associated with a number of negative health effects. High levels of fine particles have been detected at underground stations in big cities. We investigated the exposure conditions in four occupational groups in the Stockholm underground train system to identify high-exposed groups and study variations in exposure.
Methods: PM_1 and $PM_{2.5}$ were measured during three full work shifts on 44 underground workers. Fluctuations in exposure were monitored by a real-time particle monitoring instrument, pDR, DataRAM. Qualitative analysis of particle content was performed using inductively coupled plasma mass spectrometry. Nitrogen dioxide was measured using passive monitors.
Results: For all underground workers, the geometric mean (GM) of PM_1 was 18 $\mu g/m^3$ and of $PM_{2.5}$ was 37 $\mu g/m^3$. The particle exposure was highest for cleaners/platform workers, and the GM of PM_1 was 31.6 $\mu g/m^3$ [geometric standard deviation (GSD), 1.6] and of $PM_{2.5}$ was 76.5 $\mu g/m^3$ (GSD, 1.3); the particle exposure was lowest for ticket sellers, and the GM of PM_1 was 4.9 $\mu g/m^3$ (GSD, 2.1) and of $PM_{2.5}$ was 9.3 $\mu g/m^3$ (GSD, 1.5). The PM_1 and $PM_{2.5}$ levels were five times higher in the underground system than at the street level, and the particles in the underground had high iron content. The train driver's nitrogen dioxide exposure level was 64.1 $\mu g/m^3$ (GSD, 1.5).
Conclusions: Cleaners and other platform workers were statistically significantly more exposed to particles than train drivers or ticket sellers. Particle concentrations ($PM_{2.5}$) in the Stockholm underground system were within the same range as in the New York underground system but were much lower than in several older underground systems around the world.

1. Introduction

Epidemiological studies have shown associations between high concentrations of particles in urban air, which are mainly produced by traffic, and morbidity and mortality [1–4] from cancer [5] and cardiovascular and respiratory diseases [3,6,7]. In tunnel systems, particles are produced from the wear of the rails and electrical power bar, and silica dust is emitted from the support material on the ground around the sleepers. High particle concentrations have been found in underground train systems around the world, including New York [8,9], London [10,18], Helsinki [11], Rome [12], Beijing [13], Taipei [14,15], Seoul [16], and Barcelona [17].

Particle concentration measurements in the Stockholm underground train system, powered by electricity, have been performed on a number of occasions since 1982 [19]. A very high airborne particle concentration (daytime $PM_{2.5} = 264$ $\mu g/m^3$) was found at Mariatorget station [20], which led to extensive surveys aimed at determining the sources of the particles [21].

In this study, we aimed to determine the personal exposure of four occupational groups in the Stockholm underground train system to two different size fraction particles and nitrogen dioxide (NO_2). Our strategy was to obtain representative exposure concentrations for different occupational groups to identify the most high-exposed occupational groups. The results have also been used

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https://doi.org/10.1016/j.shaw.2019.06.005

for a clinical study of effects on the respiratory and cardiovascular systems in underground staff, [22,23]. The participants all gave their informed consent to participate. The study was approved by the Stockholm Regional Ethics Committee (no. 04-071/1).

2. Materials and methods

A total of 44 Stockholm underground train system workers, all aged ≤50 years, were selected for exposure measurements, from four occupational categories: cleaners/platform workers (n = 11), ticket collectors (n = 12), ticket sellers (n = 8), and train drivers (n = 13).

Train drivers' cabins are separate from other compartments in the train. The driver steps out of the cabin and stands on the platform at stations to supervise passengers boarding and alighting from the train. Train drivers in Stockholm are in tunnels for about 25% of each shift, and on average, they spend about 0.5–1 min on the platform at each station. Ticket collectors make random checks of tickets on the trains or at the platforms. Cleaners clean the platforms and escalators, mainly by dry and wet sweeping. Ticket sellers, sitting in separately ventilated toll booths often located one floor above the platforms, were selected to represent a low-exposed group.

Most participants worked morning shifts during the sampling period, but some of the workers also worked day or evening shifts. All participants in our study had a rotating shift pattern, with a focus on morning shifts, for a month. All trains used on the line studied were of Type C33, a three-carriage train for 800 passengers, all built between 1998 and 2002. We studied the part of the Stockholm underground system along the 41.3-km-long Green Line trail with 49 stations; of which, 12 are below the ground. Through the track, the train runs through many tunnels; of which, the longest is 6.1 km, under central Stockholm.

The exposure assessments were performed in the winter of 2004/5 and in the spring of 2005. Each participant wore personal sampling devices over three consecutive work shifts. Each exposure assessment lasted about 8 h. A maximum of two sampling devices were used simultaneously because the participants could not conveniently carry more. Suspended particulate matter, PM_1 and $PM_{2.5}$, samples were sampled over two shifts to allow sufficient numbers of particles to be collected on the filters for gravimetric analysis. Air was drawn through the same filter for about 8 h during each shift, so the sampled dust concentrations were 16-h time-weighted averages.

Train drivers also used log books to record their activities, for example, time spent in tunnels, at the street level, in lunch breaks, and at the terminus. This was also controlled by an industrial hygienist.

2.1. *Particulates—quantitative sampling*

We collected $PM_{2.5}$ using a cyclone GK2.05 (KTL) Respirable/Thoracic Cyclone (BGI Incorporated, Waltham, MA, USA) with an air flow rate of 4 L/min, which gave 50% collection efficiency for particles with aerodynamic diameters of 2.5 μm [24]. We collected PM_1 using an SCC1.062 Triplex Cyclone (BGI Incorporated) with an air flow of 3.5 L/min. GilAir-5 (Sensidyne, St. Petersburg, Florida, USA) sampling pumps were used. Air was drawn through the filter for a total of about 16 h, over two shifts, to collect enough particles for analysis. The flow rate was checked before and after each measurement using a DryCal DC-Lite (Bios International Corporation, Prairieville, Los Angeles, USA); 37-mm Teflon filters were used, and these were weighed using a balance sensitive to 0.001 mg in a room maintained at a constant temperature of 20°C and 50% relative humidity. The filters were conditioned in the weighing room for 24 h before being weighed.

We measured mass concentration of 0.1–10 μm particles using the DataRAM Type MIE pDR 1000 (Thermo Fisher Scientific, Waltham, MA, USA), which is a light scattering instrument that uses a nephelometric method and optimized for measuring the respirable particle fraction. A DataRAM measures 0.1–10 μm particles, records the number of particles, and then converts this into a mass concentration (mg/m^3). The DataRAM was gravimetrically calibrated using a fine test dust standard (mmd = 2 to 3 μm, $\delta = 2.5\ g/cm^3$, as aerosolized; SAE J 726 Fine Standard test dust, which conforms to ISO 12103 Pt 1). The operational range of the instrument was 1–400 mg/m^3; the instrument was calibrated with a calibrating adjustment factor at the start of the study, and the zero was checked before each use. For the measurements, the average value for every minute was logged. For five drivers, readings were made every ten seconds to assess how fast the particle concentration changes inside the drivers' cabins.

NO_2 was measured in the working environment by the participants using portable diffusion samplers developed by the Swedish Environmental Institute (IVL), which also performed the analysis. The measurement uncertainty was 10% for the passive NO_2 samplers, which were analyzed by spectrophotometry [25], and the detection limit was approximately 4.5 $\mu g/m^3$ for 8-h samples. A total of 25 full shift measurements were carried out in the working environments of the cleaners (n = 8), ticket sellers (n = 5), and train drivers (n = 5). NO_2 was not measured for the ticket collectors.

Background outdoor NO_2 concentrations at the roof level were obtained from the environmental database at SLB Analys center (the Environment Department, Flemminggatan 4, Stockholm). These were used to represent the general NO_2 levels for the public. These background ambient NO_2 concentrations are measured using a chemiluminescence real-time monitoring instrument.

Both DataRAM and the cyclones were calibrated each day before measurements. We sampled two persons in parallel for three days: Day 1, just PM_1 and $PM_{2.5}$; Day 2, PM_1 and $PM_{2.5}$ plus DataRAM; and Day 3: DataRAM plus NO_2 devices.

2.2. *Qualitative analysis*

Twenty 37-mm filters, ten for each fraction collected randomly, and two blank samples were analyzed for 13 metals by SGAB-Analytica (Luleå, Sweden), by means of inductively coupled plasma (ICP) sector field mass spectrometry, using modified US Environmental Protection Agency methods 200.7 inductively coupled plasma - atomic emission spectrometry (ICP-AES) and 200.8 inductively coupled plasma - quality management system (ICP-QMS).

Four filters, two for each fraction collected randomly from the train drivers, were analyzed for quartz by SGAB-Analytica using Fourier-transform infrared spectroscopy following the National Institute of Occupational Health and Safety (NIOSH) 7602 method.

2.2.1. *Statistical analysis*

Kolmogorov–Smirnov tests indicated nonnormality, which was confirmed by frequency distributions revealing highly skewed data regarding $PM_{1.0}$, $PM_{2.5}$, and pDR, DataRAM, respectively. Thus, natural logarithms of the data were calculated, and both the arithmetic mean and geometric mean (GM) and their corresponding standard deviations and geometric standard deviation (GSD) were calculated for each group. The GM is a mean or average, which indicates the central tendency or typical value of a set of numbers by using the product of their values. In probability theory and statistics, the GSD describes how spread out are a set of numbers whose preferred average is the GM. For such data, it may be more preferred to the usual standard deviation.

To interpret differences on the arithmetic rather than on the geometric scale, a formula presented by Zou et al. [26] was used to calculate the 95% confidence intervals of the arithmetic differences. The formula for calculating the arithmetic mean and the lower and upper limits based on a 95% confidence interval for a single group based on log-normal data is as follows:

$$\mu_{X_i} = \exp\left[\mu_{Y_i} + \frac{\sigma^2_{Y_i}}{2}\right]$$

$$l_i = \mu_{X_i} + \frac{\sigma^2_{X_i}}{2} - \sqrt{Z^2_{\alpha/2}\frac{\sigma^2_{X_i}}{2} + \left\{\frac{\sigma^2_{X_i}}{2}\left(1 - \frac{n-1}{\chi^2_{\alpha/2,\, n-1}}\right)\right\}^2}$$

$$u_i = \mu_{X_i} + \frac{\sigma^2_{X_i}}{2} + \sqrt{Z^2_{\alpha/2}\frac{\sigma^2_{X_i}}{2} + \left\{\frac{\sigma^2_{X_i}}{2}\left(\frac{n-1}{\chi^2_{\alpha/2,\, n-1}} - 1\right)\right\}^2}$$

where

$$\mu_{X_i} = \mathit{arithmetic\ mean\ for\ group\ i}$$

$$\mu_{Y_i} = \mathit{logarithmic\ mean\ for\ group\ i}$$

$$\sigma^2_{Y_i} = \mathit{logarithmic\ variance\ for\ group\ i}$$

$$Z^2_{\alpha/2} = \mathit{square\ of\ the\ critical\ value\ received\ from\ a\ standard\ normal\ distribution,\ in\ our\ case\ the\ critical\ value} = 1.96$$

$$\chi^2_{\alpha/2,n-1} = \mathit{critical\ value\ received\ from\ a\ chisquare\ distribution\ with}\ n-1\ \mathit{degrees\ of\ freedom}$$

The lower and upper limits of a 95% confidence interval for the difference between two groups i and j can then be calculated as follows:

$$L = \mu_{X_i} - \mu_{X_j} - \sqrt{(\mu_{X_i} - l_i)^2 + \left(u_j - \mu_{X_j}\right)^2}$$

$$U = \mu_{X_i} - \mu_{X_j} - \sqrt{(u_i - \mu_{X_i})^2 + \left(\mu_{X_j} - l_j\right)^2}$$

3. Results

For all underground workers, the GM of PM_1 was 18 μg/m^3 and of $PM_{2.5}$ was 37 μg/m^3. The particle exposure was highest for cleaners/platform workers, and the GM of PM_1 was 31.6 μg/m^3 (GSD, 1.6) and of $PM_{2.5}$ was 76.5 μg/m^3 (GSD, 1.3); the particle exposure was lowest for ticket sellers, and the GM of PM_1 was 4.9 μg/m^3 (GSD, 2.1) and of $PM_{2.5}$ was 9.3 μg/m^3 (GSD, 1.5). The PM_1 and $PM_{2.5}$ levels were five times higher in the underground system than at the street level, and the particles in the underground had high iron content. The train driver's NO_2 exposure level was 64.1 μg/m^3 (GSD, 1.5), which was corresponding to that of bus drivers in Stockholm. The results of the PM_1, $PM_{2.5}$, pDR concentrations, and NO_2 measurements are shown in Table 1.

The ticket collectors and cleaners, who spent most of the time on the platforms, had the highest exposures. The train drivers had slightly lower exposures, and particle exposures were the lowest for the ticket sellers. There were statistically significant differences regarding PM_1, $PM_{2.5}$, and pDR exposures between all four occupational groups. But there were no statistically significant differences regarding PM_1 exposures of train drivers vs ticket sellers and cleaners vs ticket collectors.

The group GM concentrations of NO_2 were 29.8–64.1 mg/m^3, with train drivers being exposed to the highest mean concentrations, 64.1 mg/m^3. The mean NO_2 exposure level was not statistically significantly higher for train drivers and cleaners than for ticket sellers. NO_2 exposure levels for ticket collectors were not measured (Table 1).

A quarter of the underground system is below the ground and located in central Stockholm. The system is mainly above the ground in suburban areas. Fig. 1 shows the typical pDR exposure pattern for a train driver during a standard shift, measured using the DataRAM real-time monitoring instrument. The high and wide

Table 1

Particle concentrations (μg/m^3) for 44 underground employees by occupation and particle size fraction for a total of 132 full shifts.

Numbers	Air contaminants	Number of samples	AM (μg/m^3)	SD (μg/m^3)	GM (μg/m^3)	GSD (μg/m^3)	Range (μg/m^3)
Ticket sellers	PM_1	9	6.1	3.7	4.9	2.1	1.7–11.2
n = 8	$PM_{2.5}$	8	10.1	4.6	9.3	1.5	6.0-19.4
	0.1–10 μm	7	13.2	2.7	12.1	1.4	10-18
	NO_2	5	32.4	12.1	29.8	1.6	14.0-48.5
Train drivers	PM_1	12	9.1	2.6	8.6	1.4	3.4-12.6
n = 13	$PM_{2.5}$	13	18.8	5.4	18.2	1.3	12.2-32.4
	0.1–10 μm	16	32.2	11.9	30.7	1.5	15-88
	NO_2	5	67.0	21.2	64.1	1.5	41.8-107.3
Ticket collectors	PM_1	10	26.7	18.5	23.4	1.6	14.3-79.1
n = 12	$PM_{2.5}$	9	48.9	24.7	47.5	1.3	32.1-74.1
	0.1–10 μm	13	108.3	26.3	103.6	1.4	44-184
	NO_2	*	*	*	*	*	*
Cleaners	PM_1	8	35.1	18.9	31.6	1.6	16.7-69.9
n = 11	$PM_{2.5}$	8	79.6	12.8	76.5	1.3	56.3-132
	0.1–10 μm	13	256	97.2	242	1.4	139-775
	NO_2	8	47.1	19.2	44.8	1.5	19.7-90.3

AM, arithmetic mean; GM, geometric mean; GSD, geometric standard deviation; NO_2, nitrogen dioxide; SD, standard deviation.

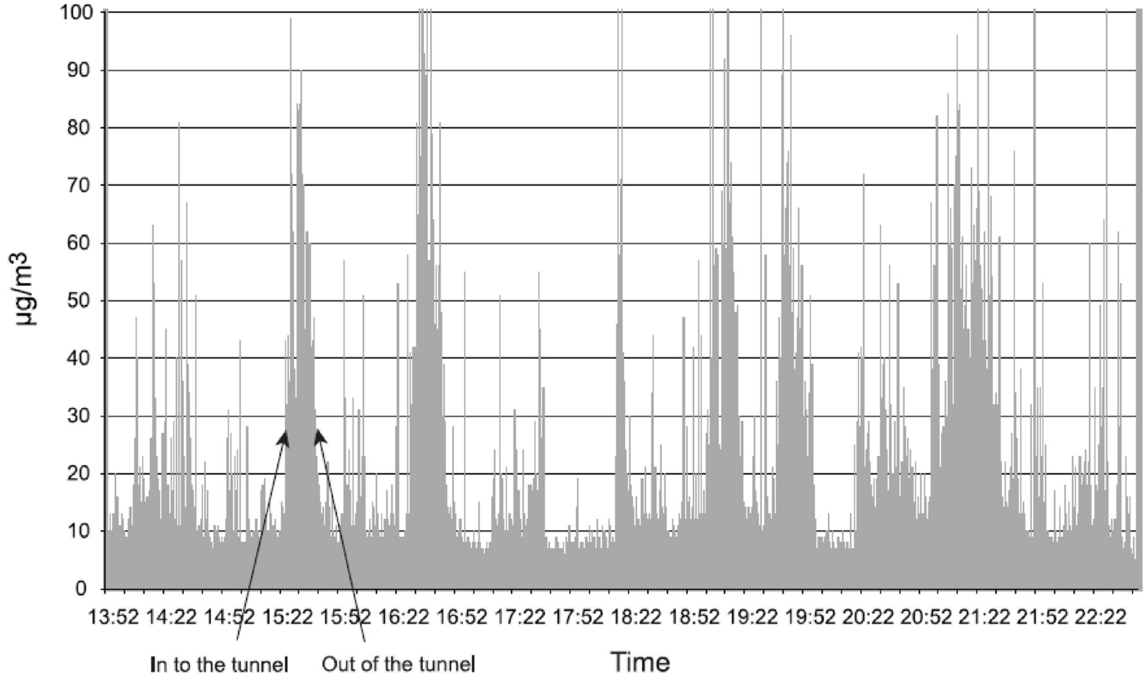

Fig. 1. A full shift particles measurement in the range 0.1 to 10 µm curve from a train driver during an average period at the studied underground line. The graph shows the average exposure for every minute. The average value during the sampling shift was 19 µg/m^3. Each thin peak illustrates the driver's exposure when she opened the train cabin door and stood on the platform. Thick wide bars indicate traveling inside the tunnel in Stockholm city.

bars indicate when the drivers are in the tunnels in central Stockholm. When the train enters a tunnel, the particle concentration increases fourfold on average, from 20 to 80 µg/m^3. Exposure is higher in some platforms because of longer stops at those stations in the center of Stockholm because the driver leaves the cabin and stays on the platform until all the passengers have boarded the train.

The results of the metal analysis are shown in Table 2. The metal contents of the particles were around 20% of the total particle masses, lower in PM_1 than in $PM_{2.5}$. Iron was by far the greatest contributor to the metals in the particles. Copper contributed around 0.4% of the total amount of metals in the particles, and the other metals contributed negligible amounts. The samples from the ticket sellers had a lower metal content than those from the other occupational groups except copper in the PM_1 size.

The quartz contents in the particles were determined only for the train drivers, and low (2.4%) amounts of quartz were found in $PM_{2.5}$. No quartz was detected in PM_1.

The time-weighted average background NO_2 concentration in Stockholm during the study period (i.e., the time period when participants were wearing the sampling devices) was 24.1 µg/m^3, recorded by SLB (the Environmental Department, Stockholm).

Table 2

Weight proportion of metals in the gravimetric sampling subdivided by the professional group and particulate fraction.

Occupation	PM_1					$PM_{2.5}$				
	n	% Fe	% Cu	% Mn	Total*	n	% Fe	% Cu	% Mn	Total*
Ticket sellers	2	3,4	0,40	0,06	4 %	2	9,5	0,36	0,10	10 %
Train drivers	4	10,5	0,48	0,10	11 %	4	21,1	0,42	0,21	22 %
Ticket collectors	2	20,6	0,38	0,19	21 %	2	30,5	0,45	0,29	31 %
Cleaners	2	21,3	0,38	0,29	22 %	2	24,1	0,33	0,24	25 %
Mean level	**10**	**13,2**	**0,41**	**0,18**	**14 %**	**10**	**21,2**	**0,41**	**0,18**	**22 %**

Mean level for each column in bold. Total metal content in all samples: <19 %, of which iron = 17.6%.

Cu, copper; Fe, iron; Mn, manganese.

* The samples were also analyzed for arsenic (As), cadmium (Cd), cobalt (Co), chromium (Cr), molybdenum (Mo), nickel (Ni), lead (Pb), vanadin (V), and zinc (Zn). The content of these substances was negligible.

4. Discussion

There were statistically significant differences regarding particle concentrations between the occupational groups.

The cleaners were exposed to the highest concentrations of all the particle sizes measured. During the measurement period, the cleaners not only cleaned the platforms but also moved between stations, spent time inside the trains, and cleaned stairs and floor areas above the platforms. The average $PM_{2.5}$ concentration to which the cleaners were exposed was similar to that measured in a study of an underground platform in Stockholm, on the same line [27].

The train drivers were primarily exposed to particles when they were outside their cabins in the underground stations. The particle concentrations were lower inside the cabins than in the surrounding air in the stations, but the concentrations increased when the cabin doors were opened at the stations. The real-time monitoring measurements showed that the pDR concentrations increased by a factor of 4–5 when the trains entered the long tunnels under Stockholm city. Drivers' cabins are equipped with efficient filters high efficiency particulate arresting filters(HEPA filters), and that is probably why lower particle concentrations were found inside the cabins. The other coaches in the trains have filters with lower efficiency. Higher particle concentrations occurred in the tunnels in Stockholm city, and the stops at the platforms are longer than in the suburban stops.

Ticket collectors normally travel on the trains for most of the time but also spend time on the platforms and in the ticket halls. Both PM_1 and $PM_{2.5}$ measurements showed that the ticket collectors were exposed to about five times the particle concentrations that the ticket sellers were exposed to, whereas the pDR instrument showed eight times higher measurements, probably due to the pDR instrument measuring other particle sizes. The instrument is calibrated with a density to 2.5 mg/m^3, but the particles have a higher density owing to the iron dust, giving an overestimation of exposure vs. gravimetric measures. The pDR instrument was primarily used to observe the variation in particle concentrations along the track.

The ticket sellers were exposed to the lowest concentrations of all the pollutants measured. The $PM_{2.5}$ concentrations to which the ticket sellers were exposed were similar to concentrations that have been found inside the dwellings in Stockholm [28], and the NO_2 concentrations were slightly higher than background concentrations (32.4 μg/m^3 in the ticket sellers' booths and 24 μg/m^3 in the ambient environment). The ticket sellers were exposed to slightly higher proportions of fine particles (PM_1), of about 60% of the $PM_{2.5}$ concentrations, than the other occupational groups, for which PM_1 concentrations were about 50% of the $PM_{2.5}$ concentrations. This difference in the PM_1 contribution is small and could be a random result but could also be a consequence of the fact that the ticket sellers are exposed to particles with a higher contribution from sources other than underground trains, such as traffic emissions. The highest particle concentrations in the ticket sellers' booths were found in suburban areas, probably caused by sources such as wood burning in houses and intensive diesel bus traffic.

The train drivers were exposed to 1/15th of the current Swedish NO_2 occupational exposure limit (OEL) [29] and had the highest exposure to NO_2 of all the participants in this study. The cleaners, who were exposed to the highest particle concentrations, were exposed to 1/20th of the OEL for respirable inorganic particles (corresponding to PM_5). The OEL for inorganic respirable dust is 5000 μg/m^3, for respirable iron is 3500 μg/m^3, and for NO_2 is 960 μg/m^3.

The results of the exposure assessment have been used for a clinical study of effects on the respiratory and cardiovascular systems in underground staff. Early markers of cardiovascular disease plasminogen activator inhibitor-1(PAI-1) and high-sensitivity C-reactive protein (hs-CRP) were statistically significantly higher in employees with high exposure than in those with low exposure [22,23]. Many similar measurements have been made in major urban underground systems, including the systems of Helsinki, London, New York, Rome, Seoul, and Barcelona [8,10–12,17]. Unfortunately, different methods were used to measure particle exposure in each of these studies, so the results of these studies are not directly comparable with our own data. Just Line L9 in Barcelona showed lower $PM_{2.5}$ levels in the train cabins than in our study, whereas it was six times higher in the train cabins in Seoul.

The aims of previous studies have usually been to identify particle concentrations at a particular place, for example, on platforms. $PM_{2.5}$ concentrations of 47 μg/m^3 (Mexico) up to 480 μg/m^3 (London) have been measured on underground platforms [11,17,30]. Long-term measurements on platforms have been performed using stationary instruments (e.g., tapered element oscillating microbalance instruments). There have been few studies of occupational exposure using portable devices, but a median exposure for underground workers to $PM_{2.5}$ of 27 μg/m^3 (range, 6–469 μg/m^3) was found in New York [9]. In that study, the highest concentrations were found in a repair shop. The median $PM_{2.5}$ concentration in our study, for all four occupational groups, was 37 μg/m^3.

Train drivers' cabins are ventilated with filtered air through HEPA filters, and the ventilation system is separate from the ventilation systems used for the other parts of the train. This makes it difficult to compare our results with the results of other studies, in which measurements were made inside the passenger accommodation, for which other sources would have been relevant. In a few studies, particulate measurements have been made inside trains [8,10,31], for example, Seaton et al. [18] measured particle concentrations on the London Underground and found $PM_{2.5}$ concentrations of 130–200 μg/m^3 in drivers' cabins and of 270–480 μg/m^3 on platforms, 6–10 times higher in the cabins and 4–6 times higher on platforms compared with our study. Aarnio et al. [11] found $PM_{2.5}$ concentrations of 21 μg/m^3 inside carriages in Helsinki. $PM_{2.5}$ concentrations of 78–158 μg/m^3 were found inside underground train carriages in Seoul; these concentrations were higher than the concentrations found on the platforms, probably because Seoul trains do not have mechanical ventilation. The average $PM_{2.5}$ exposure inside the trains in Barcelona varied between different lines, 15–57 μg/m^3 [17].

The particles measured on one underground platform in a study from 2003 contained up to 60% iron in the PM_{10} fraction [32]. The ticket collectors who spend part of their time on platforms have 20% iron content in the PM_1 fraction and 20% iron content in the $PM_{2.5}$ fraction. Probably, the iron content is influenced by the size fraction.

The qualitative metal analysis showed differences in metal concentrations between the occupational groups. We found an iron content of 4% in the PM_1 fraction and 10% in the $PM_{2.5}$ fraction as the mean level for all occupations, suggesting that some of the particles entering the drivers' cabins originated in the underground environment (i.e., from the electrical current rail, the main rails, the power brakes, and the wheels). The Stockholm underground system uses reversed electricity in the electrical power rail to stop trains, and the brake shoes only operate at speeds less than 10 km/h, so the brakes are only a minor source of dust.

High metal concentrations have mainly been found in particles on the platforms of other underground systems [10,11,18]. Up to 80% of particles, by weight, have been found to be metals [33]. Seaton et al. [18] found that $PM_{2.5}$ sampled on a platform contained 64–71% iron, which is substantially higher than that we found in the particles to which the platform workers (cleaners and ticket collectors) were exposed to (25% and 23% iron content, respectively). This difference may be because the Stockholm platform workers did not only work on the platforms. Klepczynska Nyström et al. found 58% iron content in the PM_{10} fraction on a platform in the Stockholm underground system [27]. We found low manganese concentrations in the particles, whereas higher concentrations were found in other studies [12,34]. Manganese comes from the electrical power rail. Iron was the only metal that was found in large amounts in the particles in our study, at 31% in the $PM_{2.5}$ fraction, which is 50% higher than the concentrations found in the PM_1 fraction. The same finding (i.e., higher iron concentrations in the larger particles) was observed by Grass et al. [9]. We probably did not find higher iron concentrations because the majority of <1-μm particles are generated by combustion. Wear particles are usually larger, and this may explain why 60% iron content has been found in PM_{10}, which can be produced by the wear of brakes, rails, and wheels [32,34]. The copper content (0.4%) found in the particles may have originated from the motor windings and brakes.

The quartz content in the $PM_{2.5}$ fraction was 2.5%, but quartz was not found in the PM_1 fraction. This is in agreement with previous results of 1–2% quartz in $PM_{2.5}$. The quartz particles were probably caused by road wear from streets close to the overground part of the track.

The NO_2 measurements were relatively variable, and the variation depended partly on the variations in the background concentrations on the sampling days, obtained from the SLB database. The train drivers were exposed to the highest NO_2 concentrations, which could be explained by the fact that a large proportion of the overground train routes are close to busy roads and diesel bus terminals.

The background NO_2 concentrations (both outdoor and indoor) depend on local emissions from traffic, industries, and other combustion sources and the long-range transport of air pollution, and these concentrations vary throughout the year and even throughout the day. It is not surprising, therefore, that the background concentrations varied during the measurement period, both between different days and between different geographic areas (the inner city versus suburban areas).

The ticket sellers were exposed to $PM_{2.5}$ concentrations that were similar to background concentrations because their booths were ventilated using fresh air taken from outside. $PM_{2.5}$ concentrations in Swedish dwellings have been found to be around 10 $\mu g/m^3$ [34,35], and indoor and outdoor concentrations of both NO_2 and $PM_{2.5}$ have been found to be virtually the same in Stockholm area [27].

4.1. *Strengths and weaknesses*

A relatively complex measurement scheme made it possible to compare the exposure for different occupational groups on several different parameters, among them PM_1, which was not previously reported in this environment. We have achieved the purpose of understanding how the exposure varies between the different groups, and a parallel clinical study showed a correlation between particle levels and early markers of cardiovascular disease. This study has also been a basis for interventions and future planning for better health conditions for underground workers.

The weakness is that the material has few measurements, and we have not been able to investigate seasonal variation in exposure. The DataRAM instrument was used to study variations in exposure over time. Because the dust in the tunnels has a higher density than the standard dust used for calibration, the DataRAM will underestimate particle mass concentration.

5. Conclusions

In the present study, we assessed the personal occupational exposure to particles and NO_2 for different occupational groups in the Stockholm underground train system. $PM_{2.5}$ concentrations in the Stockholm underground system were in the same range as in other relatively newer underground systems but much lower than in several older underground systems. Cleaners and other platform workers were exposed to much higher particle concentrations than train drivers and ticket sellers during the winter when this study was performed. Gravimetric sampling is the most appropriate method for assessing exposure to particles, but real-time monitoring of pDR-measured particles (0.1–10 μm) illustrates variations in exposure throughout the day.

Conflict of interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors thank Eva Lenell for carrying out most of the exposure measurements. The authors also thank the project managers and union representatives at Connex for helping them select the study participants. The study was financed by FAS (the Swedish Council for Working Life and Social Research, Stockholm, Sweden).

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